Proceedings of the Final Conference in Innsbruck

Sustainability of Constructions
Towards a better built environment

COST C25 - sustainability of constructions

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Proceedings of the
International Conference
Sustainability of Constructions
Towards a Better Built Environment
Final Conference of the COST Action C25

Innsbruck, 3-5 February 2011

Editors:
L. Bragança, H. Koukkari, R. Blok, H. Gervásio, M. Veljkovic,
R.P. Borg, R. Landolfo, V. Ungureanu, C. Schaur

COST is supported by the EU RTD Framework Programme and ESF provides the COST Office through an EC contract

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Proceedings of the International Conference
Sustainability of Constructions - Towards a Better Built Environment

Final Conference of the COST Action C25
Sustainability of Constructions - Integrated Approach to Life-time Structural Engineering

Innsbruck, 3-5 February 2011

Editors: Luís Bragança, Heli Koukkari, Rijk Blok, Helena Gervásio, Milan Veljkovic, Ruben Paul Borg, Raffaele Landolfo, Viorel Ungureanu, Christian Schaur

Cover Design: Bogdan Oprescu
Cover illustration is based on a painting of Gerda Medinaceli.

The production of this publication was supported by COST: www.cost.eu

ISBN: 978-99957-816-0-6

Published by: Department of Civil & Structural Engineering,
Faculty for the Built Environment,
University of Malta, Malta.

Printed by Gutenberg Press Ltd, Malta.

February 2011

Contents

Foreword

The built environment has evolved to frame and facilitate nearly all human activities. Simultaneously, its constant expansion has become more and more harmful to the natural environment. In order to turn the global trends toward the optimistic transition scenario of the sustainable development, the built environment needs to be rethought. The construction and building sector play a key role in creation the better future.

In 1999, CIB - International Council for Research and Innovation in Building and Construction, adopted the goal of sustainable construction as "…creating and operating a healthy built environment based on resource efficiency and ecological principles" and later on articulated the 7 Principles of Sustainable Construction: 1) Reduce resource consumption; 2) Reuse resources; 3) Use recyclable resources; 4) Protect nature; 5) Eliminate toxics; 6) Apply life-cycle costing and 7) Focus on quality. The sustainable construction involves ways and means to implement life-cycle thinking in the built environment. In the early stages of the concept development, the environmental impacts were emphasised but the social, economic and cultural aspects of sustainable development are regarded as important nowadays.

This publication is the Proceedings of the Final Conference of the COST Action C25, opened to the public under the theme "Sustainability of Constructions - Towards a better built environment". The Action C25 "Sustainability of Constructions - Integrated Approach to Life-time Structural Engineering" was established to promote science- and research-based approaches for life-cycle building technologies. It is one prominent landmark of a worldwide movement aiming at knowledge creation and dissemination in the field of sustainable construction. The amount of researchers, stakeholders and practitioners conscious of sustainability has grown from some tens of pioneers to tens of thousands. The methods of sustainable architecture and life-time engineering are been developed and implemented more often as a part of everyday practices. Several international networks and organisations have been organised in order to promote the sustainable construction like e.g. the International Initiative for a Sustainable Built Environment (iiSBE) and the International Association for Life Cycle Civil Engineering (IALCCE).

The Kick-off Meeting of the Action C25 was held on the 3rd of October 2006 in Brussels. In total, 28 countries (Austria, Belgium, Bulgaria, Croatia, Czech Republic, Cyprus, Denmark, Finland, fyr Macedonia, Germany, Greece, Hungary, Italy, Latvia, Lithuania, Luxembourg, Malta, The Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovenia, Sweden, Switzerland, Turkey and The United Kingdom) and one EC Joint Research Centre joined this network. The participating countries nominated almost one hundred Management Committee (MC) delegates and Working Group (WG) members, which represent different fields of expertise, different cultures, different approaches and different visions of the society and the world. Ten Management Committee meetings have been organised in nine COST countries during the course of four years that the Action was active.

These Proceedings cover a wide range of up-to-date issues that reflect research in the participating countries in the field of sustainable constructions. The issues presented include:

- Eco-efficient materials and technologies
- Innovative construction systems
- Sustainability Assessment of Constructions
- Adaptation to Climate Change
- Design and Technologies for Energy Efficiency
- Life-time structural engineering
- Maintenance and Monitoring
- Renovation and Retrofitting
- Policy for sustainable development

The Organizing Committee wants to warmly thank all the keynote speakers and authors of conference papers. Their efforts reflect their commitment and dedication to Science and Sustainable Construction. The conference received more than one hundred abstracts and after the revision process about 75% were accepted to be published. About half of the papers are from non-C25 members which denote the public interest on the conference.

A special gratitude is also addressed to Dr. Thierry Goger and Ms. Carmencita Malimban from COST Office and ESF (European Science Foundation) for their support and help in administrative matters.

This publication represents one more important milestone in fulfilment of the main aims of the COST Action C25. The organisers of the conference hope that it will inspire all participants to work for changing the trends of construction sector and use of the built environment.

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European Lead Market Initiative and Sustainable Construction

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ABSTRACT: Sustainable Construction (SC) is one of six lead markets in the EU which have been selected for their high potential of innovation and market growth. Within the lead market initiative (LMI) for Europe individual action plans of 3-5 years were developed to support the lead markets by innovation-friendly and barrier-reducing policy instruments. One barrier is the high market fragmentation and high administrative costs due to uncoordinated regulation on different levels. Taking Germany as an example the framework for SC is analyzed with respect to public and private measures and initiatives. The establishment of a national strategy for SC coordinated on national level by a public central body is determined as one central element to reduce administrative burdens and to optimize and communicate initiatives and public research activities. To support SC a consistent national regulatory framework is essential, including functional, performance-based building related regulations, concentrating on certain objectives through the optimization of the planning process and by looking at the structure as a whole. A widening of the current approach which focuses strongly on energy efficiency, technical issues and construction products by social, cultural and aesthetic aspects and a more integrated approach are requested. A single national building evaluation system including LCA is been figured out as an important driving force for SC.

1 INTRODUCTION

Since the UN Conference on Environment and Development (UNCED) in Rio de Janeiro in 1992, sustainable development has become popular worldwide with inter- and intragenerational equity (WCED 1987) and the simultaneous pursuit of economic, ecologic and social goals—often entitled as dimensions of sustainability—being the core of the concept. Buildings and construction play a key role in sustainable development for several reasons. Buildings have a service lifetime of often more than 100 years touching per se intergenerational aspect and throughout their entire lifecycle they show strong impacts and relationship with respect to all dimensions of sustainability. Consequently, interest in Sustainable Construction (SC) has increased considerably in recent years.

The European Commission (EC) identified SC as one of six lead markets in the EU with high innovative and growth potential in the coming years. Through its lead market initiative (LMI) decided in 2007 the Commission intends to foster SC by a thematic and demand driven approach implementing a process to better streamline the legal and regulatory framework and to accelerate the growth in demand (EC 2007a). Faced challenges include the operationalization of SC and in particular the complexity of the topic. The rather recent concept of SC addresses numerous aspects of construction in an integrated way already covered before but under a different heading and in an isolated way leading to a highly complex and uncoordinated or even contradictory legal and regulatory framework at the regional, national and EU level. Furthermore, numerous public and private sector activities and initiatives have emerged.

This contribution aims at providing an overview of the LMI and the existing framework for SC in the EU taking Germany as an example. A focus lies on regulation and standards as well as effective measures and initiatives for SC on national and EU level.

2 THE EUROPEAN LEAD MARKET INITIATIVE

2.1 *The Initiative and the Lead Markets*

The lead market initiative (LMI) for Europe was developed by the European Commission (EC), the executive body of the EU, to enhance and secure the economic strength and competitiveness of the EU in emerging markets with a high innovative potential. In 2007 this broad innovation-strategy was decided with the aim to double the total volume of identified lead markets and to create one million new jobs in the EU by 2020 (EC 2007a). With the help of various policy instruments and measures, being the body of the LMI, the Commission wants to stimulate economic growth, to facilitate access to better goods and services and to increase employment (EC 2007a). Overall six promising emerging markets were identified by the Commission as lead markets taking into account inter alia the market potential in the EU and worldwide on the short-term, the number and broadness of offered products and services, benefits for the society, effectiveness of policy instruments and the risk of disturbing fair market competition (cf. EC 2007c for details). This analysis and stakeholder consultations led to the identification of SC as well as eHealth, protective textiles, recycling, bio-based products and renewable energies as lead markets. For each lead market a 3 to 5 years action plan was developed comprising four groups of policy instruments/measures: i) legislation, ii) public procurement to increase demand, iii) standardization, certification, labeling and certification, and iv) complementary actions such as promotion, exchanges, and qualification etc. (EC 2007b).

2.2 *The EU Lead Market SC*

2.2.1 *Characteristics of the EU Construction Sector*

The construction sector is of high economic relevance in the EU. It counted 3.1 million enterprises in the 27 member states in 2007 that together generated a combined value added of EUR 562 billion (EUROSTAT 2010). This corresponds to 10.7% of the GDP and 51.5% of Gross Fixed Capital formation. With 14.8 million people employed it is also the largest industrial employer in the EU, providing 30% of the industrial employment. Among this workforce, only 81.1% were paid employees, which reveals a relatively high rate of self-employment in the constructions sector. 92% of the EU construction enterprises were micro organizations, 7% small organizations with 10 to 49 employees, 1% with 50 to 249 employees, and only 0.2% large organizations.

The construction sector and buildings account also for major environmental impacts in the EU. They demand for 42% of the total final energy and 50 wt. % of extracted materials (EC 2007a; ECTP 2005). Furthermore, 35% of greenhouse emissions are connected to buildings and 22 wt. % of waste generation.

2.2.2 *Sustainable Construction (SC)*

In SC all construction processes and products are regarded taking the three pillars of sustainability representing environmental, economical and socio-cultural issues into account. The long-term perspective of sustainability requires accounting for life-cycle aspects of buildings. The different aspects covered by SC like environmental impacts (e.g. emissions, resource consumption), health (e.g. in-door air-quality), well-being and comfort (e.g. accessibility for elderly people), life-cycle- and living-costs are not new. However, SC introduces an integrated and long-term point of view accounting for all the aspects simultaneously in a balanced way. All this makes SC a rather broad concept which is in practice difficult to tackle, as grown structures addressing different, sometimes inconsistent and fragmented areas each with its specific stakeholders have to be brought together and amended by missing parts to form the balanced and integrated point of view in line with SC.

2.2.3 *The Lead Market Initiative for SC*

In the EU the construction sector is typically characterized by predominantly local SMEs as well as various and diverse stakeholders. The local company structure in combination with extensive but at the same time fragmented and insufficiently coordinated national regulations leads to administrative burdens and a highly fragmented market structure hindering the development and diffusion of innovate solutions (EC 2007c).

Within the LMI an action plan was developed and three working groups (WG) were installed: WG-1 for regulatory and standardisation framework, WG-2 for life cycle costing and public procurement, WG-3 for strategies for SC. Due to thematic overlap, WG-2 was closed meanwhile. The action plan comprises 11 fields of actions under 4 policy instruments (legislation, public procurement, standardization, labeling and certification as well as complementary actions) for the period 2008 to 2011. The actions include (EC 2007c; cf. EC 2009a for a midterm report): An analysis of the existing national legal frameworks aims at including building performance targets and standards in the frameworks and improving conditions for innovative solutions in the future. Guidance documents and pilot schemes are developed to strengthen life cycle costing in procurement. In the area standardization, labeling and certification, a framework for sustainability assessment of buildings is foreseen to make sustainable performance measurable on a voluntary basis, new standards are developed to integrate sustainability aspects in the design phase and getting European Technical Approval for innovative products is facilitated. Complementary actions aim at facilitating collaborative working, reducing liability barriers for innovative products and determining future qualification needs.

3 FRAMEWORK FOR SC IN GERMANY

3.1 *General Legal Framework*

The legal framework for SC in Germany is rather complex for mainly two reasons. First, the concept of SC with its three pillars itself is broad and the number of addressed issues is high. Secondly, the legal framework for SC encompasses several levels: from the international and EU level, over the national and the federal state level down to the local level.

International treaties like the UN Framework Convention on Climate Change (UNFCCC) (1992) with the Kyoto Protocol (1997) give a framework for national policy but are non-binding for citizens or companies. Also directives like the Energy Performance of Buildings Directive (EPBD) must be implemented by national legislation. The advantage is that flexibility exists for the member states to integrate it in the best way into their legal framework, this, however, at the expense of differences in implementation between EU member states. EU regulations on the other hand are directly binding. In some areas like urban planning both a national law and a federal state ordinance for detailing exist. Another prominent example is the use of renewable heat in buildings. The Renewable Energy Directive (2009/28/EC) was anticipated by the federal Renewable Energy Heat Act (REHA or EEWärmeG) which itself had a predecessor, the Renewable Heat Act (RHA or EWärmeG) of the federal state of Baden-Württemberg. RHA required both a minimum share of renewable heat in new and in existing buildings in case that the heating is exchanged. As federal law beats state law and REHA sets only minimum shares for new buildings, RHA is replaced by REHA for new buildings in the State of Baden-Württemberg but is still valid for existing ones. The legal framework is complemented by a number of technical standards and norms which can become compulsory if regulation refers to them.

3.2 *Laws, Regulations and Standards*

In June 2006 the European Council, i.e. the heads of state or government of EU member states along with the EU President and the President of the EC, adopted the Renewed Sustainable Development Strategy as an overall strategy for and a fundamental objective of EU policy. One key element of the strategy is sustainable consumption and production. The EC presented the corresponding action plan (SCP/SIP) in July 2008. The focus lies on the environmental performance of products and production technologies as well as on green public procurement (GPP), which has a great impact on activities within the construction industry (EC 2009b). The key EU

directives for SC are the Construction Products Directive (CPD, 89/106/EEC) introducing European Technical Approval (ETA), i.e. a technical assessment of the fitness of a construction product for an intended use, and the Energy Performance of Buildings Directive (EPBD, 2002/91/EC). The EPBD obliges member states to enhance their building regulations by energy efficiency requirements, to introduce energy certification schemes for buildings and to have inspections of boilers and air-conditioners. In general, EU legislation focuses on energy efficiency, whereas sustainability issues such as integrated planning, award of the most sustainable proposal, urban development and efficient land use, optimization during the use phase of a building, accessibility as well as deconstruction and recycling are little or not accounted for.

In contrast, the German legal framework focuses on environmental aspects such as energy efficiency, renewable energies, environmental impacts, including emissions, waste generation and life cycle assessment of construction products as well as on social aspects, including barrier-free construction and thermal comfort. The focal life-cycle phases within the legal framework are the design and planning phase and the use phase. Integral planning and awarding based on sustainability criteria are, however, not and the construction and deconstruction phases barely covered.

3.3 *Measures and Initiatives*

3.3.1 *National Strategy and Coordination*

The German federal government supports SC in various ways. A national strategy for SC was defined, coordinated centrally by the Federal Ministry of Transport, Building and Urban Development (BMVBS). The strategy is linked to the Integrated Energy and Climate Protection Program (IEKP) decided in 2007 by the German government and addresses renewable energy, energy efficiency, energy refurbishment, measurement and control of power consumption and calculation of operating costs of a building.

3.3.2 *Public Initiatives*

BMVBS established a national information platform for SC to publish and spread information about national and European measures and initiatives. Especially the activities of the LMI and of the round table for SC - an advisory board for the BMVBS with representatives of construction industry, associations, public authorities and research institutes - are presented. Additionally, guidelines for SC are downloadable which are compulsory for federal authorities.

A national system for integrated assessment of building performance (BNB) was developed. It aims at measuring the sustainable performance of existing and planned buildings in an easy and transparent way. The system addresses all aspects of SC, such as environmental, economic, social-cultural, functional, technical, processes and location quality and with a special focus on life-cycle-assessment (LCA). The system - originally developed for office and administrative buildings - is further developed for other constructions. The system will become obligatory for the construction of federal buildings in mid 2010 in order to make them a model for SC (BMVBS 2010).

3.3.3 *Private Initiatives*

Besides public initiatives also industry supports research, development and the dissemination of SC and related products, for instance the steel and concrete industry. Initiatives of manufacturers of construction products promote and develop environmental product declarations (EPD) for building materials and products (IBU 2010).

Besides the governmental building evaluation system (BNB), also private building certification systems are developed, such as the Certification system of the German Sustainable Building Council (DGBN 2009).

Furthermore, a range of databases had been established, for instance with data of LCAs of construction materials and complex structures, to make those aspects of SC more transparent and easier to calculate and to support collaboration between experts (BMVBS 2010).

3.3.4 *Financial Incentives*

Financial incentives are offered by the federal government for private and public new and old buildings to encourage activities with regard to energy efficiency and barrier-free design of buildings. Social and esthetic aspects with regards to urban development and integration in the local environment are also supported (BAFA 2010; BINE 2010). Other financial incentives are provided by federal states, regions or municipalities. The main focus is on energy efficiency, renewable energies and reduction of greenhouse gas emissions.

Incentives are provided as subsidies and low-interest loans. The use of renewable energies (biomass, geothermal and solar thermal heating in buildings) is supported by a special governmental program which amounted to 256 Mio. € in 2010. Furthermore, energy saving consultancy for buildings is subsidized.

3.3.5 *Publicly Funded Research*

In 2006 the research initiative 'Future Building' was launched to overcome technical, cultural and organizational deficits in the construction sector and to strengthen the competitiveness of the national industry on a European level by stimulating and supporting innovations. The research plan encompasses allocations and contracts touching diverse topics related to SC, such as LCA, market transparency, architectural, technological, ecological, functional and economic quality of a building, general technical and legal conditions within the construction sector, as well as new materials, techniques and procedures (ZB 2010). Another research focus is on tools to evaluate the sustainable performance of buildings like BNB.

4 DRIVING FORCES AND SUPPORTIVE ACTIONS FOR SC IN GERMANY

In addition to the literature study expert phone interviews were conducted in order to get a clear picture about SC in practice and its perception by experts. Special interest was paid to possible improvements with respect to SC. Interviewed experts represent the main stakeholder groups of construction:

- Civil engineers
- Architects
- Construction companies
- Construction product manufacturer
- Facility managers
- Real estate industry
- Consultants in construction issues.

(Schultmann et al. 2010)

4.1 *National Strategy and Coordination*

The central coordination of SC by BMVBS and the role of public authorities as a model (guidelines for public buildings and green public procurement) were appreciated. Some experts called for a long-term and all-encompassing approach which includes socio-cultural aspects such as urban development and esthetics. Strategic considerations need to be made within an European context.

4.2 *Legal Framework for SC*

Experts agree that the legal framework for SC should be target oriented and not fix the means to achieve the targets. This implies a move away from focussing on the construction material to the planning process. The supportive framework needs to be consistent and transparent and should allow for long-term planning. At present, regulation addresses mainly the use phase and energy efficiency. Hence experts require taking also other aspects of SC into account, such as water consumption and waste management. For instance, wood-based heating is legally fostered in REHA but no legislation stimulates the use of wood as construction material. Experts demanded also for regulation for the design and evaluation of tender documents making use of

LCA as well as for the selection of the most sustainable proposal. Finally, the question of liability in case of innovative solutions needs to be resolved.

4.3 *Effective Measures and Initiatives*

First of all experts called for a clear, EU wide accepted and known definition for SC.

4.3.1 *Central Coordination and Communication*

Overall, experts favored central coordination, communication and consulting of SC bringing all levels from the European down to the local together. A central national body for all issues related to SC but also LMI was therefore considered as beneficial. The importance of a central, public information platform for communication and information transfer was also stressed by most experts. The existing platform and other media provided by BMVBS were considered as steps in the right direction. Especially, publicly accessible, reliable, up-to-date, transparent and easy understandable data, information and tools to calculate LCC and LCA are required. Communication of available incentives and critical evaluation of existing best practice is helpful to increase the awareness and to reduce barriers restraining SC. Additionally, articles and statements in national and international professional journals need to be published to communicate SC on a wide basis and to reach experts as well.

4.3.2 *Financial Incentives*

Not surprisingly, experts demanded financial incentives in addition to legal requirements to support SC. But also the design of the incentives was a topic. Different types of incentives such as subsidies, tax reduction and better insurance conditions were asked. Like legislation, incentives should be functional, i.e. aiming at targets instead of focusing on means, and should not only account for energy efficiency but all aspects of SC, preferably in an integrated manner.

4.3.3 *Building Evaluation/Certification Systems*

Building evaluation/certification systems are regarded as effective measures when they are in agreement with EU and national regulations and obligatory for public buildings. Currently, there are two building evaluation systems in Germany, the governmental BNB and a privately organized, so-called DGNB system, with the possibility that further private building certification systems can be approved by the government. However, experts prefer to have only one certification system in Germany for reasons of transparency and reliability. An EU wide system was considered as favourable by some experts but also judged difficult due to different climate and political conditions. Also consensus reaching was expected to be problematic but if possible as very useful.

There is disagreement about whether such a system should be obligatory or voluntary for the private sector. On the one hand the system is only successfully applied, if there are certain incentives and also obligations. Experts expressed their wish that only aspects which do not cause additional costs and time effort should be compulsory. An obligatory system was considered by some experts as less flexible and as hindering innovation and even SC as SC might loose its distinctiveness.

The optimum complexity is another controversial point. Some experts state that focusing on essential criteria is associated with lower effort and costs and is easier to communicate and can inspire design quality. Others argue a large integrated set of criteria represents the idea of SC best and allows optimizing the structure including all life-cycle-phases and increasing the technical quality.

For the present BNB system experts expressed their wish to extend it to other building types and infrastructure and to make it compulsory for all public buildings, not just the federal ones. Also assistance for single life-cycle-phases in addition to LCC and LCA, and for all actors in construction was desired.

4.3.4 *Publicly Funded Research*

According to the experts interviewed, research cooperation between public and private actors is important. Private actors have the knowledge and resources and the public sector can act as a model and can communicate SC to the general public.

The research perspective should change from focusing on primarily technical issues and construction products to an integrated approach which includes social, cultural and esthetic aspects and looks at the whole structure and its sustainable performance as a complete system. Given the importance of the reduction of GHG emissions, research on renewables in buildings should be further strengthened. Furthermore, research funding for creativity, art and diversity in design practice should be increased.

4.3.5 *Other Measures*

Interviewed experts consider qualification of actors as highly important for the future development in SC. Therefore, consistent and uniform benchmarks for education and training are needed.

5 CONCLUSIONS

The analysis of the present framework for SC in Germany and its integration in the European context allowed identifying major supportive actions and driving forces for SC.

The establishment of a national strategy for SC coordinated on national level by a public central body is determined as one central element to reduce administrative burdens and to optimize and communicate initiatives and public research activities in this field.

To support and push the national strategy for SC a consistent national regulatory framework including functional, performance-based building related regulations are essential, which focus on certain objectives through the optimization of the planning process and by looking at the structure as a whole. In compliance with this set national regulatory framework a single national building evaluation system including LCA is been figured out as an important driving force for SC. The system should include different versions, applicable for different construction types, such as residential, non-residential, private, public buildings and infrastructure as well as for different levels, such as on the level of a single structure, on quarters, town and regional level. Definite statements about the degree of complexity and the dimensions of obligatory and voluntary aspects within these systems ask for further research and analysis.

The overall approach and a functional orientation have been identified as major characteristics of effective incentives for SC. For the communication of these incentives and for further dissemination one central, neutral and newsworthy national information platform is beneficial to enhance awareness and acceptance of SC in society.

Though the interviewed experts are selected to be representative for the different stakeholder groups in construction in Germany, bias cannot be excluded. Nevertheless, we are confident that findings provide a good snapshot of the framework of SC in Germany and possible improvements which are also of interest for other countries.

ACKNOWLEDGMENTS

Part of this work uses results of a project on behalf of the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR).

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Politics for sustainable development – key documents

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ABSTRACT: Sustainable development became in the last twenty years the main conceptual framework for the world politics. Being an evolving concept, the possibility of incorporating new elements proved to be one of its most important strengths. This paper aims to examine the main political documents at global and European level regarding sustainable development. The analysis highlights the changes made to the concept over time and what are the innovations introduced by each of the main political documents. As specialists in different fields it is important to fully understand all the aspects and the dynamics of the problem in order to identify the real opportunities of research related to sustainability issues. It is also important to be aware of the need of cooperation between various disciplines in order to produce a viable result.

1 INTRODUCTION

The definition of sustainable development was given by Brundtland Report in 1987: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." The definition was later criticized because of insufficient clarity of the concept. Since then sustainability has been an evolving concept and constantly subjected to changes (as we will present in the second chapter of this paper).

As can be seen from a closer analysis, the possibility of incorporating new elements in this conceptual framework is in fact one of the most important strengths of sustainable development as a key concept in current world politics. The tendency is to let the freedom to continuously redefine this concept, which involves a reflexive and critical thinking at each level (globally, regionally, nationally and locally and finally at individual level). Aspirations of sustainable development can not be achieved without understanding the problem and require the active participation of all. Sustainable development is not one of the options, it is the only one. Hence the cultural dimension, because it implies a paradigm shift.

The paper is divided into chapters, as follows. First chapter presents a short introduction. The second chapter examines the key moments and the main documents about sustainability as conceptual framework in the world politics. The third chapter presents sustainable development in European politics, the main anchor of European legislation - the Sustainable Development Strategy of the EU (2006) and a brief review of the National Strategy for Sustainable Development of Romania (2008). The fourth chapter presents the conclusions of this analysis.

2 SUSTAINABLE DEVELOPMENT AND THE WORLD POLICY – KEY MOMENTS

This chapter examines the key moments and the main documents about sustainability as conceptual framework in the international politics. The analysis highlights the changes made to the concept of sustainable development over time and what are the innovations introduced by each of the main political documents.

2.1 *United Nations Conference on the Human Environment, Stockholm, 1972*

The first United Nations Conference on the Human Environment was held in 1972. The main document of this conference is known as "Stockholm Declaration." This is the first document which introduces the idea of environment as one of the essential dimensions of human development. In the first part of the document is a statement of crucial importance: man is both active and passive subject of the environment (in the sense that he creates it and he is a product of the environment at the same time) and he is responsible for the living environment not only in the present, but also for the future.

2.2 *Meadows Report – "The Limits to Growth", 1972*

In the same year the Club of Rome presents Meadows Report "The Limits to Growth" entered into history for its global vision of interdependence between the various components of the environment. The document has a descriptive nature, not a legal one. Given the continuing deterioration of environmental conditions, the report proposes that the new term the idea of "zero growth" in the two fundamental variables: population and investment, considering it as an opportunity to reach a global equilibrium state. The purpose of the report was not to make specific predictions, but to explore how exponential growth interacts with finite resources. It attracted controversy as soon as it was published, but its relevance is that it represents a pioneering report.

It should be noted that 1972 corresponds to the first major economic crisis after World War II, an important moment to introduce such ideas on the world political scene. During those years many countries started the environmental research. Unfortunately, after the end of the crisis, the issue was forgotten for over a decade, global development policies becoming increasingly unsustainable.

2.3 *Brundtland Report – "Our Common Future", 1987*

Another important moment is the presentation of the Brundtland Report "Our Common Future" in 1987 by the World Commission on Environment and Development (WCED), founded in 1983 and representing 21 countries. The aim of the paper was to redefine the relationship between development and environment, focusing on a vision of a more rational development.

From this moment the concept of sustainable development became the framework for the global political agenda. The fundamental definition of sustainable development as a "development that meets the needs of present without compromising the ability of future generations to meet their own needs" (dating from 1987) has not changed for over two decades.

According to the Brundtland Report, the main characteristics of sustainable development are:
- it has a spatial dimension - global policy;
- it has a long-term temporal dimension;
- its purpose is to support the progress of humanity;
- it refers to inter-generational equity;
- it doesn't have absolute limits (as Meadows Report claimed in 1972);
- it must meet the basic needs of all inhabitants of Earth so that everyone can cultivate their aspiration for a better life;
- it must harmonize the relationship between man and nature.

The principles of sustainable development and the definition of the term cited above have become the standard formulas in politics and international law. In reality there is no single definition of sustainable development, since, as it can be seen, the concept has a multidimensional nature. The report also defined the three pillars of sustainable development: environmental, social and economic.

2.4 *The United Nations Conference on Environment and Development, Rio de Janeiro, 1992*

The UN Conference on Environment and Development (UNCED) known as "The First Earth Summit" aimed to define more precisely sustainable development and to establish it as a fun-

damental principle of all international environmental policies. Among the documents of the Conference, the most important were “Rio Declaration on Environment and Development” and “Agenda 21” – an instrument of great importance, used as a base for the action plans of the governments, municipalities and environmental agencies. Through its documents mentioned above, the Rio Summit makes a number of clarifications and updates regarding the vision:
- the anthropocentric, yet holistic approach, based on unity and global interdependence;
- every sovereign state can exploit their own resources;
- the principle of common but differentiated responsibility (depending on the conditions of each state);
- another important principle is that of equity and it refers to access at the natural resources and the preservation of the natural and cultural heritage; therefore the principle of fairness is a common assumption, but differentiated between countries;
- the fight against poverty is integrated for the first time at international level as a fundamental requirement for sustainable development;
- cultural development of people is the fundamental instrument in the fight against poverty, so it is the main instrument for achieving a truly sustainable development.

As we can see, one of the most important ideas is the emphasis on culture as a key element to a truly sustainable development. This was the moment when culture became to be recognized as the fourth pillar of the sustainability issues.

2.5 *The Kyoto Protocol, 1997*

The Kyoto Protocol is an international environmental treaty aimed at fighting global warming. The Protocol was negotiated in December 1997 by 160 countries. The Agreement provides for industrialized countries a reduction in emissions by 5.2% in 2008-2012 compared with 1990. To enter into force, it had to be ratified by at least 55 nations of those that produce 55% of global emissions of carbon dioxide. The first condition was met in 2002, when the EU Members States ratified the protocol, but the second one was met only in October 2004 with the ratification of the protocol by Russia, responsible for 17.4% of the greenhouse gas emissions. The Kyoto Protocol entered into force only in February 2005, after eight years of negotiations. At the end of 2004 there were 127 countries who have signed the Protocol, including EU members, Romania and Bulgaria, Russia, Japan, India, China.

The most notable non-party to the Protocol is the Unites States, which was responsible for 36.1% of the 1990 emissions level of the Annex 1 UNFCCC countries (United Nations Framework Convention on Climate Change). At the end of 2009, 187 countries and one regional economic organization (the EC) have ratified the agreement, representing over 63.9% of the 1990 emissions from Annex I countries.

2.6 *The World Summit on Sustainable Development (WSSD), Johannesburg, 2002*

The Second Earth Summit was held ten years after the first one (The Rio Summit). Of the two major documents of the Summit, The Johannesburg Declaration and The Johannesburg Plan of Implementation (the action plan), the most important is the second one. It is a programmatic document (in the category considered "soft laws"), referring to concrete actions in order to achieve sustainable development. The Action Plan which comes in addition to the United Nations Millennium Declaration (2000) asserts the need to consider the issue of sustainable development as one of the basic and fundamental values of international relations in the 21st century.

The main innovative aspects of these documents are:
- strengthening the multidimensional vision of sustainable development;
- ecosystem approach to environmental issues, which are no longer considered a fragmented manner, but in a uniform manner with respect to ecosystems;
- positive side of globalization is first outlined in a document related to international environmental problems; because globalization is possible to create a system of rules with the participation of countries in a system of free trade benefits all, the emphasis is on participation of the developed countries;
- principle of shared, but differentiated responsibilities reiterates the idea that each state has a responsibility for its own development, while developed countries have a higher responsibility;

- declaring the need to develop a multilateral institutional structures, based on democracy, peace and security within each state to achieve a truly sustainable development; in fact once again after the Rio Summit (1992) and the Millennium Declaration (2000), the Johannesburg Summit has pointed the trinomial idea of peace - development - environment as interlinked elements.

2.7 *The Copenhagen Climate Summit COP 15, Copenhagen, 2009*

The United Nations Conference on Climate Change held in Copenhagen in 2009 was considered by some political analysts as potentially the most important event since Yalta, in terms of consequences over time. But the conference was a failure due to inability of the 193 participating countries to create a clear document to be ratified. The agreement is rather a statement of intentions, mainly due to negotiations between the few key players (US, China, EU).

Among the important points of the agreement may be mentioned the following:
- the global limits for the emissions are not clearly established, even though each participating country is invited to set their own target;
- large amounts of money are provided for vulnerable states ($ 30 billion over the next three years, an amount expected to reach 100 billion by 2020 – amounts that will be paid by developed countries which already have high costs for reducing their own emissions);
- nothing is mentioned about alternative energy sources or the current unsustainable model of economic development.

Given the competitive climate of international markets and the increasing of the greenhouse emissions globally since the Kyoto Protocol (instead of reducing them), one can say that the ideas set out in Copenhagen remain rather utopian. But at the same time a global agreement is desired, since 55 states have signed the agreement by the end of January 2010, representing 80% of the global polluters.

In this context EU position is salutary, as it keeps a common and consistent position on the issues concerning sustainable development, with clear objectives and a pragmatic approach in order to achieve its goals.

3 SUSTAINABLE DEVELOPMENT IN EUROPEAN POLITICS

3.1 *Short history of sustainable development in European politics*

The process of introducing the idea of sustainable development in the European policy has been slow and clearly subordinate to world politics.

In Europe we can talk about the foundation of such a concept in the Treaty of Rome (1957) - 15 years before the Stockholm Declaration and the Meadows Report. The main objective of the Treaty of Rome, which established the European Economic Community, is the harmonious development of economic activities of the Member States, ensuring a continuous and balanced expansion.

Sustainable development became one of the fundamental values of the EU policy since 1993, through its inclusion in the Maastricht Treaty. Other important moments concerning European politics are the Treaty of Amsterdam (1997, came into force in 1999) and the Nice Treaty (2001, came into force in 2003), which bring to the fore the need for a harmonious, balanced and sustainable economic activity in relation to a high level of environmental protection.

The Treaty of Rome (2004), which adopted the European Constitution, states that sustainable development must be regarded as a general goal whose components (economic, social and environmental) should be treated equally.

Finally, the Treaty of Lisbon (2007, came into force in 2009) states that one of the Union's objectives is to work for the sustainable development of Europe based, in particular, on a high level of protection and improvement of the quality of the environment. Although the idea of sustainable development was included in the existing treaties, the Treaty of Lisbon reinforces and better defines this objective. Sustainable development became the framework for all the European policies and the basis for the relations with the other states of the world. This common and consistent position was underlined at COP 15.

3.2 *European national policies and strategies for sustainable development (1989-2002)*

In the 1990s many developed countries have initiated the creation of national policies for sustainable development, with common goals and an integrated and long-term approach. Despite the fact that there are some common features of these strategies, they were in fact very different. Because of this, Sustainable Development Strategy of the European Union created in 2002, subsequently revised in 2006 became later the reference point for all the national strategies.

In Europe, among the first countries that have formulated a national strategy were Netherlands with NEPP - The Nederland's National Environmental Policy Plan (1989) and UK with This Common Inheritance: Britain's Environmental Strategy (1990), and the National Strategy for Sustainable Development (1994).

In the mid 90s almost all Western European countries had formulated their own national strategy. There are a number of common features of these national strategies (Meadowcroft, 1999):

- a broader and inclusive vision of all environmental issues;
- integrative ambitions: to emphasize the idea of interdependence between biophysical and social factors and to propose regulatory and remedial strategies based on cross-disciplinary actions;
- a long-term approach, focusing directly on the next five years, but based on a script for 20-30-50 years;
- the idea of sustainable development is a conceptual framework for these strategies, providing a context for decisions about the integration of the economic environment.

Despite the common title and form, there are notable differences between these strategies:

- some of them are focused on overall objectives (UK, France), while others have specific objectives, including strict deadlines for solving the problems (Netherlands, Austria);
- some have been developed based on cooperation between different ministries (Austria), while others have suffered from a lack of coordination between them (France);
- some have proved their viability in short term, while others have formed the basis of a process which is reviewed periodically.

Even today there are countries where such plans remain at a symbolic level in the sense of imposing national standards under the pressure of international politics, which are not well understood, and as such, nor implemented. This is usual in the case of some developing country.

3.3 *The renewed EU Sustainable Development Strategy, 2006*

In 2001 the European Council adopted the EU Sustainable Development Strategy in Gothenburg. An external dimension was added in 2002 in Barcelona, after the Johannesburg Summit. In 2005, the European Council launched a review of the Strategy, after a critical assessment of progress since 2001. The document also pointed to some unsustainable trends, with negative environmental impacts that could affect the future development of the European Union. After wide consultation, the European Council presented on 13 December 2005 a proposal for revision of the Gothenburg strategy.

The renewed Sustainable Development Strategy for an enlarged Europe was adopted on June 9, 2006. The document presents a coherent and unified strategic vision. It aims at the continuous improvement of the quality of life and well-being on Earth for present and future generations. To that end it promotes a dynamic economy with full employment and a high level of education, health protection, social and territorial cohesion and environmental protection in a peaceful and secure world, respecting cultural diversity.

EU and its Member States are responsible for implementing the strategy, involving all components of the EU and national institutions. The strategy emphasizes the importance of close cooperation with civil society, social partners, local communities and citizens to achieve sustainable development goals.

The strategy defines the four key objectives and the policy guiding principles. The key objectives are:

- environmental protection;
- social equity and cohesion;

- economic prosperity;
- meeting the international responsibilities of EU.

The policy guiding principles of EU SDS are: promotion and protection of fundamental rights, solidarity within and between generations, open and democratic society, involvement of citizens, involvement of business and social partners, policy coherence and governance, policy integration, use the best available knowledge, precautionary principle, polluters pay principle.

The EU SDS identifies seven key challenges and corresponding targets, operational objectives and actions and two cross cutting policies concerning education and research. The seven key challenges are:
- climate change and clean energy;
- sustainable transport;
- sustainable consumption and production;
- conservation and management of natural resources;
- public health;
- social inclusion, demography and migration;
- global poverty and sustainable development challenges.

Every key challenge has an overall objective clearly defined, operational objectives and targets and proposed actions. Many of the targets are set in percentage or numerical expression, with strict deadlines for implementation and they are mandatory for all Member States. Important issues in order to achieve the goals of the strategy are:
- the cross cutting policies contributing to the knowledge society: education and research;
- finding the proper financing and economic instruments;
- communication, mobilizing actors and multiplying success;
- monitoring the implementation of the SDS.

3.4 *Cross cutting policies in EU SDS: education and research*

The two cross cutting themes contributing to the knowledge society are: education and training – on one hand and scientific research, innovation and technological development – on the other hand.

Education is a precondition for promoting changes in behavior and in the unsustainable lifestyle patterns and thus, providing all citizens the key skills necessary for achieving sustainable development. Education can contribute to greater social cohesion and well-being through investment in equity and ensuring equal opportunities, participation of citizens to gain a greater awareness and understanding of the complexities and interdependencies in the world today. In the context of the United Nations Decade for Education for Sustainable Development (2005 - 2014), Member States could further develop their national action plans, especially using the Program "Education and training 2010". Some of key areas are: construction, energy and transportation.

Research projects for sustainable development should include support for short-term decisions and long-term vision concepts, and must address issues of regional and global perspective. Approaches need to promote inter-and trans-disciplinary involving social and natural sciences and also to make the connection between science, policy making and implementation. The positive role of technology for smart growth needs to be developed further. There is still a great need for thorough investigation of the connections between social systems, economic and ecological methodologies and tools for risk analysis, systems of prevention, diagnosis and prognosis. Universities, research institutes and private enterprises have an essential role in promoting research for sustainable development.

3.5 *National Sustainable Development Strategies, 2002-2008*

After the first EU SDS adopted in 2002, the Member States of EU redefined their strategies according to it, in order to have a common working frame. Between 2005 and 2007 all the National Strategies have been updated. The Eastern European countries adopted their National Strategies in 2007 and 2008.

Although the EU SDS provides a common platform for all these documents, they are very different, as they reflect the countries present position in implementing the principles of sustainable development. The most developed European states have already implemented for some years the actions proposed by EU SDS and have monitored the process. For the developing countries the process is slow. There are states where the strategies remain at a symbolic level because they are not fully understood by the actors involved (firstly the governments and municipalities and secondly by the civil society), and as such, nor implemented.

3.6 *The National Sustainable Development Strategy of Romania 2013-2020-2030, 2008*

The National Sustainable Development Strategy of Romania (SNDDR) was adopted in 2008. This National Strategy aims to connect Romania to a new philosophy of development, adopted by the EU and widely shared globally - that of sustainable development.

In 2010, after a long transition to pluralistic democracy and a market economy, Romania still needs to overcome significant gaps relative to the other Member States of the EU, while seeking to absorb and implement the principles and practice of sustainable development in the context of globalization. Despite the notable progress it has made in recent years, it is a fact that Romania's economy still relies on intensive consumption of resources. Society and the administration have not developed yet a shared vision about the future.

The Strategy sets specific objectives for moving, within a reasonable and realistic timeframe, toward a new model of development. In terms of general orientation, this document addresses the following strategic objectives for the short, medium and long run:

- horizon 2013: to incorporate the principles and practices of sustainable development in all the programs and public policies of Romania as an EU Member State;
- horizon 2020: to reach the current average level of the EU countries for the main indicators of sustainable development;
- horizon 2030: to get significantly close to the average performance of the EU Member States in that year in terms of sustainable development indicators.

The text of SNDDR is structured in five parts:

- the first part presents the conceptual framework, defines the notions with which it operates, describes the main parts of the renewed EU SDS (2006), the current status of the development of basic indicators of sustainable development and relevant measures taken by Romania during the pre-and post-accession to EU;
- the second part contains an assessment of the current natural and human capital and the social situation in Romania;
- the third part presents a perspective view, setting clear targets for the three time horizons, following the strict logic of the key challenges and cross cutting themes;
- the fourth part analyzes the specific problems faced by Romania and set targets for accelerating the process of transition to sustainable development model, while reducing and eliminating gaps in relation to the average performance of other Member States of the European Union;
- last part contains concrete recommendations for the institutional arrangements in order to assure implementation, monitoring and reporting on results SNDDR.

As a general remark, the analysis of the current situation of Romania is realistic and most of the proposed targets (short, medium and long term) are attainable in conditions of normal development. But the deep economic and social crisis which marked Romania in the last two years has undermined the implementation of short-term measures defined by SNDDR. For this reason we can say that short-term goals (2013) tend to be unrealistic, considering the present situation.

4 CONCLUSIONS

In the past two decades sustainable development has become the anchor of an integrative approach to global policy. Over time, the concept was dilated, the environmental policies including economic and social dimensions. In recent years the focus was mainly on the cultural and

educational aspects of sustainable development. In Europe policies and strategies for sustainability are rapidly advancing in all areas, as sustainable development is regarded as one of the fundamental values promoted by the EU in its relations with the rest of the world (EU declared the intention to become a leader in this effect).

As specialists in different fields, why is it important to know and understand how the concept of sustainable development evolved on the political scene? Because without a deep and complete understanding of this integrative approach:

- sustainability tends to remain only a fashionable topic (especially in the developing countries), instead of being understood as the only solution to the global crisis;
- we will not understand that the crisis of contemporary society requires a paradigm shift;
- we will continue to think and work in an analytical manner, instead of making the first steps towards a holistic and systemic approach;
- we will not understand the real opportunities of research in all the fields related to sustainable development and neither the importance of cooperation between various fields.

In addition, all construction-related policies are founded on general policies for sustainable development. Without a knowledge base about this subject, we can not understand neither the dynamics in the field of building legislation and nor the importance of these changes.

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Sustainability of the urban planning of the Fortress (Cetate) neighborhood from Timisoara – how can 3D models help us to understand the historic evolution of the city

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ABSTRACT: Sustainability of the urban planning, by comparing the old historic city plans and overlapping them with today satellite views of the city is used. In this paper the experimental studies on Timisoara and the old bastioned fortress, using 3D restorations and detailed means of constructions are presented. All the theoretical work has been performed by the author having as a basis the various studies of Military Architecture Theory. In the first part of the article are described the various plans of the city before the year 1716 (Hapsburg siege) and the siege. The second part is dedicated to the new city, the ideal planning of the Austrian citadel with its three belts of city walls fortifications. In the final part the conclusion and our day's studies, according with the current situation of the fortress are presented.

1 INTRODUCTION

The urban history of Timisoara was always a subject of debate between scientists, architects and urbanists. There was a lack of information in this matter till now. The new 3D virtual reality programs, capable to restore the old view of the city allow us to see, analysis and compare the most important stages in city evolution. During this experiment have been analyses several historical stages in the evolution of Timisoara city and its fortification, beginning with de IX-th century till modern era. The particular stages subjects for study were: IX-th - XI-th century, 1240, 1300, 1350, 1450-1500, 1660-1716, 1716 (see Figures 3 to 8). For the first time is presented the overlap of the Turkish city over the actual city. The square area, perimeter, of the Turkish city is compared and overlap on the actual city map (see Figure 1 and Figure 2).

Figure 1. Overlap of the Turkish city.

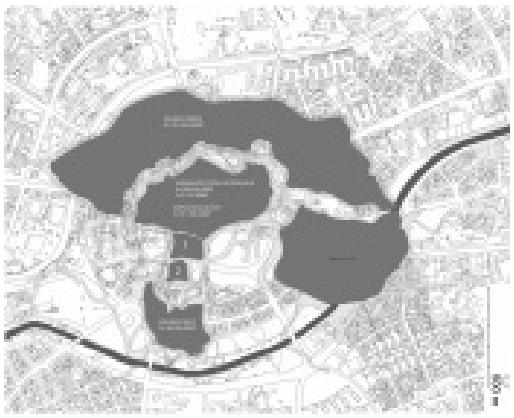

Figure 2. Area and perimeter of the Turkish city.

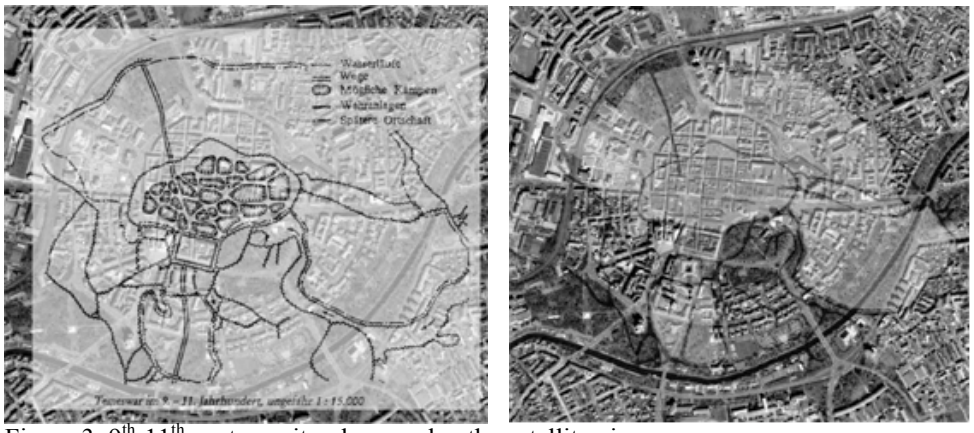

Figure 3. 9th-11th century-city plan overlap the satellite view.

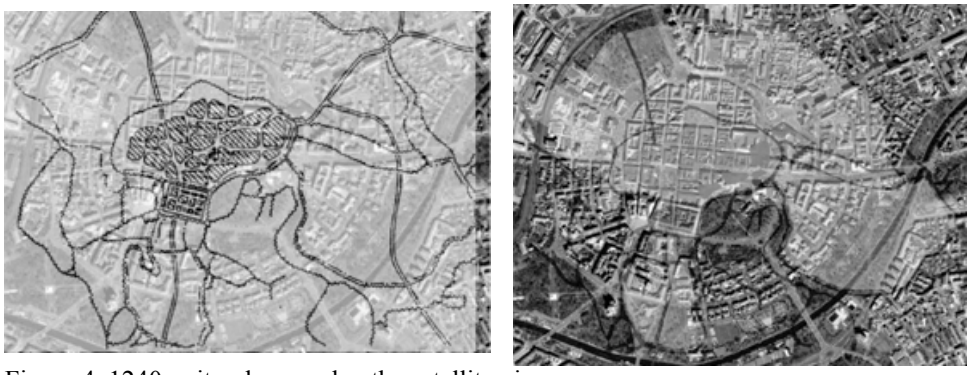

Figure 4. 1240 - city plan overlap the satellite view.

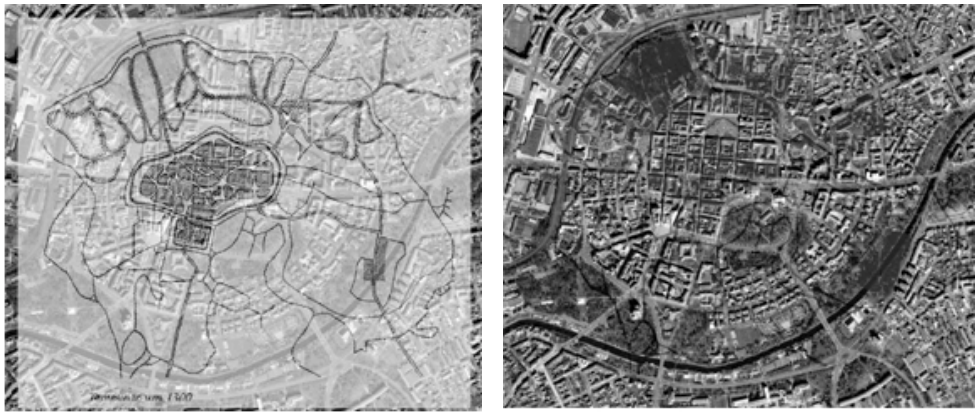

Figure 5. 1300 - city plan overlap the satellite view.

Figure 6. 1350 - city plan overlap the satellite view.

Figure 7. 1450-1500- city plan overlap the satellite view.

Figure 8. 1600-1716- city plan overlap the satellite view.

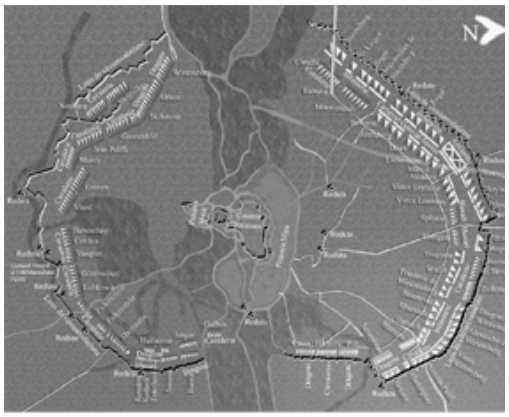

Figure 9. The reconstitution of the 1716 siege.

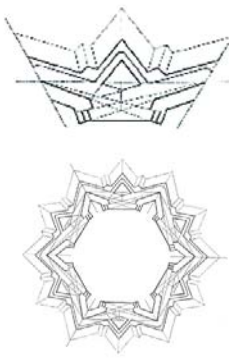

Figure10. Pagan System and the Method of Pagan.

The siege of Timisoara led by Austrians in 1716 and the army-corps disposition, generals name is revealed in a digital restoration of the battlefield (see Figure 9).

In following lines are revealed the geometrical theory and methods adopted by the Austrians to construct the new fortifications. In particular is up to study Count Pagan`s Method, which is applied at Timisoara. This Method is a proof that Timisoara is NOT a Vauban-type Fortification (see Figure 10).

Several other systems were studied since 1716 until 1730 when the work for the new fortifications was begun. Some important phases in the evolution of the bastioned fortress are presented in Figures 11 to 17 (years 1730 – 1732 – 1736 – 1740 – 1744 – 1748 – 1756 – 1760 – 1770 – 1790 – 1808).

Continuing, the study is presented the detailed geometrical trace, component elements and the tracing method of the fortress. It is then detailed explained the geometrical method for the bastions and for the ravelin tracing according with the Pagan`s Method which was then adopted by

Vauban in his First System-The tracing method used at the Timisoara fortress. This study continues with a chronology of the city and its fortress evolution since 1808 to 2009. Making a restoration of the way the city could looked like in our days if the fortification wall were not demolished in 1892-1907.

For this study have been used historical maps from that period, or representing the situation from that period of time. Figures 11 to 17 relates the fortress 3D models showing important stages of urban evolution: 1730 – 1732 – 1736 – 1744 – 1790 – 1808.

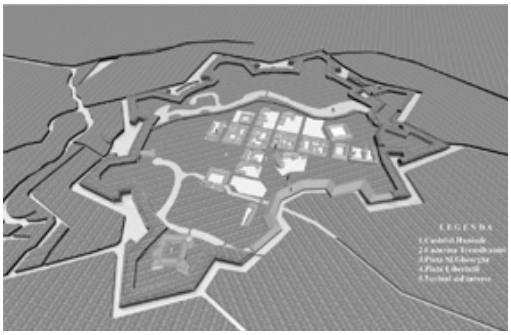

Figure 11. The city fortress in 1730.

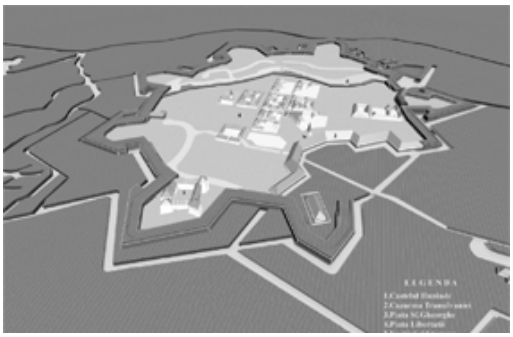

Figure 12. The city fortress in 1732.

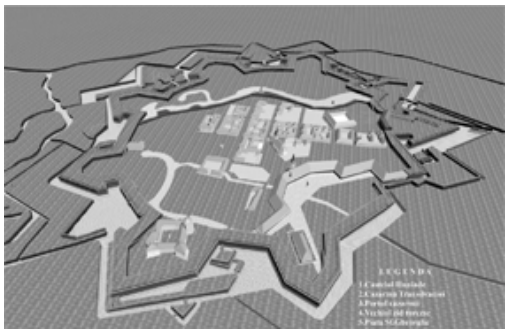

Figure 13. The city fortress in 1736.

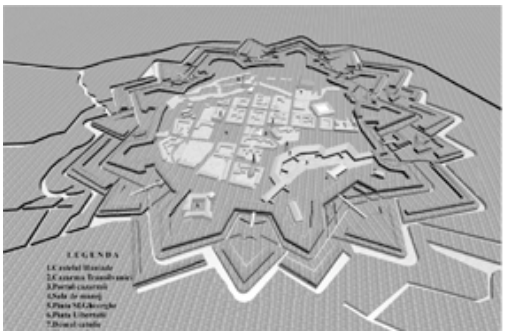

Figure 14. The city fortress in 1744.

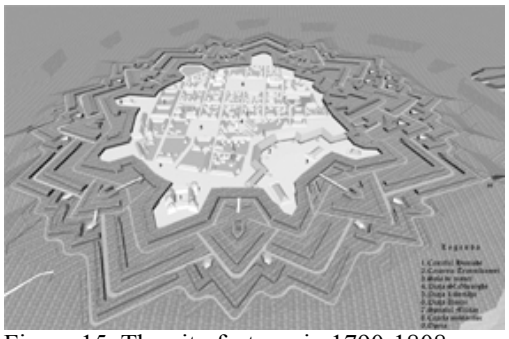

Figure 15. The city fortress in 1790-1808.

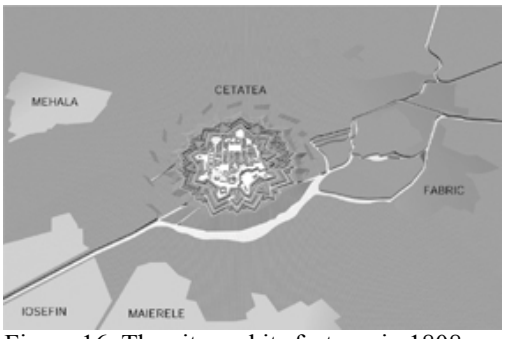

Figure 16. The city and its fortress in 1808.

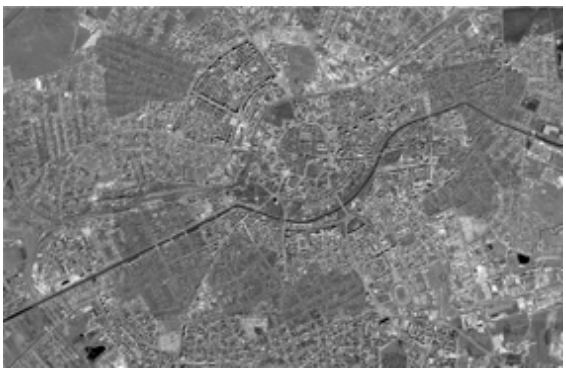

Figure 17. The overlap of the 1808 situation over the actual view of the city.

2 SUSTAINABILITY OF THE *CETATE* NEIGHGORHOOD BY COMPARING WITH THE OLD CITY-FORTRESS

The research program was carried out in order to study the way we can rehabilitate urban the old historic neighborhood of the city (Old Fortress). For this reason has been study theoretical and practical models (other cities) with common features like Timisoara. The analysis has been made having as basis the historical maps of the city and 3D reconstruction of some important stages in the history of the citadel. It has been demonstrated in this study the membership of Timisoara to the *Ideal City Concept*, by finding out the geometric method of the citadel tracing which, was discovered after a detailed analysis of the fortress plan and the geometric decomposition of the citadel plan.

As a result of this study had been demonstrated that the fortress is a particular case unique in Europe with three geometric centers $0_1 0_2 = 0_2 0_3$ (see Figure 19).

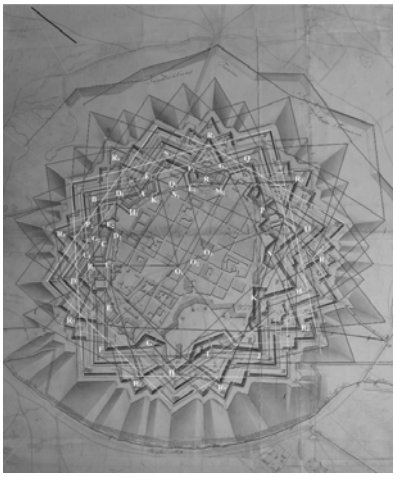

Figure 18. Geometric trace of the fortress.

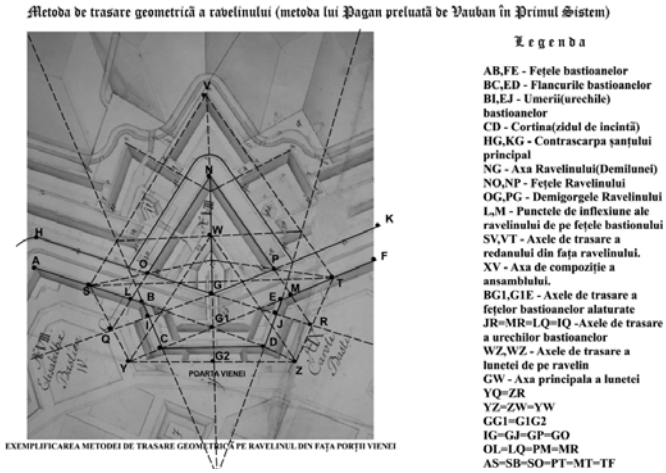

Figure 19. The geometric trace of the fortress ravelin.

Figure 20. The geometric trace of the fortress bastions.

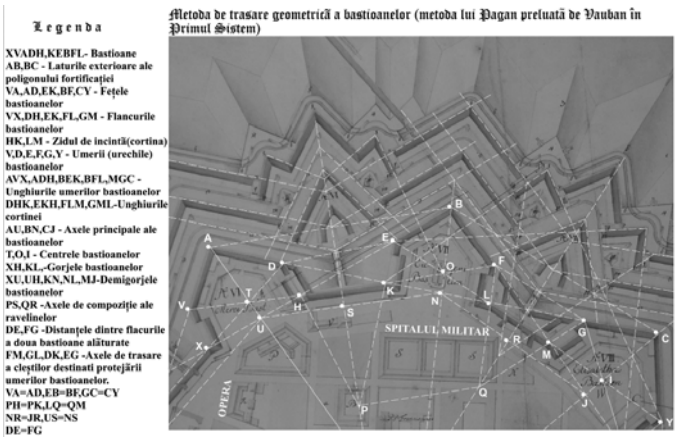

Figure 21. The overlap of the old fortress over the actual satellite view of the city.

Based on the studies performed, respectively on the models and maps, the following conclusions were drawn:

1. The theoretical models used in the study approximate with sufficient accuracy and a detail analysis of the 3D models demonstrate that *Timisoara is an ideal city concept*;
2. The overlap of the historical maps over the satellite view allows the chronology and dating of the buildings and architectural ensemble from *Cetate* neighborhood with a 95% accuracy (see Figure 21).

3 PROBLEM SOLUTION

Although the existence of the three wall-belts of the fortress has been known since the 80`s, because of a absence of a detailed map with the overlap of the old fortifications over the actual city (satellite view), many remains of the fortifications that came out during various construction sites, have been deliberated destroyed or without knowing. This study is a solution for the Timisoara`s fortification and their position on the actual map of the city. The new GPS technologies combine with satellite images with a maximum accuracy have helped to delimitate the archeological sites which contain old fortification remains, thus now, any constructor can find out precisely if, on its construction site there are or not fortification remains.

Another solution of this matter results from the study of the *accesses, circulations and urban density* within *Cetate* (Fortress) neighborhood starting with the 19th century to our days. The study of the circulation and density helps for a good solution for the auto and pedestrian traffic problems within *Cetate* (Fortress) neighborhood.

Figure 22 represent the 3D reconstruction of the old fortress the way would look like if the city wall were not been demolished and Figure 23 represent the communication ways in with the citadel if the fortification would be intact today.

Figure 22. 3D reconstruction.

Figure 23. 3D reconstruction.

4 CONCLUSION

The aim of this research program was the theoretical and experimental (based on 3D models) study regarding the sustainability of the urban planning in *Cetate* neighborhood.

Based on the results the intention was to clarify some of the aspects regarding the interaction between the ideal geometric methods of ideal fortification realized at Timisoara and the present day concepts of urban planning and revitalization of the historical centre. After this study the results show that *Cetate* neighborhood has kept in 80% its *ideal-city* characteristic from the old citadel, but unfortunately in the urban context (related with the rest of the city) through the communication ways and squares (urban spaces) this *ideal-city* no longer function.

It has been made a study containing in the digital restoration of the old citadel over the satellite view of actual city. It has been observed that if the fortification walls had been kept, the fortress would be much easier to rehabilitate and reorganize (see Figure 22 and Figure 23).

In the Figures 24 to 26 are presented the entire city map with and without keeping the fortifications. Here it can be seen the relations and the links between the city and the historical centre. Here it can be seen what the urban impact of the fortress is over the entire city. The role as a *centre*, the ideal-concept developed at Timisoara is still remaining in the general view of the city plan. Timisoara is a radio-centric city, the urban core been formed by the inner fortress, or the urban area which once was the interior of the fortification, behind city walls. As seen in Figure 24, only three ways were available to access the fortress if this one was kept. The Bega Channel and the railroad are traced beside the old fortress in order to can in the range of the artillery fire (military and strategic reason).


Figure 24. Communication ways.


Figure 25. Fortress relation with the city.


Figure 26. Represent the communication ways in
with the citadel if the fortification would be intact today.

In our days, without the city-walls the situation is different, a huge belt of parks and green spaces have emerged in the center of the city because of the fortification demolition process and the suppressing of the glacis and *non-aedificandi* area.

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Sustainability: The new principle of Urban Rehabilitation in Portugal

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ABSTRACT: The planning policy of the last years in Portugal has been based on the construction of urban expansion areas, as much for industrial ends as for residential ends. Many of these new urban areas are much bigger than is necessary with problems in terms of waste of infrastructures, creating urban voids or discontinuity. Recently, there has arisen new legal legislation designed to encourage a planning praxis that goes against the current trend and gives incentives to urban rehabilitation actions. There are unequivocally signs of policies which are aimed at the rehabilitation of consolidated areas and cultural heritage to the detriment of new areas of urban expansion policies. These diplomas define a policy of urban rehabilitation in articulation with the municipal plans, namely with the contents of the detailed local plans (the most detailed of the Portuguese planning system). For the first time in the Portuguese planning system the sustainability (financial, social, cultural and environmental, in which each of the parties contributes with their resources towards the urban rehabilitation in a process of what amounts to self-financing) is defined as a principle of urban rehabilitation. The decree law nr. 307/2009 explains the principles of the new regime of urban rehabilitation as an instrument of urban politics. This article aims to present a reflection on the new challenges to the urban rehabilitation as an agent of urban sustainability.

1 TOWN PLANNING IN PORTUGAL

1.1 *The town planning system*

The Portuguese town planning system comprises of three administrative levels: central, regional and local (or municipal). It is at the municipal level, especially by means of the contents of Municipal Director Plan, at which the urban expansion areas are designed.

The most important town planning legislation consists of the different decrees/laws that define each type of town planning instrument.

On a central level, there are three kinds of instruments:

·National Program of Town Planning Policies;

·Sectoral Plans;

·Special Plan, of which there are four kinds: Special Plan for Coastal Zone, defining the land uses in the coastal zone, as well as the location of the main infrastructures which support such uses; Special Plan for Areas of Protected Landscape, defining the map of restrictions to land uses or territorial transformations such as areas reserved for agricultural purposes and areas for nature preservation. The third type of special plans refers to Special Plan for Public Reservoir and the last one is the Special Plan for Estuaries (a new planning instrument created recently).

On a regional level there is only one type of plan (given that there are no Regions with political autonomy in Portugal), the Regional Plan,

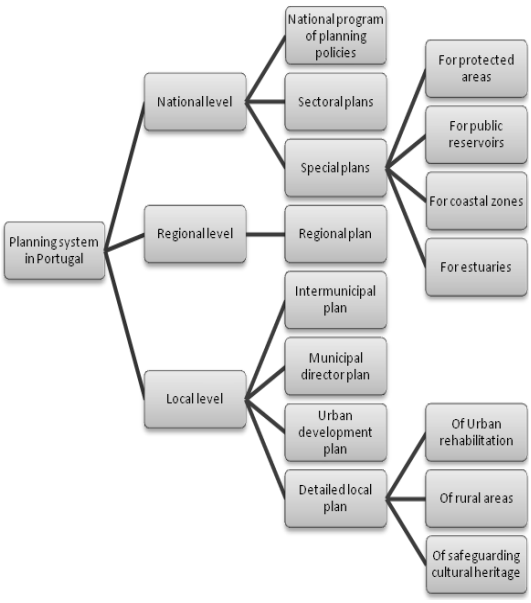

Figure 1. Town planning system in Portugal.

which defines at regional or sub-regional level the criteria for the spatial organisation of activities and the use of land.

On a local level there has been, since 1999, a new kind of plan relating to groups of two or more municipalities; the Intermunicipal Plan; and in addition to these there are three which relate to single municipalities. The three latter are as follows: Municipal Director Plan, the main spatial planning instrument at a municipal level, aimed at structuring the municipal territory for development control purposes; the Urban Development Plan, defines the spatial organisation of urban areas and Detailed Local Plan, establishing urban design and things such as the typology of housing for a specific area of the municipality. Each of these plans relating to the municipality is elaborated by the local authorities.

1.2 *Urban expansion: the last years policy*

The town planning policy of the last years has been based on the construction of urban expansion areas. As we noticed before, the town planning legal framework for Portugal is spread over a number of legal documents emphasising the procedural aspects of plan preparation, plan implementation and development control.

Recently, there has arisen a new legal diploma in order to encourage a town planning praxis that goes against the current trend and gives incentives to urban rehabilitation actions.

There are unequivocally signs of policies which are aimed at the urban rehabilitation of consolidated areas to the detriment of the construction of new urban areas.

This diploma defines a policy of urban rehabilitation in articulation with the municipal plans, namely with the contents of the detailed local plans, which are the most meticulous town planning instruments of the Portuguese town planning system, the main contents of which are urban design proposals.

In this context it is currently on the agenda to reflect on the following: the sustainability as a new principle of urban rehabilitation.

2 URBAN REHABILITATION CHALLENGES

2.1 *The new rules*

The recent changes to the rules of instruments of town planning in Portugal confirm the tendency shown in 1998 in the General Law of the Town Planning Policy which explicitly appealed to the contention of urban perimeters. Since then, few have been the signs in the municipal plans which have evidenced in the sense of response to this appeal.

On the one hand, the upload versions of municipal director plans; most of them from the beginning of the 90's; which define the urban perimeters and the new expansion areas, are slow.

On the other hand, few are the detailed local plans with rules regarding the carrying out of urbanization through the urban design proposals.

Understanding that the appeal of the General Law of Town Planning Policy to shrink the urban perimeters has remained without response, all the most recent rules of town planning are now addressing this recommendation. This imposition is carried out by performing on various fronts: in terms of classification of land use, because land use for new urbanisations was abolished "those having a possibility to be urbanized". This land use was until now, the only one which could not being urbanized and where this task could not been programmed and where the urbanization could occurs at any time, depending only from the land owner decision.

The production of urban space has been running with no urban design for the city, but by single private acts of urbanization, without taking into account the city as a whole; in terms of detailed local plans, with the different types of these plans reinforced in the urban spaces already existent and consolidated. This reinforcement is by means of the contents of local detailed plans.

Until now we had the figure of detailed local plans for new expansion areas, but this figure was abolished. Now we have only two kinds of detailed local plans for the interior of urban perimeters: the detailed local plan for urban rehabilitation and the detailed local plan for the safeguarding cultural heritage. These plans are limiting the possibility of elaborating detailed local

plans in urban areas, within the urban perimeters confined to spaces which have been built and urbanized.

The new regime of urban rehabilitation, established in the decree law nr. 307/2009 of 23 October, in practice regulates the content of the new figure in the municipal planning level: the detailed local plan for urban rehabilitation.

These new incentives for urban rehabilitation are trying to reverse the town planning model of the last few years, based on urban expansion areas whose negative consequences are well known to all: the waste of over-sized infrastructures; the spread of urbanization within the urban perimeters, with no continuity of urban fabric; the urbanized ruins of new neighbourhoods which are still waiting for buyers.

For the first time in the city history an urban rehabilitation action is required for new buildings and new neighbourhoods that became old without ever having been inhabited. The empty spaces require special strategies of urban rehabilitation.

2.2 *The principle of sustainability*

The new regime of urban rehabilitation establishes two modalities by which the urban rehabilitation actions can be performed: simple urban rehabilitation, where responsibility and expense is on the building owners; systematic urban rehabilitation, defined by the head office of the detailed local plan of urban rehabilitation where the responsibility is with the municipal authorities.

The detailed local plan of urban rehabilitation is the town planning instrument designed to insure urban rehabilitation. This plan states that urban rehabilitation today is an indispensable component in city politics and of rehabilitation.

The new principles of this regime as an instrument of urban rehabilitation politics are the following:

- Principle of responsibility – understanding the urban rehabilitation actions as a private sector responsibility, at the expense of the building owners.
- Principle of subsidiarity- recognizing the general interest of urban rehabilitation actions, but which should be financed by free market rules and not by public funds, in which the unilateral solutions should be the final ratio.
- Principle of inter-generation solidarity - which transfers the financial bill of the urban rehabilitation to the following generation.
  Principle of the protecting of what exists, principle of integration, principle of coordination, principle of a just consideration and, finally, the principle of equality.
- Principle of sustainability - in terms of financial, sociocultural and environmental issues, in which each of the agents which participates contributes with their resources towards the urban rehabilitation in a process of what amounts to self-financing; principle of contracting - as a form of streamlining the executions of the operations of urban rehabilitation.

The importance of the principle of sustainability in the urban rehabilitation is in the fact that the ecological structure and the building structure of the urban system are two of the main components of the city. However, it is common praxis in planning to privilege the urbanized structure of the city in its building component to the detriment of the natural structure in its ecological component. This practice promotes disregard for the ecological structure of the urban system, like marginal zones, in the collective image of the city, leading to the inevitable degradation of the level of enjoyment by the citizens and the disqualification of the urban image as a whole.

The ecological structure is a component of the city that includes the most ecologically sensitive areas, fundamental to the ecological balance of the city.

We can say that in 1999, we gave an important step in the city sustainability because the ecological structure of the urban system became one of the land uses in urban perimeters along with urbanized areas and planned urbanizations. The second step is the introduction of the principle of sustainability in urban rehabilitation.

In one word, the detailed local plan of urban rehabilitation includes the task of identifying not only the necessities of rehabilitation cities, modernization or demolition of buildings, rehabilitation of urban infra-structures, equipment but also the concern for creating green spaces for collective utility, in order to promote urban sustainability.

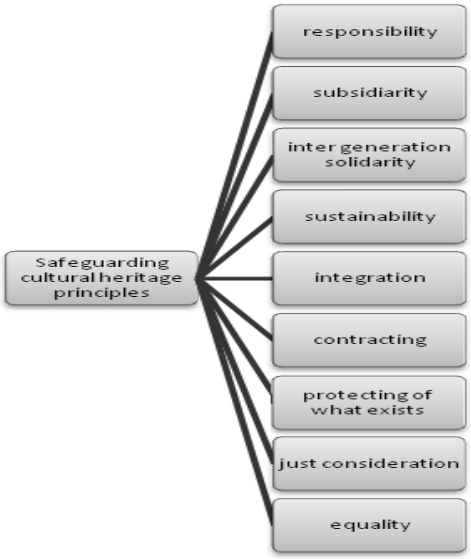

Figure 2. New principles of Urban Rehabilitation.

3 CONCLUSIONS

The object of this article was to share concerns and hope for a coming victory in the urban rehabilitation process at least on a legislative level, especially with the new principle of sustainability as a way of urban rehabilitation.

More than finding answers, this paper aimed to formulate some questions that arise now in the town planning domain. Above all, the new ideas for urban rehabilitation through the detailed local plans need to be developed by experts who are aware of the complexities of the city.

The town planning management on the municipal level in terms of urban rehabilitation still needs to be conducted on a local scale, i.e. through the urban design proposals.

One of the steps for the success of urban rehabilitation actions is the integration and bringing together the efforts of the municipal authorities and the building owners, in order to guarantee success.

In conclusion, the definition of the principle of sustainability is in its three dimensions; financial, sociocultural and environmental; in urban rehabilitation actions requires the definition of the issues, their framework within the municipal plans and the careful definition of the type of urban rehabilitation to make (simple for the buildings or systematic for the urban fabric).

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Mechanical Behaviour and Life Cycle Assessment of Fibre-Reinforced Timber Profiles

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ABSTRACT: The objective of this research project is to provide engineered wood products on the basis of formed wood profiles being optionally reinforced with technical fibres and textiles for structural purposes. This paper discusses the load-carrying behaviour of light-weight timber columns with circular hollow cross section. Full-scale axial compression tests were conducted to evaluate the performance of the profiles. Following parameters were investigated: (a) type of fiber reinforcement, (b) fiber orientation, (c) thickness of the reinforcement, (d) loading conditions - centric or eccentric, (e) slenderness of the tubes and (f) influence of connections. Due to the high buckling strength the tubes are capable to sustain high axial loadings. Furthermore, the tests demonstrated that load-carrying capacity and ductility of the timber profiles can be significantly enhanced by additional fibre reinforcement. The Life Cycle Assessment of the novel product indicated that due to the efficient use of the material, formed wood and wood composite profiles have a lower environmental impact in the production phase than comparable glulam elements. The use of resin and fibres for the reinforced timber profiles may have certain additional impacts on the environment but as also the load capacity is nearly doubled the functional unit has to be extended as well. Thus, the interpretation of the outcomes has to be discussed more detailed.

1 INTRODUCTION

In timber construction, round or rectangular solid cross sections prevail. Compared to technical profiles, the area of these cross sections only yields a poor moment of inertia. These facts and the losses incurred when turning raw timber into load-bearing cross sections affect the efficiency of the material, generating competitive disadvantages compared to alternative construction materials. Haller (2004) created load-carrying cross sections by transforming plain wood panels into profiles by applying a thermo-hygro-mechanical process. Although profiles provide a number of advantages, in general, solid cross-sections are used in timber engineering. This is caused by the low costs for the material and the strong anisotropy that in combination with the relatively thin-walled profiles results into certain difficulties with regard to the design of connections (tension perpendicular to grain and shear), stability of members and behaviour in fire. These difficulties can be mitigated and/or avoided by combining wood profiles with technical fibers and textiles as well as appropriate matrices. Technical fibers and textiles are particularly suitable for reinforcing curved surfaces. The degree of reinforcement, fiber orientation and material can be tailored to meet the relevant static requirements. The fiber reinforced plastic (FRP) enhances the tensile strength perpendicular to grain, shear strength and embedding strength of the wood and provides protection against weathering and other environmental influences. Because of the good compatibility of wood and FRP, both materials can benefit from synergies. On one hand, wood profits from the outstanding mechanical and physical characteristics of FRP with load adapted fiber confinement strengthening the wood in

transversal direction. On the other hand, FRP can profit from the mechanical characteristics, environmental friendliness and low price of the wood. The use of a wooden tube as a permanent winding core (Figure 1b) can help to reduce manufacturing costs.

Fiber or textile reinforced wooden profiles can be created by employing different techniques –braiding and winding or by wrapping the profile with woven fabrics – see Figure 1.

Figure 1. (a) braiding and (b) winding of wooden tubes, (c) tube with a tubular knitted fabric
Figure 2. Test set-up for a 3.8 m carbon reinforced column

The development of a novel manufacturing process for composite reinforced wood profiles requires the assessment of the environmental and economic performance of the proposed solution. For assessing the environmental performance the ISO standard 14040 is chosen, for the economic performance the Life Cycle Costing (LCC) concept shall be applied. Both allow the identification of important drivers that can be used as indicators for decision-making in construction. This part shall focus on the Life Cycle Assessment (LCA) study, whereas the economic valuation shall be discussed in the keynote lecture on LCC.

2 MATERIALS AND METHODS

2.1 *Material properties for the wood and fibre reinforcement*

The process of manufacturing wooden tubes is described in (Haller, 2004). Compared to sawed and glued laminated timber, formed wood profiles have some characteristics that require testing. To evaluate the performance of FRP confined wooden profiles, full-scale axial compression tests were conducted. The mechanical properties of the partially densified wood were determined in three-point bending and compression tests on small clear specimens. The remaining mechanical properties are mean values taken from published data (Bodig, 1982) – see Table 1. The tubes were reinforced by E-glass or carbon fibers embedded in an epoxy matrix and compressed by peel ply to achieve an improved bonding. The material properties of the FRP composite given in Table 1 comprise empirical data provided by Tsai (1992) for uni-directional (UD) composites. To assess strength and stiffness of various composites it is necessary to account for the individual fiber volume fractions. For instance: to obtain the mechanical properties of a GRP with a fiber volume fraction of 33% the empirical data have to be multiplied by the corresponding ratio of the fiber volume fraction (33/45).

Table 1. Material properties of densified wood and FRP composite

property	symbol	units	densified wood	FRP composite (unidirectional) GRP [(1)]	CRP [(2)]
fiber volume	v_f	%	--	45	60
density	ρ	kg/m^3	610 (40)*	1800	1500 +
bending strength	$f_{m,0}$	N/mm^2	105 (18,6)*	--	1670
compression	$f_{c,0}$	N/mm^2	66.7 (6)*	610	1470
strength	$f_{c,90}$		7.5 (0,74)*	118	168 +
tensile	$f_{t,0}$	N/mm^2	90	1062	2550
strength	$f_{t,90}$		1.4	31	69
modulus of	E_0	N/mm^2	15600 (2300)*	38600	135000
elasticity	E_{90}		770 (320)*	8270	9650 +
Poisson's ratio	$\nu_{0,90}$, $\nu_{z,\varphi}$	--	0.35	0.26	0.3 +
	$\nu_{90,0}$, $\nu_{\varphi,z}$		0.017	0.056	0.021 +
specific strength	$f_{c,0} / \rho$	GPa /(g/cm^3)	0.11	0.34	0.98
specific stiffness	E_0 / ρ	GPa /(g/cm^3)	26	21	90

(1) GRP- glass fiber reinforced plastic - empirical material properties provided by (Tsai, 1992)
(2) CRP- carbon fiber reinforced plastic – TORAYCA T700S data sheet (TORAY Carbon Fibers America, Inc.)
+ estimate, data provided by (Tsai, 1992) for T300-F934
* average value determined from 10 experiments (standard deviation)
z: axial (0°), φ: tangential, r: radial (90º) - transversal isotropic material

2.2 *Specimen geometry and test set-up*

The load-bearing capacity of formed wooden tubes was tested in a 6 MN hydraulic press. Loading was displacement-controlled at a speed of 1.2 mm/min. Compression tests were performed according to DIN EN 408. The upper compression plate was hinge-ended; the plate at the bottom was fixed so that the column was restrained to large degree. The test set-up for a 3.8 m column is shown in Figure 2. The unreinforced tubes had an outer diameter of 274 mm and a wall thickness of 19 mm, both average values. The sectional properties (diameter and wall thickness) varied from specimen to specimen by max. ±2 mm. Variations are caused by differences in the process of manufacturing and machining the tubes. The thickness of the reinforcing layer t_{FRP} ranged from 0.55 mm to 1.4 mm depending on manufacturing process and the type of textile. The areal weight of the textiles was approx. 900 g/m^2. For details in regard to the thickness of the composites, fiber volume fraction and fiber orientation etc. - see Table 2.

Altogether 53 specimens were tested: 11 unreinforced (REF) and 42 fiber reinforced (FRP) profiles. The specimen had various lengths from 0.5 m to 3.8 m (columns). The unreinforced tubes had a unit-weight of approx. 10 kg/m. Depending on the type of reinforcement the weight of the composite layer ranged between 0.6 kg/m and 1.7 kg/m. In order to account for eccentric load conditions 7 columns were subjected to an eccentric load. The eccentricity was realized by shifting the column 60 mm out of the axis. The deformation in axial and radial direction was recorded by eight strain gauges (SG) and eight inductive displacement transducers (DT). The displacement transducers, located at l/2, recorded the deformation in radial direction, while the strain gauges, six in circumferential direction ($SG_{\varphi,0°}$, $SG_{\varphi,90°}$, etc.), and two in longitudinal direction ($SG_{z,0°}$, $SG_{z,90°}$), measured the strains in selected locations. The length of the tubes is currently limited to 2.5 m due to manufacturing limitations. In order to increase the length of the specimen two tubes were finger-jointed to produce 5 m tubes. Resorcinol resin was used to glue the finger jointed ends (large finger joint with finger length of 50 mm) together.

3 EXPERIMENTAL RESULTS

The test matrix and experimental results incl. ultimate loads and corresponding stresses are given in Table 2. Following parameters were investigated: (a) type of fiber reinforcement, (b) fiber orientation, (c) thickness of the reinforcement, (d) loading conditions - centric or eccentric, (e) slenderness of the tubes and (f) influence of connections.

In average the reference tubes reached an ultimate load of 564 kN corresponding to compression stress of 41.6 N/mm^2. The load-deformation behaviour until failure is linear elastic. Compared to the reference specimen, remarkably higher loads and ductility levels were

obtained with the FRP reinforced tubes. The average ultimate load for all types is 900 kN corresponding to compression stress of 56.7 N/mm^2. Compared to unreinforced tubes, this is an increase of about 60%. The experimental data reveal that the columns with a 45° confinement (FRP45) had higher ductility than the FRP85 columns.

Table 2: Test matrix and experimental results

	FRP reinforcement					tube length	ultimate load / stress			eccentric load e = 60 mm		
	type of FRP	fiber angle °	areal weight g/m^2	thick. t_{FRP} mm	fiber vol. %	l mm	No.	F_u kN	σ_u N/mm^2	No.	F_u kN	σ_u N/mm^2
reference						2500	8	564	41.6	1	481	35.2
(REF)						800	2	653	43.7			
	GRP	±45	2*410	1	33	2500	3	1019	61.7	1	602	35.0
glass	GRP	±45	2*410	1	33	800	1	922	53.7			
winding	GRP	±85	2*410	1	33	2500	6	952	58.5	2	647	38.9
	GRP	±85	2*410	1	33	800	5	903	54.1			
glass	GRP	±85	2*450	1	33	2500	1	740	45.3	2	651	39.8
braiding	GRP	±85	2*450	1	33	800	5	819	48.5			
knitted	GRP	90	900	1.4	25	2500	1	796	48.3	1	546	34.7
fabric	GRP	90	900	1.4	25	800	2	818	48.9			
woven	GRP	0/90	3*300	1.4	25	2500	3	761	55.9			
fabric	GRP	0/90	3*300	1.4	25	500	3	788	57.9			
	CRP	±45	2*300	0.55	60	3000	1	782	49.1	finger jointed		
	CRP	±45	2*300	0.55	60	1800	1	809	50.8			
carbon	CRP	±85	2*300	0.55	60	3800	1	638	39.5	finger jointed		
winding	CRP	±85	2*300	0.55	60	1000	1	772	47.8			
	CRP	±5/±45	4*300	1.1	60	3800	1	985	59.1	finger jointed		
	CRP	±5/±45	4*300	1.1	60	1000	1	1111	66.6			

Figure 3 shows the typical failure modes of the columns. The reference tubes failed due to splitting of the wood section into a large number of single lamellas. This separation is a result of the tensile stresses perpendicular to grain at the circumference.

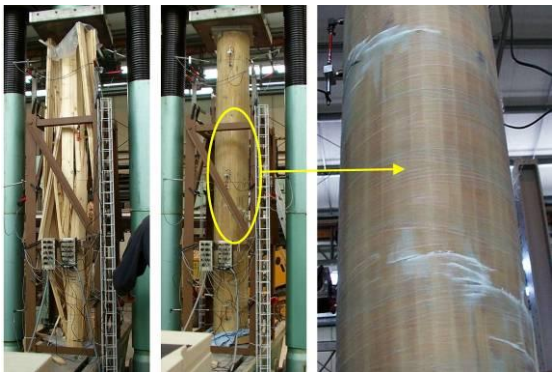

Figure 3. Failure modes: (a) splitting of REF, (b) local crushing/buckling of GRP85

Figure 4. Crushing of fibers near the contact zone (CRP5/45) and failure of finger joint (CRP45)

In contrast to the reference specimen, the reinforced tubes show ductile behaviour by crushing of wood fibers parallel to grain accompanied by a local buckling and a partial delamination of the FRP layer. Carbon fiber reinforced tubes with fiber orientation ±5/±45 (CRP5/45) showed a different failure mode. While splitting of wood was prevented by 45° or 85° confinement, a reinforcement with fibers oriented parallel (5°) to the column axis strengthened the tube in a way such that significant compression forces are transferred by the CRP. In this particular case this was about 20% of the axial force (depending on the distribution of the stiffness). The column failed in the contact zone between the tube and the supporting plate by crushing of

fibers (see Figure 4). The failure can be attributed to local effects. The reinforcement expands in the radial direction, accompanied by the delimitation and crushing of the CRP and wood. The fibers of the outer ±45° layer, cut at the tube ends, are unable to support the longitudinal 5° fibers. To prevent such failure, an additional 90° confinement at the supports is required. Finger jointed tubes without longitudinal reinforcement (CRP45 and CRP85) failed by exceeding the compression strength limit of wood at the finger tips (see Figure 4). The 5° reinforcement (CRP5/45) was able to prevent such failure. For a detailed analysis of the load-carrying behaviour displacement and strain measurements were analyzed. Figure 5 shows the radial deformation at different load-levels. To improve the readability the values recorded by the DT's were scaled by the factor 25. The data reveal that the initial circular section increasingly becomes oval, especially the REF columns. Causes of the distortion are bending moments that can be attributed to three factors: (1) material inhomogeneity, (2) initial crookedness of the column, and (3) eccentric loadings.

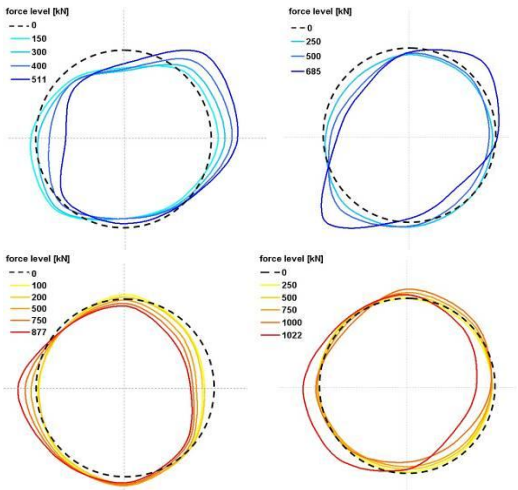

Figure 5. Distortion of REF and FRP tubes for subsequent loading

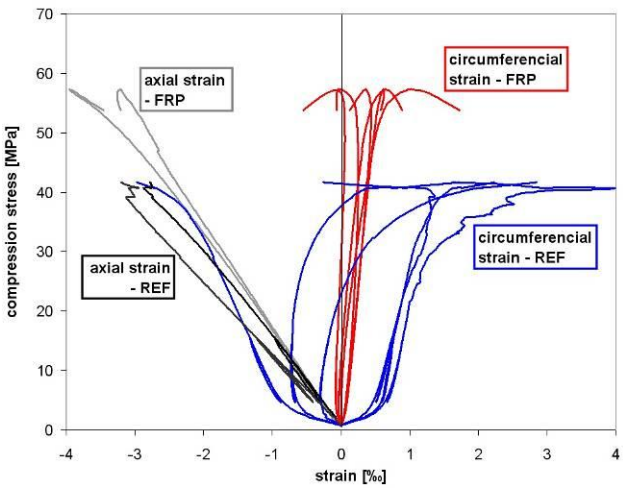

Figure 6. Stress-strain curves in circumferential and longitudinal direction

Such a distortion/buckling may have a significant effect to the load-carrying behaviour of the cylinders since local transverse stresses will occur. In addition, positive circumferential strain is developing due to Poisson's effect of the axially loaded cylinder that results in an expansion of the tube. The measured stress-strain relations in circumferential and longitudinal direction for selected tubes are shown in Figure 6. As shown, there are significant differences between the reference and the FRP reinforced columns. The stress-strain curves of FRP columns confirm the theoretical considerations. The circumferential elongations are positive and the differences in between sensors are negligible, meaning that the curves show no signs of local buckling. The load-carrying behaviour of the REF columns is characterized by relatively large deformations at a low load level - below 5 N/mm^2. Since the recorded circumferential strains are ether positive or negative it can be concluded that the buckling mode is similar to a deformation of a tube subjected to bending. After initial buckling, the columns reach an equilibrium position. At compression stresses above 30 N/mm^2 the behaviour is non-linear ending in a brittle failure.

From the experimental results it can be concluded that:
(a) GRP and CRP reinforced tubes behave similarly. The influence of the type of fiber (glass or carbon) is negligible, as far as the fibers are primary oriented in circumferential direction (±45° to ±90°) and act as a classical confinement. In this case the strength of the composite will be the decisive parameter, which is similar for glass and carbon composites - see Table 1. The same yields for the different types of textiles (manufacturing process) which were designed to strengthen the tube in circumferential direction. For this reason the differences in load capacity are small. (b) In order to take advantage of the high stiffness of the carbon composite, the fibers need to be oriented in the direction of the applied load (into the column axis ~ 0°). (c) The tests showed that a relatively small degree of reinforcement (less than 1 mm in circumferential

direction) is sufficient to avoid splitting of the tubes. A further increase in confinement thickness is inefficient. Only additional fibers, oriented in column axis will significantly improve the structural performance (see above). Since the stiffness of the composite is the important parameter it is recommended to use carbon fibers in order to utilize the strength of the FRP. (d) The eccentric loading (60 mm off axis) resulted in a decrease in load-carrying capacity of about 25% (min 12%, max 43%). (e) Since the differences in load-carrying capacity between FRP tubes having a length of 0.8 m and 2.5 m are small, it can be concluded that the testing of short cylinders is sufficient for determining the ultimate load of compact columns (of intermediate length) with no risk of buckling (Euler type). (f) In general, connections have a large influence on the load-carrying capacity of structures. Glued connections (finger joints) can reach the strength of non-connected, clear sections. In case of large finger joints, it can be assumed as conservative that the strength of the connection reaches at least 80% of the strength of a clear section. The tests of finger jointed columns CRP45 and CRP85 confirm this estimate. The columns reached 92% of the strength of short cylinders. Both columns failed in the connection area. In case of CRP5/45 such failure was prevented by the 5° fiber reinforcement. This connection did not fail, the failure occurred near the support.

4 LIFE CYCLE ASSESSMENT

According to ISO 14040:2006 the first phase of an LCA study is the goal and scope definition. Undertaking an LCA is an iterative task, so the first steps to a complete and ISO-conform LCA-study can be taken in an explorative way, well-knowing and taking into account that the scope of the study may have to be refined. Nevertheless it is necessary to clearly define goal and scope of the study and what is planned to do with the outcomes of such an investigation.

In the following first results at this early point of the LCA study are documented showing, on the one hand, conclusions drawn by a software-based calculation of the environmental load and, on the other hand, problems to be solved in further steps of the research.

4.1 *Goal and scope definition*

In the first step the environmental performance for the following construction materials shall be compared: solid wood, glue laminated timber (GLT), formed wood profiles (with and without reinforcement) and steel. In the second step the formed wood profiles shall be optimized by controlling the relevant drivers. To reach these goals, three questions have to be answered: What is an appropriate functional unit and where are system boundaries to be set? What life cycle impact assessment (LCIA) methodology shall be used? What requirement shall be set for the data quality?

4.2 *Functional unit*

Approaching LCA for a complex system like composite wood structures, for a start the functional unit is reduced to a column with a bending stiffness EI of 1800 kNm^2. The bending stiffness is a measure for the Euler-type buckling load of a column we can expect. Thus it is possible to define comparable columns made of other construction materials like steel or traditional wood columns made of solid wood, glue laminated timber or steel. So far the life cycle is examined just up to the production phase.[1] This can also be interpreted as a "cradle to gate"-LCA, which leads to the definition of the system boundary.

4.3 *System boundary*

Cradle-to-gate LCA include the consumed energy and material flows as well as the outputs, e.g. emissions caused from the exploration of resources (cradle) to the production process before leaving the company (gate). The use and disposal phase are not taken into account. In

[1] Nevertheless the CO_2 absorption during the growth stage of the wood is disregarded as it will be released in the disposal phase, which has to be part of the complete LCA anyway. In this way the outcomes of the "cradle-to-gate LCA" is more objective.

consideration of these limitations a first Life Cycle Inventory Analysis (LCI) of a formed wood profile is conducted based on the process flow diagram (Figure 7). Inputs and Outputs, which "should be more fully identified after additional data are collected during the course of the study (ISO14040, 2006), are used as available at this point of the study, so the essential parts of the production phase, as seen in the process flow diagram, could be taken into account. At some points cut-offs had to be made. For example for the process "profile planing" no data was available, also the water consumption for wetting the GLT board during the heating process could not be recorded yet.

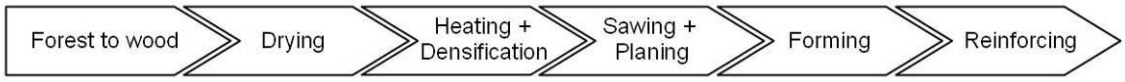

Figure 7. Process flow diagram formed wood profile column

4.4 *Data sources and assumptions*

The initial identification of inputs and outputs is based on material and energy data, supplied by the databases ETH-ESU 96 (Frischknecht, 2004) and IDEMAT[2] (both integrated in LCA Software SimaPro©), as well as on first data collections in pilot plants. Also the environmental impact of the formed wood profile is calculated based on the GLT data, which can only represent a first approximation. Therefore all input data for the wood profile are calculated pessimistically.

Table 3. Impact assessment - Eco-indicator99 (I) after initial identification (CO_2-storage disregarded)[1]

Column Type	Material / Energy input	Database	Points Eco(I)
Solid wood	50.8 kg of non-dried wood (square)	ETH-ESU 96	0.33
Solid GLT	48.7 kg of GLT (square cross section)	ETH-ESU 96	1.90
Formed wood profile	30 kg of undensified wood	ETH-ESU 96	1.17
	19 kWh process energy *	ETH-ESU 96	0.49
Formed and Reinforced wood profile	1 formed wood profile	(see above)	1.66
	1.9 kg glass fiber	IDEMAT	0.034
	1.7 kg epoxy	IDEMAT	0.058
	0.7 kWh process energy	ETH-ESU 96	0.018
Steel column	50.3 kg of steel low alloy ETH S[3]	ETH-ESU 96	5.53

* 80% energy loss for all process steps assumed

The main energy input during the production of GLT needed for drying of the boards. The energy required for the manufacturing of the formed wood profile is a summation of drying (70%) and heating (30%) for densification and forming the profiles. The mechanical energy inputs for the densification of wood - pressing and rolling into a profile are marginal. It has no relevant influence on the environmental impact of the formed wood profile.

4.5 *Impact assessment*

Figure 8 shows the first results of impact assessment choosing the Eco-indicator99 (I) for impact assessment. 1 Point is "representative for one thousandth of the yearly environmental load of one average European inhabitant (Ministry of Housing, 2008). The environmental impact caused during the production phase is mostly influenced by the material flow of wood as it is the main input. Timber structures are in a competition with steel structures. Therefore an adequate steel column is used as a reference in this early stage of LCA. The advantages of the renewable material wood are significant.

[2] http://www.io.tudelft.nl/research/dfs/idemat/index.htm Database with a focus on the production of materials, developed at Delft University of Technology

[3] Only material input is taken into account. Assumed composite, as supplied by database: 93% primary iron, 5% scrap and 1% alloy metals.

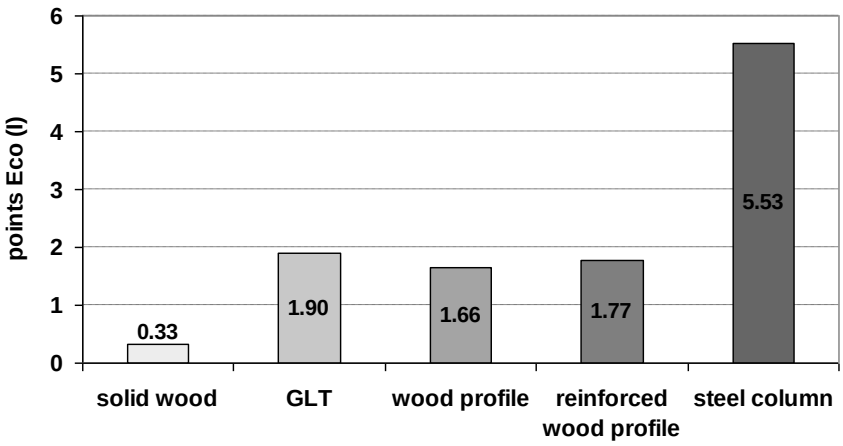

Figure 8. Environmental load (production phase) of columns built with different construction materials

5 CONCLUSIONS

In a test program 53 wooden tubes of different slenderness ratios were subjected to axial compression loads. Results have shown that with unreinforced tubes considerable load-bearing capacities can be achieved. Remarkable are the large deformations at a low load level characterizing the development of an initial buckling shape. The unreinforced tubes showed brittle failure by splitting into a number of single lamellas. Moreover, the experiments demonstrated that the load-bearing capacity and ductility of wooden tubes can be significantly improved by a minor degree of fiber reinforcement. The reason for the increase in load capacity is the fiber confinement that is strengthening the wood across the grain. In consequence the compression strength of the wood parallel to grain can be fully utilized. Additional work is needed in order to establish the failure sensitivity of the tubes for all load conditions, e.g. bending and torsional loads. Due to its material efficiency formed wood and wood composite profiles have, regarding the initial identification of inputs and outputs and using the available data, a lower environmental impact in the production phase than comparable GLT or steel columns. As these first outcomes are, in some parts, based on assumptions and approximations and can only be seen as a cradle-to-gate LCA, the next steps will be the refurbishing of the data quality and the extension of the life cycle.

6 ACKNOWLEDGEMENTS

The authors would like to thank the German Federal Ministry of Education and Research (BMBF - Project-Nr. 0330722A “High-Performance Timber Structures”) for the financial support of this research.

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Effect of Mineral Admixtures on the Compressive Strength of Green Concrete with Coarse Recycled Aggregate

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ABSTRACT: The paper presents part of the results of experimental investigation of green concrete made with coarse RCA and with large amount of inert, pozzolanic and highly reactive mineral admixtures. The purpose of this research was to define the individual and combined effects of different mineral admixtures on the basic properties of concrete composites, as well as to identify possible applications of these concrete composites in practice. The test results of compressive strength of investigated concretes for ages of 2, 7, 28, 60 and 90 days and their comparative analysis are presented in this paper. With the analysis of obtained results it was concluded that the combination of different mineral admixtures can reduce the basic disadvantages of concrete with high content of mineral supplements - the relatively low strength in the period up to 28-day age, which allow the structural application of this type of "green" concrete.

1 INTRODUCTION

At the end of the twentieth century, sustainable development and environmental protection have become key goals of modern society. Important role in the sustainable development of the built environment, reduction of pollution, conservation of natural resources and energy saving certainly has the entire civil engineering, especially construction materials industry.

In this context, main problems that industry of construction materials needs to solve are:

- issue of exhaustion of natural aggregate deposits and landfilled of C&D waste and
- high consumption of portland cement and deposition of industrial waste materials.

Construction waste, which occurs as a result of new construction and demolition of existing structures, is one of the biggest environmental problems in the European Union, as in many developed countries. For example, it is estimated that the main construction waste is about 180 million tons per year or 480 kg / person / year in the EU (Fisher, 2009). The usual method of "management" of construction and demolition waste in the recent past was the disposal in landfills. In this way, they made huge landfills of construction waste, which occupy the land and represent an environmental problem (Marinkovic, 2010).

Concrete is decades most used construction material in the world and the production of concrete in the world has reached a value of one ton of concrete per capita of planet. It is known that $1m^3$ of concrete contains more than $1m^3$ of aggregates and that the trend of excessive aggregate consumption raises the question of the exhaustion of natural resources of aggregates and the need to find new opportunities for obtaining aggregates. As a sustainable solution to the problems of construction wastes and the depletion of natural aggregate deposits, imposed is the process of recycling C&D wastes, primarily concrete.

Cement production is energy intensive process which uses approximately 5% of world industrial energy consumption and the production of 1 ton of Portland cement emits a 1 ton of CO_2. In this way, the very cement industry generates about 7% of total CO_2 emissions.

The energy required for cement production represents 80% of the total energy needed to produce concrete. The most effective way of reducing the influence of concrete on the environment

is the reduction of participation of PC clinker and its substitution with mineral supplements. Substitution of Portland cement clinker with mineral admixtures to reduce CO2 emissions reduced consumption of raw materials and contributes to a cleaner environment by "recycling" of industrial waste materials such as blast furnace slag and fly ash.

Previously exposed facts were guidelines in setting objectives of this research - obtain concrete that will simultaneously meet the requirements of modern civil engineering, sustainable development and environmental protection. Concrete types that we investigated belong to the special group of green concrete composites with the RCA.

The first step in developing green concrete with the RCA was an investigation of cement concrete with coarse RCA in order to investigate the possibility of obtaining structural concrete. The results of this study were encouraging and they have confirmed that with the quality RCA, with no increase in the amount of cement, can be produced concretes that are in their mechanical properties close to natural aggregate concretes (NAC) (Malesev, 2007, 2010).

Substitution of cement by different mineral admixtures in concrete with RCA was the next stage in the development of green concrete with the RCA. As mineral supplements were used fly ash and milled limestone. The aim of this study was to evaluate changes in selected properties of concrete in function of types of mineral supplements and age of concrete. The results showed that with such a composition of concrete cannot achieve the mechanical properties corresponding to structural concrete. This type of green concrete had a very slow increase of compressive strength and low values of the reference strength.

Using chemical admixture from HRWRA group, in the third phase, some increase in strength due to reduction of water cement ratio was achieved, but this improvement was still insufficient to classify these concrete composites into a group of structural concrete. The research was continued by introducing small amounts of highly reactive mineral admixtures (silica fume and metakaolin) and encouraging results were obtained.

2 EXPERIMENTAL INVESTIGATION

Based on the testing results of RAC, for further study was selected concrete in which the entire amount of coarse natural aggregate was replaced by RCA. In this phase of the research, influence of the type of mineral admixtures to the basic properties of concrete, was determined.

For testing of the basic properties of hardened concrete 250 specimens were made in total. Mixture proportions of the tested composites were determined in accordance to the following conditions: same binder content, same workability after 15 min, same maximum grain size (16 mm), same grain size distribution for aggregate mixture, same type and quantity of fine and coarse aggregate and variable type and quantity of mineral admixtures. All three groups of mineral admixtures (latent hydraulic, inert and highly reactive mineral admixtures) were used for substitution of part of cement. As the main mineral admixtures, fly ash and milled limestone were selected, and as a corrective mineral admixtures, silica fume and metakaolin, were chosen. The share of basic mineral admixtures in the total weight of binder was 40 or 50%. Participation of corrective mineral admixtures in the total weight of binder was 10%. Based on all these conditions, appropriate component materials were selected and concrete mixtures were defined.

2.1 *Component materials*

Component materials for concrete mixtures were:

- Portland cement CEM I 42.5R, (Lafarge-BFC Serbia, γ_s=3100kg/m^3),
- Fine aggregate (natural aggregate, river Morava, 0/4 mm, γ_s=2660kg/m^3),
- Coarse aggregate (recycled concrete aggregate, 4/8 and 8/16mm, γ_s=2350kg/m^3),
- Fly ash (type "V", power plant "Nikola Tesla B" Obrenovac – Serbia, γ_s=2100kg/m^3),
- Milled limestone (quary "Jelen Do" – Serbia, γ_s=2720kg/m^3),
- Silica fume ("Sika Fume HR", "Sika" – Switzerland, γ_s=2200kg/m^3),
- Metakaolin HR ("Metamax" – USA, γ_s=2500kg/m^3),
- HRWRA ("Sika ViscoCrete 5390", "Sika" – Switzerland, γ_s=1080kg/m^3),
- Water.

Recycled concrete aggregate was produced by crushing of "old" concrete from demolished RC structure and laboratory cubes used for compressive strength testing. The strength class of old concrete cubes was C30/37 and the corresponding value of compressive strength for demolished RC structure was C40/50 (Radonjanin, 2009).

2.2 *Mixture proportions*

In order to determine possible applications of investigated concretes, depending on the composition of the binder in concrete, ten concrete mixtures were divided into five groups:

- Group A – (3 concrete types) reference concrete (RAC) witch as a binder contains only portland cement or portland cement and a highly mineral admixtures (silica fume or metakaolin). The designed consistency of concrete from this group was achieved using chemical admihture HRWRA.
- Group B – (2 concrete types) in which the binder consists of 50% Portland cement, and the remaining 50% is fly ash or limestone. The designed consistency of concrete is achieved by adding water.
- Group C – (1 concrete type) in which the binder consists of 50% portland cement, and the remaining 50% is fly ash. The designed consistency was achieved with HRWRA.
- Group D – (2 concrete types) in which the binder consists of 50% portland cement, and the remaining 50% is a combination of mineral admixtures (FA or limestone) and SF. The designed consistency was achieved using chemical admihture HRWRA.
- Group E – (2 concrete types) in which the binder consists of 50% portland cement, and the remaining 50% is a combination of mineral admixtures (FA or limestone) and metakaolin. The designed consistency was achieved using chemical admihture HRWRA.

Concrete mix proportions were determined based on the following assumptions:

- D_{max}=16mm,
- The total quantity of binder in the mix is m_{bin}=350kg/m^3 (cement, fly ash, limestone, silica fume, metakaolin),
- 50% of the total aggregate is fine river aggregate (0/4mm) and 50% is recycled aggregate (4/8 and 8/16mm),
- Same consistency,
- Effective water content is 200 kg/m^3, except in mixtures without chemical admixtures,
- Air content is approximately 1%,
- Recycled aggregate water absorptions are: 2.6% for fraction 4/8 and 2.1% for 8/16mm.

Concrete mix proportions are shown in Table 1 and designed ratios of component materials are given in Table 2.

Table 1. Concrete mix proportions for referent concretes and for green concrete composites.

Concrete type	Cement (kg/m^3)	Water $m_{w,tot}$ (kg/m^3)	Aggregate m_a (kg/m^3)			Mineral admixture m_{mad} (kg/m^3)		Highly reactive mineral admixture m_{hrad} (kg/m^3)		Chemical admixture m_{ch} (kg/m^3)
		m_w+$m_{w,add}$*	NA 0/4	RCA 4/8	RCA 8/16	Fly ash FA	Limestone LS	Silica fume SF	Metakaolin MK	HRWRA
A	350	200+19,1	845	845		-	-	-	-	-
A-SF	315	200+19.0	838	838		-	-	35	-	1.4
A-MK	315	200+19.0	840	840		-	-	-	35	1.4
B-FA	175	240+17.3	761	762		175	-	-	-	-
B-LS	175	200+18.9	835	835		-	175	-	-	-
C-FA	175	200+18.3	808	809		175	-	-	-	3.5
D-FASF	175	200+18.3	808	809		140	-	35	-	3.85
D-LSSF	175	200+18.7	829	830		-	140	35	-	1.4
E-FAMK	175	200+18.3	810	810		140	-	-	35	3.5
E-LSMK	175	200+18.8	832	833		-	140	-	35	1.4

$m^*_{w,add}$- water that is added due to the open porosity of recycled aggregate. Additional water quantity was calculated on the basis of water absorption of recycled aggregate.

Table 2. Designed ratios of component materials.

Concrete type	$m_{w.tot}/m_{bin}$	m_w/m_{bin}	m_a/m_{bin}	m_{mad}/m_{bin} %	m_{hrad}/m_{bin} %	m_{hc}/m_{bin} %
A	0.626	0.571	4.829	0	0	0
A-SF	0.629	0.574	4.789	0	10	0.4
A-MK	0.629	0.574	4.800	0	10	0.4
B-FA	0.735	0.686	4.351	50	0	0
B-LS	0.625	0.571	4.771	50	0	0
C-FA	0.631	0.578	4.620	50	0	1.0
D-FASF	0.631	0.579	4.620	40	10	1.1
D-LSSF	0.628	0.574	4.740	40	10	0.4
E-FAMK	0.631	0.578	4.629	40	10	1.0
E-LSMK	0.628	0.574	4.757	40	10	0.4

2.3 *Concrete compressive strength*

Measured compressive strengths of referent concretes and green composites are shown in Table 3. For each concrete type and each age three samples (15 cm cubes) were tested and the average values are presented.

Table 3. Concrete compressive strength at different ages.

Concrete type	Concrete compressive strength (MPa)				
	2	7	28	60	90
	$f_{c,2}$	$f_{c,7}$	$f_{c,28}$	$f_{c,60}$	$f_{c,90}$
A	18.4	37.1	44.2	49.5	50.8
A-SF	15.9	32.4	45.0	52.5	54.5
A-MK	19.2	36.2	50.0	54.0	55.4
B-FA	5.0	8.8	17.3	24.3	26.2
B-LS	5.7	11.8	15.7	17.5	17.3
C-FA	7.7	14.1	26.0	30.9	32.3
D-FASF	8.1	17.9	29.3	34.1	37.7
D-LSSF	6.0	12.4	20.0	23.1	24.7
E-FAMK	8.6	19.7	31.0	40.5	44.7
E-LSMK	5.5	18.3	28.8	31.7	31.7

Testing results are also presented in relation to 28-day compressive strength of referent concrete "A" and in relation to corresponding strength of referent concrete "A". These results are given in Table 4.

Table 4. Concrete compressive strength development in relation to referent concrete "A" (%).

Concrete type	In relation to 28-day strength of referent concrete "A" ($f_{c,ij}/f_{c,28A}$)					In relation to corresponding strength of referent concrete "A" ($f_{c,ij}/f_{c,iA}$)				
	$f_{c,2}$ (%)	$f_{c,7}$ (%)	$f_{c,28}$ (%)	$f_{c,60}$ (%)	$f_{c,90}$ (%)	$f_{c,2}$ (%)	$f_{c,7}$ (%)	$f_{c,28}$ (%)	$f_{c,60}$ (%)	$f_{c,90}$ (%)
A	42	84	100	112	115	100	100	100	100	100
A-SF	36	73	102	119	123	86	87	102	106	107
A-MK	43	82	113	122	125	104	98	113	109	109
B-FA	11	20	39	55	59	27	24	39	49	52
B-LS	13	27	36	40	39	31	32	36	35	34
C-FA	17	32	59	70	73	42	38	59	62	64
D-FASF	18	40	66	77	85	44	48	66	69	74
D-LSSF	14	28	45	52	56	33	33	45	47	49
E-FAMK	19	45	70	92	101	47	53	70	82	88
E-LSMK	12	41	65	72	72	30	49	65	64	62

3 DISCUSSION OF RESULTS

Graphical presentation of compressive strength development of all tested concrete composites is shown in Fig. 1.

Based on the lines distribution, which shows the strength development, it can be seen that all concrete types can be roughly divided into two groups. The first group encircles referent concretes. Common characteristics of this concrete group are:

- High values of compressive strength. This statement is confirmed with the mean compressive strengths for tested ages (18MPa, 35MPa, 46MPa, 52MPa and 54MPa, respectively). The standard deviation of corresponding mean values is max ±3 MPa.
- Rapid strength development in the period up to 7 days.
- Slower strength gain after 28 days.

The second group consists of concretes from series B, C, D and E, i.e. green composites in which 50% of cement is replaced by mineral admixtures. These composites have:

- Significantly lower compressive strengths in relation to referent concrete. Mean compressive strengths are 7MPa, 14MPa, 22MPa, 27MPa and 25MPa, respectively. Standard deviation increases with the age of concrete.
- Slower development of compressive strength.
- Spreading of the strength spectrum with increasing of concrete age. This is confirmed by constant increase of the standard deviation from ± 1MPa (for age of 2 days) to ± 10MPa (for age of 90 days).

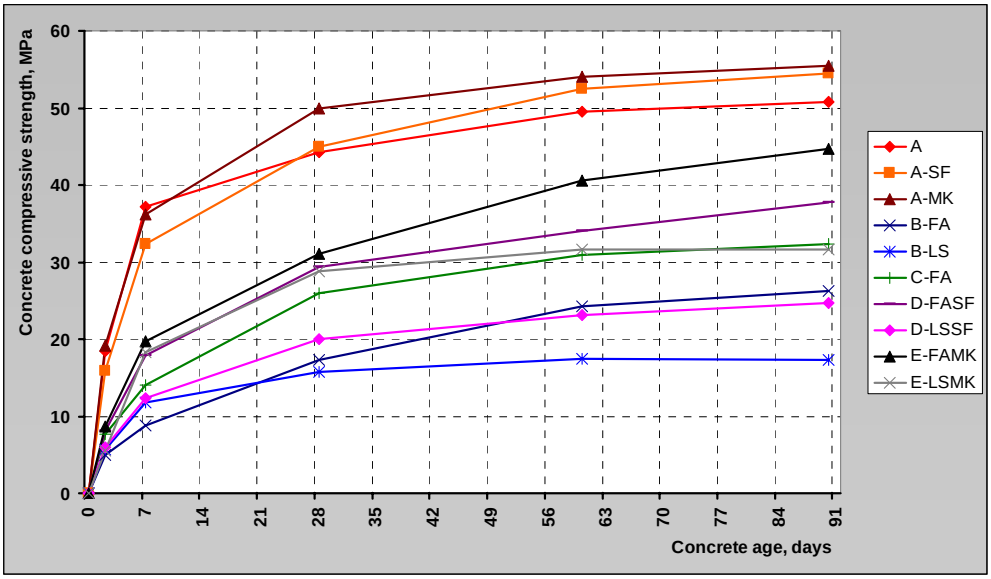

Figure 1. The compressive strength of concrete composites at various ages.

The influence of mineral admixture type on the strength development can be seen by analyses of the results in the group of referent concretes (group A).

Metakaolin in quantity of 10% of the total weight of binder, influence the strength gain in the period up to 28 days. Concrete type "A-MK" has the same strength as the concrete "A" for age of 2 and 7 days, and then, due to chemical reactivity of metakaolin, has rapid increase of strength up to 28 days. The difference between concrete "A" and "A-MK" is approximately 6MPa (13%) at this age. In the period after 28 days, the difference in strength is still kept, with its gradual reduction (to 9% at the age of 90 days). This confirms the fact that the highly reactive metakaolin is mineral admixture with rapid hydration (aluminosilicate).

Silica fume, as different type of highly reactive mineral admixture (amorphous silicates) gives concrete "A-SF" different characteristics. Concrete "A-SF" has a slightly lower early strength in relation to the referent concrete "A". Concretes "A" and "A-SF" have equal strengths at age of 28 days and after that, concrete "A-SF" has a more intensive strength development up to 90 days. This type of concrete at age of 90 days has almost the same strength as the concrete "A-MK". The results of this analysis confirm the fact that amorphous silicates contribute to strength of the concrete in the later period, as for their hydration the calcium hydroxide, a product of cement hydration, is required.

The analysis of results of tested green composites B, C, D and E (Tables 3 and 4 and the diagram in Fig. 1) shows that they could be classified into two subgroups.

First subgroup includes concretes E-FAMK, E-LSMK, D-FASF and C-FA. These are concretes that contain fly ash and superplasticizer, with or without highly reactive mineral admix-

ture and concrete with limestone in combination with metakaolin and superplasticizer. Characteristics of these subgroups are:

- Relatively high compressive strength regardless of the small amount of cement. Compressive strengths for selected ages are ~ 8MPa, 18MPa, 29MPa, 33MPa and 35MPa, respectively. Highly reactive mineral admixtures in concrete made with limestone, provided that the underlying concretes do not significantly differ in their strengths, for the age to 28 days, from concrete with fly ash.
- Widening of the strength spectrum after 28 days. The value of standard deviation of compressive strength for concrete ages 2, 7 and 28 days does not exceed ±2MPa, while for the concrete age of 60 and 90 days, the standard deviation is significantly larger and is ±5-6MPa. Fly ash as a type of active mineral additive that predominantly hydrates in the period after 28 days and contributes to the increase of compressive strength of concrete in this period, was primarily responsible for this strength arrangement.

In second subgroup concretes D-LSSF, B-FA and B-LS are included. These are concretes with a high content of limestone, with superplasticizer and silica fume, concrete with a high content of fly ash limestone and concrete with high limestone content. Characteristics of this subgroup are:

- Lower values of concrete compressive strength for all ages. Compressive strengths are ~6MPa, 11MPa, 17MPa, 20MPa and 21MPa, respectively for the defined ages.
- Widening of the strength spectrum for concrete age greater than 28 days. The value of standard deviation of compressive strengths for the concrete age 2, 7 and 28 days does not exceed ± 2MPa, while for the age of 60 and 90 days, the standard deviation is significantly higher and is approximately ±4MPa. Causes for larger differences in compressive strength for concrete age of 60 and 90 days are silica fume and fly ash, which subsequently hydrates and contribute to strength development after age of 28 days. This conclusion is especially connected to concrete B-FA.

For easier comparison of all concretes types that contain fly ash to referent concrete "A", chart in Figure 2 is analyzed.

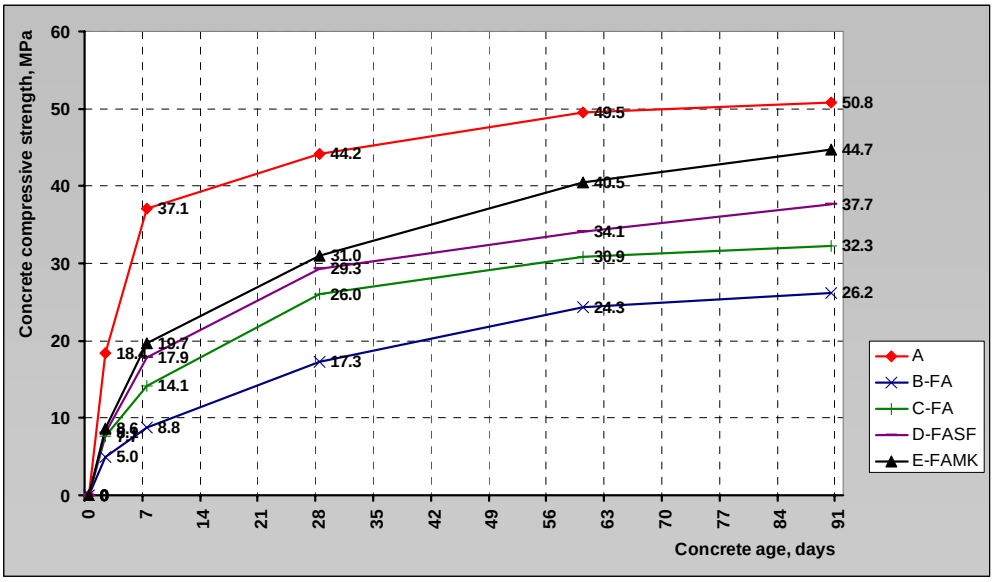

Figure 2. The compressive strength development of concrete composites with fly ash.

The analysis of strength development shows that there are significant differences between the reference concrete and all concretes with fly ash, but that there are also significant differences in strength values within the group of concretes containing fly ash, depending on the presence of superplasticizers and highly reactive mineral admixtures. The difference between the reference concrete "A" and concrete "B-FA", as the concrete with the lowest strengths among concrete containing fly ash, is 13.4MPa (73%) for the age of 2 days, or 24.6MPa (48%) for age of 90

days. The difference between a referent concrete "A" and concrete "E-FAMK" as concrete with the highest strengths of the concrete family containing fly ash, is 9.8MPa (53%) for the age of 2 days and 6.1MPa (12%) for age of 90 days. Besides differences in strength values, there is a difference in the strength development. Referent concrete has fast strength development in the initial period, while all concretes with high content of fly ash show a tendency towards a significant increase in strength after 28 days.

Comparing the strength of concrete B-FA, C-FA, D-FASL and E-FAMK it is concluded that the lowest strength has concrete B-FA, in which 50% of cement is replaced with fly ash. This type of concrete does not contain any chemical admixture and has the highest effective water/cement ratio, due to increased amount of water, in order to achieve the required workability. Biggest compressive strength is achieved in concrete E-FAMK, i.e. concrete that in addition to fly ash and superplasticizer contains a metakaolin. Corresponding compressive strengths of concretes D –FASF and E-FAMK, that contain superplasticizer and highly reactive mineral supplements, have a very slight difference (less than 2MPa) for ages up to 28 days, but afterwards the difference reached 7MPa (18%). It is interesting to compare concrete C-FA and B-FA, by which contribution of the superplasticizer can be seen, because these concretes differ only in the required quantity of water or water/cement ratio. By use of superplasticizer and conservation the water quantity at the level of 200l, compressive strengths for all ages are significantly increased. A common characteristic of concretes containing fly ash is constantly increasing of the strength with increasing of concrete age.

Comparing the compressive strengths, a big difference between the reference concrete "A" and all concretes containing limestone, can be noticed (Figure 3).

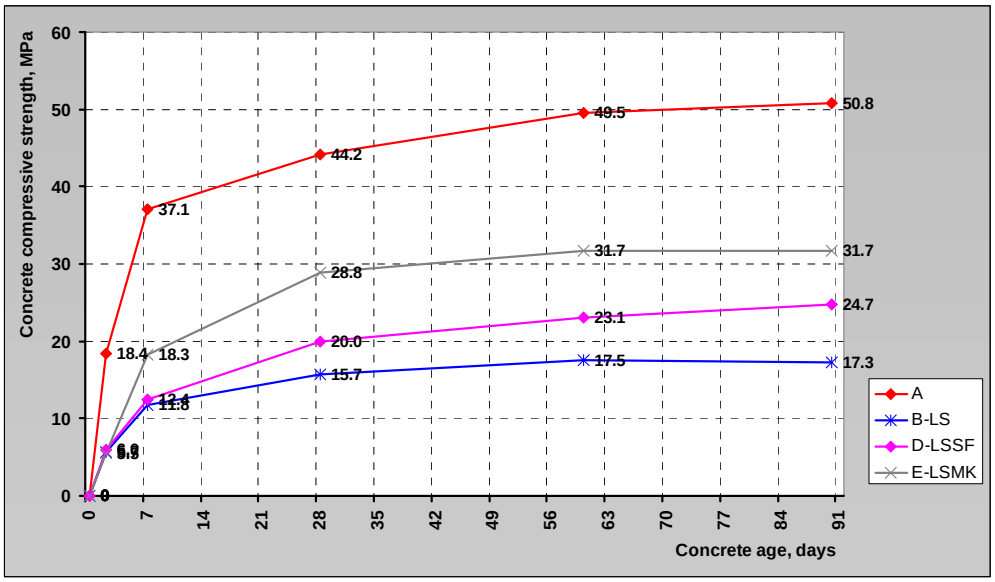

Figure 3. The compressive strength development of GRAC composites with milled limestone.

Analysis of compressive strengths within the concrete family containing limestone (B-LS, D-LSSF and E-LSMK) shows that among them there are significant differences depending on the presence of superplasticizers and highly reactive mineral supplements. The lowest strength has concrete B-LS, in which 50% of cement is replaced by limestone. This concrete has the highest effective water/cement ratio in the group, in order to achieve the required workability. Maximum compressive strength is achieved for concrete E-LSMK, i.e. the concrete that contains limestone, superplasticizer and metakaolin. A common characteristic of concrete family containing limestone is a very small strength increase with increasing of concrete age over 28 days, regardless of the type of highly reactive mineral admixture.

4 CONCLUSIONS

Investigated green composites are concretes in which the coarse natural aggregate is replaced with RCA, while half of the amount of cement is replaced by various mineral admixtures. Technological and especially the physical and mechanical properties of these composites were further improved by applying and adding of chemical admixtures and relatively small amount of highly reactive mineral supplement.

Production of these concretes follows the idea of sustainable development in sense of preserving and protecting the environment by reduction of emission of CO_2, decreasing depletion of resources of natural row materials, decrease consumption of energy. This is also sustainable solution for C&D waste and industrial by products and waste management.

Way of application of investigated green concretes depends of the concrete composition and of mineral admixtures that are used for substitution of part of PC. Based on the results of research, primarily concrete compressive strength, there are two possible areas of application:

- In reinforced and non reinforced concrete structures made of C16/20 to C25/30 concretes without high initial strength, for concreting at high temperatures and for the construction of massive structures because of their low heat of hydration. Composites that can be used for this purpose are E-FAMK, E-LSMK, D-FASF and C-FA, or in other words all the concretes containing fly ash and superplasticizer, with or without metakaolin or silica fume and concretes with milled limestone in combination with metakaolin and superplasticizer.
- In prefabrication, for hollow blocks in masonry and floor structure, for screeds, sloping layers and substrates. Composites that can be used for this purpose are D-LSSF, B-FA and C-LS, that are all concretes with high content of milled limestone, superplasticizer and silica fume and concretes with high content of fly ash.

Concretes containing only milled limestone as 50% of the total mass of binder are not justified to use in structures due to very low strength.

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Utilization of subtle structures from high performance concrete - contribution to sustainable building

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ABSTRACT: Concrete is the most widely used construction material in the world. The production of cement creates up to 5% of worldwide man-made CO_2 emissions. Therefore optimization of concrete structures can lead to the significant environmental savings. Experimental investigation and case studies performed by authors in the frame of long term research, focused on environmental optimization of building structures, support the expectation that it will be possible to reach factor 3 or even more through utilization of high performance concrete (HPC) while keeping structural reliability on the needed high level. Developed structural concepts have been proved not only by theoretical and experimental results, but also by practical application in construction of several buildings. Paper presents three case studies – ribbed / waffle floor structure with minimized thickness of upper deck to 30 mm, light precast RC balcony element and light precast RC frame for passive house.

1 INTRODUCTION

Concrete is due to its mechanical parameters, durability, availability of the original materials and possibility of variable design undoubtedly the most wide spread structural material. New composite high performance concrete reach significantly better properties from the aspect of mechanical resistance, durability and resistance against extra loads. These high performance materials could be used for construction of stronger, more durable and at the same time slender "shell" structures, enabling design with significantly reduced use of materials. This leads to reduction of environmental impacts associated with the use of primary natural sources and with depositing and recycling of the structure at the end of its life cycle. It has been already shown that for many structures it is possible to reduce amount of used concrete by 30 – 60% - when materially and shape optimized solution is applied (Hájek & Fiala 2007). The complex LCA and LCC of optimized high-performance concrete (HPC) structures would show not only environmental benefits, but also the cost efficiency - in spite of the fact that HPC is more expensive and has higher values of unit embodied parameters. Moreover, high performance material properties (higher ductility, fire safety, water tightness, frost resistance, etc.) make structures more durable and more resistant against climatic effects and also safer in case of exceptional loads (like climatic disasters or terrorist attacks). This all creates the potential for wider application of HPC in building construction in the future. Further are three examples of applications of optimized HPC structural elements for the use in building construction, followed by evaluation of environmental profiles showing advantages of proposed solutions.

2 WAFFLE FLOOR STRUCTURE FROM HPC

2.1 *Description of the structure*

Representative segments of waffle floor structure with minimized thickness of upper deck (30 mm) were made from two different mixtures: HPC105 with 25 mm long steel fibres Fibrex A1(tensile strength of 350 MPa) and HPC140 with 13 mm long steel fibres (tensile strength of 2400 MPa) from Stratec GmbH. Deck of this thickness cannot be reinforced by conventional reinforcement therefore utilization of fibres was tested. Both mixtures contained 1% per volume of fibers. The first mixture HPC105 had the maximal grain size of 8 mm whereas the HPC140 was designed from fine aggregate with maximal grain size of 0.6 mm. The compressive strength of HPC105 was 105 MPa, respectively 140 MPa for HPC140. Test samples had the following dimensions: upper deck 30 mm, ribs 50-70/170 mm, the size of the section 1.2 x 1.25 m. Ribs were reinforced by steel rods 10 mm in diameter and contained no conventional shear or torsion reinforcement. Samples were tested on combination of flexure and torsion.

Figure 1. Bottom view on the waffle floor structure.

Mechanical tests of specimens showed very good structural performance and verified the concept of light waffle slab with very thin top slab and slim ribs without conventional shear and torsion reinforcement from fibre reinforced HPC (Hájek, Kynčlová, Fiala, 2009).

2.2 *Environmental evaluation*

Four alternatives of floor structures have been compared: i) full RC slab from ordinary concrete C30/37, ii) waffle floor structure from ordinary concrete C30/37, iii) waffle floor structure from HPC105 and iv) waffle floor structure from HPC140. All structures were designed for the same performance – dead load 4 kN/m^2, live load 1,5 kN/m^2, span 5 x 5 m, same thickness of 200 mm. The waffle floor from ordinary concrete had 60 mm thick upper deck and the width of ribs was 80 mm. While waffle slab from HPC105 and HPC140 had dimensions: upper deck 30 mm, ribs 50/170 mm. The data source used in the analysis was Passivehaus-Bauteilkatalog (Waltjen 2008) and (Schießl&Stengelt 2007). The graph shows evident environmental advantages of all waffle structures. The reduction of concrete consumption in optimized shape of waffle FRC floor structure can reach up to 50 to 70 % in comparison with full RC slab. Moreover this results in lower load from self weight and consequently lower load on supporting structures (columns, walls, foundations).

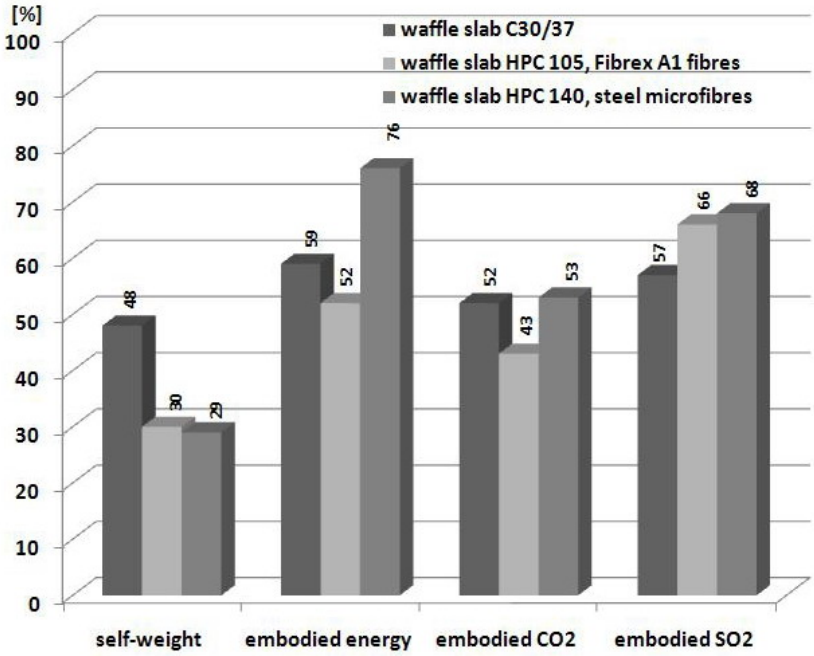

Figure 2. Comparison of environmental parameters of RC floor slabs. Reference level 100% is represented by a full RC slab.

3 LIGHT PRECAST BALCONY ELEMENT

3.1 *Element description*

The shape solution of new fibre concrete railing comes from the shape of standard railing ground plan. The shape is demonstrated on following pictures, the length is 3410 mm and the height is 1050 mm. The original railing balcony element was designed from ordinary reinforced concrete having constant thickness of railing slab 80 mm and conventional reinforcement. The aim of optimization was to eliminate the amount of the conventional reinforcement (2 reinforcing meshes) in the slab and to minimize the railing thickness in order to achieve maximal savings in structural materials, concrete and steel.

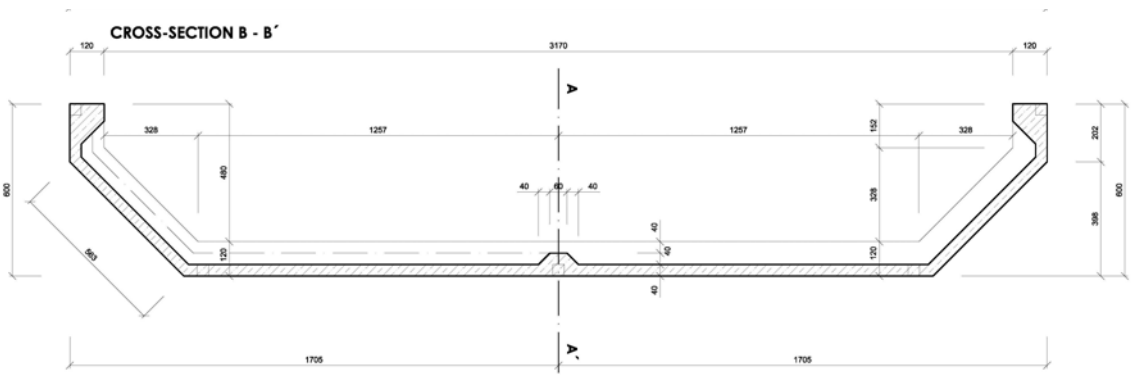

Figure 3. Cross-section of the railing.

The new design of railing slab has the thickness of 40 mm and therefore it cannot be effectively reinforced be the conventional reinforcement. Hence, it is designed from the fibre concrete. The railing shape and the shape of stiffening rib along the prefabricate element perimeter come out from the cross-section optimization. The stiffening rib has the thickness of 120 mm, the height of 60 mm and under the angle of 45° runs to the thickness of 40 mm (Fig.3).

Five different mixtures containing polypropylene fibres with different admixtures (CSF – microsilica Chryso, MK – metakaolin Metaver I) were designed and used for experimental verification of cross-sections, see Table 1.

Figure 4. Sections of balcony railings.

Experimental verification of mechanical properties of a thin railing slab between the reinforcing ribs was performed on 1.0 m wide testing specimens. The shape of the test sample is apparent on the Figure 4. The theoretical span of specimen for four-point bending test was 1.0 m. Concrete properties of various balcony railing sections were tested in laboratories ŽPSV Uherský Ostroh and they are listed in the Table 1.

Table 1. Properties of concrete for the experimental balcony railing sections.

Series – production date		23.7.09	21.9.09	30.9.09	7.10.09	8.10.09
Compressive strength	[MPa]	75.9 ± 2.5	93.1 ± 0.1	86.3 ± 2.0	91.7 ± 2.2	93.4 ± 2.0
Tensile bending	[MPa]	11.1 ± 0.5	11.3 ± 0.3	9.6 ± 0.2	11.9 ± 0.5	10.8 ± 0.5
Density	[kg/m^3]	2136 ± 10	2255 ± 20	2185 ± 2	2310 ± 25	2264 ± 30
Admixture		CSF 8%	MK 4%	MK 4%	MK 5%	CSF 8%
Fibres Chryso 22 mm		3,2 kg/m^3	2,5 kg/m^3	5 kg/m^3	5 kg/m^3	5 kg/m^3

A standard four-point bending test was performed in order to verify mechanical properties of cross sections fibre concrete balcony railings. The best in terms of deflections and strains appeared mixture of 21 September 2009, which contained 4% metakaolin Metaver I and 2.5 kg/m^3 Chryso fibre length of 22 mm. Measured deflections for all 5-mixtures ranged between approximately 0.5 to 1.0 mm, which represents the deflection of approximately L/2000 to L/1000. Deflection limit L/250 is 4.0 mm (for the span L = 1.0 m).

Table 2. Summary of static values for each experimental railing cross-section.

Railing section	23.7.	21.9.	30.9.	7.10.	8.10.
M_{exp} [kNm]	1.65	1.97	1.64	1.64	1.96
$M_{cal.}$ [kNm]	3.75	3.81	3.24	4.02	3.65
$F_{max.}$ [kN]	9.91	11.83	9.86	9.82	11.78
$f_{ctm,fl}$ [MPa]	11.1	11.3	9.6	11.9	10.8

3.2 *Environmental evaluation*

Embodied energy, embodied emissions $CO_{2,equiv}$, embodied emissions $SO_{2,equiv}$ were compared in the environmental evaluation of prefab balcony railing alternatives. Environmental impacts

(embodied energy, embodied emissions $CO_{2,equiv}$, embodied emissions $SO_{2,equiv}$) and self weight of individual variants of railing are shown in following graph (Fig. 5).

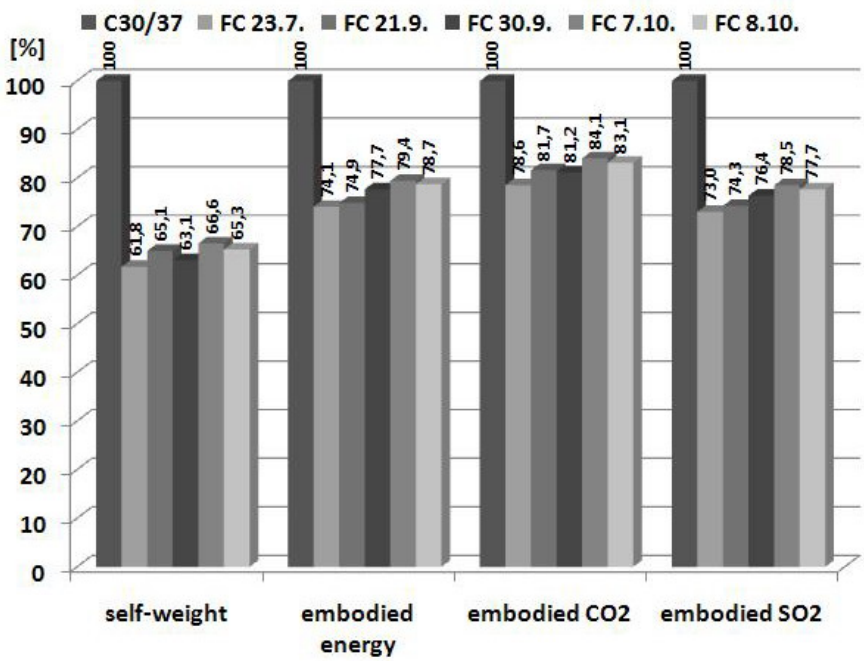

Figure 5. Relative comparison of environmental data.

It is obvious from the relative comparison that fibre concrete railings variants reduce the weight of utilized structural materials (concrete and steel) by approx. 35%. The second variant with polypropylene fibres (FC 23.7.) is the most favourable solution from the environmental point of view; in contrary to standard solution it has lower environmental impact by approx. 25%.

Environmental and economical benefits are related to (i) decrease of raw material consumption (savings in concrete and its components – aggregates, cements etc.), (ii) decrease in transportation demands and material handling (lower amount of concrete), (iii) savings in supporting structures and (iv) the longer durability of prefabricated elements.

4 LIGHT PRECAST RC FRAME FOR PASSIVE HOUSE

4.1 *Description of the construction system*

A combination of light subtle RC frame structure with external walls and internal partitions from timber elements represents effective structural solution from economical as well as environmental point of view. Significant savings in concrete and steel consumption follow from subtle sections of precast RC members. Consequently savings in transport and manipulation costs are evident. This all makes this structural concept more environmental efficient.

This approach has been utilized in the construction of passive family house on the suburb of Prague. Load bearing structure of the 1st floor is made from precast RC light frame. The section of precast columns is 150 x 250 mm. It was made from common concrete C35-45XC1, reinforcement was 4 x R12. Edge columns were composed from two column elements creating L shape section. Columns supporting beams have thickness 150 mm. Floor slabs are RC composite with precast filligran lower part and cast in site upper part – total thickness 210 mm (Fig. 6).

Figure 6. Light precast RC frame structure.

Load bearing structure of the 2nd floor and roof structure is timber structure (Fig. 7). Entire load bearing structure is covered with timber external wall containing 400 mm of thermal insulation from mineral wool. The total expected energy consumption will be less than 20 kWh/m^2 per year.

Figure 7. Timber frame structure on the top of RC precast part; fixing of timber external wall.

4.2 *Environmental evaluation*

Three alternatives of structure applied for construction of the same family house have been assessed in the study. Reference alternative is common structural solution from ceramic brick blocks Porotherm 44 P+D (thickness 440 mm) and RC floor structures with ceramic hollow fillers MIAKO (VAR. 1). Second alternative VAR. 2 has also load bearing structure from ceramic bricks (Porotherm 24 P+D) and the same type of ceramic floor slab. The external walls are insulated with 300 mm of PPS (polystyrene). VAR. 3 is light RC frame structure with timber external walls and timber internal partitions This alternative was applied in the construction of family house in Prague - Modrany (Fig. 6 and 7).

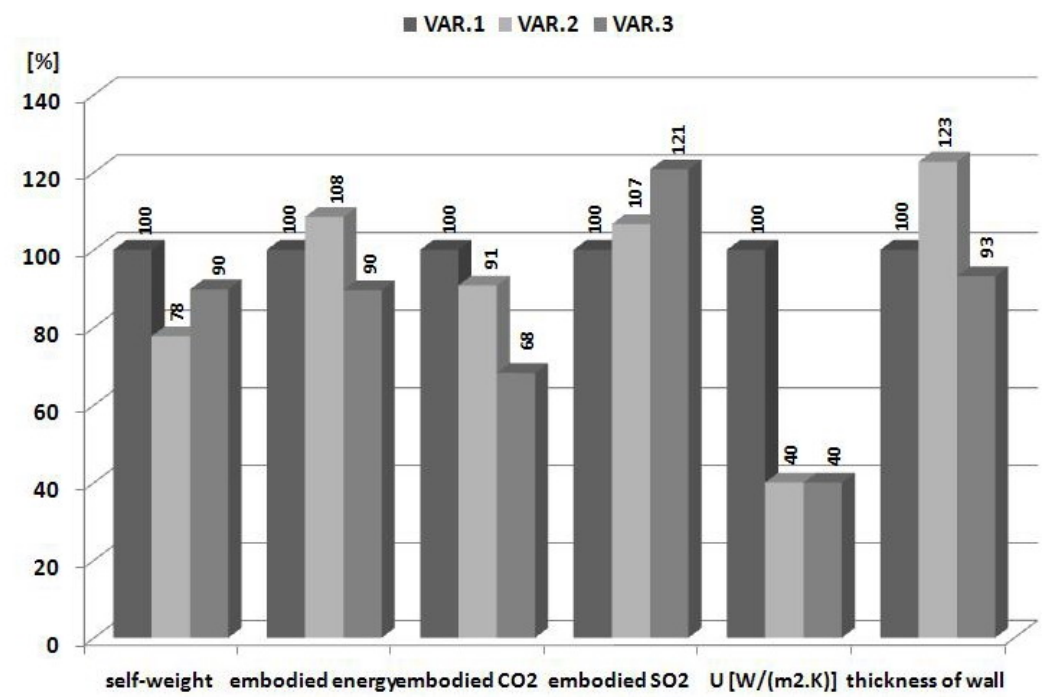

Figure 8. Comparison of environmental parameters of three alternatives of load bearing structure for passive family house.

The analysis has been made just for one storey (1st storey) in which the combination of light RC frame and timber external walls and partitions was used. In the Figure 8 are presented results - comparison of environmental profiles of described three alternatives. It is evident that alternative with light RC precast frame and timber external wall show better results in embodied energy (10% savings in relation to reference alternative) and embodied CO_2 emissions (32% less). The thickness of external wall is also the lowest – this can represent important economical advantage, especially in urban regulated areas with high density of houses.

5 CONCLUSION

Increasing production of concrete is associated with increasing environmental impacts caused by high energy consumption and high non-renewable material use. It has been already shown that utilization of optimized light subtle concrete structures can result in reduction of concrete consumption up to 50 – 70%. This could be achieved e.g. by the use of high performance concrete with significantly better mechanical properties and higher durability in combination with shape optimization. Application of this approach can lead to environmental savings and represents important contribution to sustainable building. Three case studies presented in the paper showed, that wider implementation of these principles into construction practice is possible, applicable, feasible and sustainable.

This outcome has been achieved with the financial support of the Grant Agency of the Czech Republic Grant Project No. 103/08/1658 and with the financial support of the Ministry of Education, Youth and Sports of the Czech Republic, project No. 1M0579. All support is gratefully acknowledged.

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Wood Wool Cement Boards – solutions for sustainable buildings

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ABSTRACT: Wood Wool Cement Boards are new "green" low tech solutions for sustainable construction that are used for internal linings or for entire façades. They rise to the cradle-to-cradle thinking and resource-efficiency, because they can be reused/recycled several times over a long lifecycle of more than 400 years, and be converted back to basic ingredients at the end of lifecycle to make a new material. They are easy to handle and to work with, and they facilitate an improved energy performance. Products based on combination of wood wool and cement have been around for over 100 years but they have evolved especially over the last 15 years into solutions that fit perfectly with needs of sustainable buildings. Further developments have resulted in construction solutions for climate and geological zones all over the world. The great variety of Wood Wool Cement applications extends from luxury houses to social houses in earthquake and hurricane zones. Especially in countries of hot climates WWCB buildings help to substantially reduce costs caused by air-conditioning.

1 INTRODUCTION

The challenge of eco-efficient and sustainable building demands new manufacturing and execution methods that allow radical reductions in resource consumption in the building and construction sector. The future products and buildings need to suit for recycling and reuse. The cradle-to-cradle-thinking will rearrange the supply networks and the relationships of the stake-holders. The role of manufacturer of machinery for manufacture of construction products can be very crucial for the performance of a final completed building. Development of several new types of wood wool cement board are successful examples of innovations that are based on a new manufacturing technology and aim at green buildings.

Products based on the combination of wood and cement have been around for over 100 years. However, the solution has evolved especially over the last 15 years thanks to the increased awareness for environmental friendly material and energy consumption. The wood wool cement material became preferred by cement producers as it reduces the need of fossil fuel and quarried base materials for production of new cement. The wood wool cement board WWCB was put it in the spot light as one of the few cradle-to-cradle building materials. Its carbon footprint is reduced by the fact that up to 50% of the CO_2 from the cement manufacture is converted back into the end-product while curing.

In Europe the production of the Wood Wool Cement Board has been modernized since the invention of a rotating wood wool machine by Eltomation resulting in a much more automated and safe production process compared to the process on hand filled wood wool/excelsior machines that where customary till the mid 1990s. WWCB in Europe is produced in a range of densities from 280 kg/m^3 to 1100 kg/m^3.

2 GREEN CHARACTERISTICS OF WOOD WOOL CEMENT BOARDS

2.1 *Basic material properties*

The first boards made of combining wood fibers and cement appeared to the construction market as early in 1900, and have proven their value ever since. In the Wood Wool Cement material (wood wool is also known as excelsior in the USA), each fiber is coated with a thin film of Ordinary Portland Cement that, when cured, partly petrifies the wood. In that way the fiber will last indefinitely as long as the cement film is not damaged.

Wood wool cement is available in densities ranging from 280 kg/m^3 up to 1100 kg/m^3. This allows for a wide range of applications depending on the required properties of the product. Low density material is used for sound and thermal insulation, medium density material is applied more structurally as the higher density also gives higher bending strength than the low density material. In situations where one needs the qualities of the low density material for walls, the structural resistances of the building has to come from reinforced concrete, steel or wood framing.

The wood wool cement material is truly long-lasting and durable in many kinds of atmospheres and circumstances. Boards used as wall insulation in buildings in Italy were in good condition after 70 years and were re-used in other buildings when the old building had to be torn down. The material can with-stand numerous freeze thaw cycles and has been applied in Scandinavia for over 60 years in the open without any sign of deterioration.

Looking at the environmental discussions, cement has a large carbon footprint despite of the fact that when cement cures in the wood wool cement process it binds up to 50% of the CO_2 that was created in producing the cement. When applied in WWCB the wood also binds a lot of CO_2 during growth that stays in the WWCB product until it is no longer used. When after several life cycles it is finally ground down it decomposes into compostable wood and lime. Both are harmless to nature and as a result all homogeneous WWCB products have green labels in Europe.

A recent study of a large EU based cement producer showed that WWCB is also very effective to produce new Portland cement. The wood partly replaces fossil fuels in the kiln where the cement breaks down to components that again can re-act to water. So more WWCB in the kiln also means less new quarried base materials needed. So WWCB can be considered to be both Cradle to Cradle and a green building material.

2.2 *Applications of Wood Wool Cement Board*

The wood wool cement material is used in several types of structural applications depending mainly on the density of the material. Low density material (from 280 to 900 kg/m^3) is used for insulation and lining, medium density material (from 900 to 1100 kg/m^3) is applied more structural as the higher density also gives also bending strength. Historically WWCB has been produced in Europe mainly for acoustic and thermal insulating applications like ceilings for public buildings like concert halls, libraries and swimming pools.

The most used board dimensions have resulted in a board width in production of approximately 600 mm. As the production process is a continuous mat, the board length is determined by the length of the mould whereby the height of the mould rim gives the thickness of the resulting board. Over the years European producers have developed a wide range of different boards with bevels, rims and colors that can all be produced on one type of WWCB production line (figure 1).

Figure 1. Types of WWCBs.

In areas where earthquakes and/or hurricanes occur WWCB with a dedicated specific weight can provide insulating permanent shuttering for reinforced concrete multi story buildings. Reinforced WWCB normally used for roofing can also be used for construction of strong and well insulated single and multi story (social) houses in developing countries all over the world.

The medium density boards have specific applications that make it a fire and vermin/termite resistant competitor to conventional boards currently used in stick build construction.

New types of the WWCB products are the very low density (≤ 300 kg/m^3) Large prefab wall

Elements (LE) and medium density boards (1100 kg/m^3) that due to their specific product properties appeal to builders all over the world as alternative green solutions that both fit in conventional building concepts as well as open ways for new energy saving designs.

The LE prefab walls have a very high heat buffering capacity combined with an excellent R-factor of 5.3 p/m^2 at 40 cm thick. As prefab solid SIP's they are excellent for fast and efficient building. All the walls for a single story 100 m2 house can be placed in just a few hours. Also an energy plus building comes into reach when building with LE's.

Further developments have resulted in construction solutions with WWCB for climate and geological zones all over the world, not only for luxury houses but also for social houses in earthquake and hurricane zones. Especially in countries with hot climates WWCB buildings help to substantially reduce de cost of air-conditioning.

The properties of wood wool cement boards can be summarized as follows:

- Good thermal insulation
- Excellent heat buffering capacity
- Wet and dry rot resistance
- Fire resistance (B1 classified) (ASTM E84: Class A)
- Termite/Vermin resistance
- Good sound absorption
- Excellent base for stucco and plaster
- Light weight to handle
- Easy to process in construction
- Relative low energy consumption to produce
- No fossil fuel or binders used
- Limited impact on local natural resources
- No waste product at end of life cycle
- Nice and attractive ‘natural look’ visual appearance.

To define between the low density WWCB and medium density boards the medium density boards are promoted as Wood Strand Cement Board WSCB or EltoBoard® as the 25cm (10") long wood fibers in WSCB give it much more structural strength than the cement bonded (short) fiber boards currently in the market. WSCB/EltoBoard® can also be seen as the lighter and stronger replacement of Cement Bonded Particle Board (CBPB). Due to the relative high OPC content WSCB is heavier than OSB, but has none of the disadvantages of OSB type products. (see properties). Types of wood that are suitable are species of pine, poplar/aspen and eucalyptus. Preferably from FSC certified sources. Other wood species are sometimes suitable.

3 LOCALIZATION OF CONSTRUCTION METHODS

3.1 *Temperature*

The wood wool cement boards WWCB and wood strand cement boards WSCB are used all over the world in buildings that are specifically designed for local conditions ranging from extreme cold to extreme hot and humid. Which type of construction method is used depends both on the local economic situation, local building regulations and the willingness of builders to work with the material when it is new to a specific market.

Depending on the local constraints it is possible to build walls with solid insulating WWCB boards or use the boards as insulating casing/shuttering for pouring reinforced concrete. In Siberia WWCB is used in combination with a layer of polystyrene to further improve insulating for extreme cold. Recent regulation forbids the use of polystyrene in Russian buildings. Therefore it is likely that it will be replaced by mineral wool which has similar properties. As WWCB can easily combine with a wide range of insulation sandwich materials there is no con-straint for the WWCB producer to switch to alternative insulating materials as the individual Eltomation production lines are flexible in this respect. When applied as a solid large prefab element there is no need to add either polystyrene or mineral wool. The material itself provides the required insulation value. See large WWC Wall Elements.

3.2 *Earthquakes/hurricanes*

Both Earthquakes and hurricanes may set specific additional construction requirements for a building. WWCB and WSCB/EltoBoard® should be used within the physical limitations of a specific product and complementary to the wooden, steel or concrete design that complies to the local regulations set for the construction/building in a specific geographical and geological setting. If used for permanent shuttering the boards are more densely pressed (600-900 kg/m3) and used in countries like Japan to give both insulation and additional strength to a (high rise) building in case of a natural disaster.

3.3 *How to choose board dimensions for a specific building*

As the Eltomation production line has a 2 stage mould filling operation it is possible to insert all kinds of sandwich materials (see Figure 1) like mineral wool or wooden laths/poles to create load bearing roofing boards.

Both WSCB/EltoBoard® and the Large WWCB prefab wall elements are relatively new developments. EltoBoard® being a patented medium density board from Eltomation while the large elements are a development of Träullit in Sweden. The latter has also developed a pole reinforced low density building board (240x60x10-15cm) that shows high potential for affordable, well insulated social housing anywhere in the world. Depending on the construction and local conditions it is now possible to build all types of well insulated housing with WWCB from 3,5 cm thick for moderate climates to walls up to 60 cm thick for extreme cold or hot climates. Especially the use of the thicker low density WWCB material results in very substantial reduction of energy cost for air conditioning and/or heating while the indoor living climate is strongly improved because these walls are breathing. They absorb heat and moisture and release it gradually over a 24 hour period.

WSCB/EltoBoard® is a class in its own and as a product it has to compete with other structural boards like OSB. This means that one of the essential requirements is that it should be available in board sizes of at least 240x120 cm (8'x4'). As WSCB is produced on a standard low density WWCB line with an added special hydraulic press, board size is currently limited to 60 cm wide. For most structures this is not a problem, especially if the builder applies the boards horizontally over a stick frame construction. A production plant for 120cm wide WWCB/WSCB awaits a launching customer. Meanwhile tests have proven that it is very effective to use PU kit to fix 2 or more 60 cm wide boards together to form larger board sizes that can be used to produce for SIP's and/or prefab walls.

In the following chapters the use of WWCB as ceiling boards is left aside as this use is well documented by a number of EU producers like Knauf, Celenit, Troldtekt and Träullit. Detailed instructions for use have been documented in the LeichtBauPlattenFibel. An instruction for use in the German language (last printed in 1985) is also available in pdf. The next part of this article delves a bit deeper on how to implement WWC boards and panels in load bearing structures.

4 WOOD WOOL CEMENT BOARDS AND MASSIVE WWC ELEMENTS

4.1 *Climatex system: labor intensive but simple*

This system consists of assembling large self supporting wall elements at the building site out of several Wood Wool Cement Boards and a reinforced concrete framing. A foundation is only needed for the outer walls; the interior walls are placed in recesses on the floor slab. The walls are assembled from WWCB and laid-out on a flat surface according to their size, windows and doors on simple wooden frames. At about every meter, one reinforced concrete pillar is poured in between the boards as well as along the edges of the wall elements. The mould frames are placed one on top of the other with the lower rim in the direction of their final installation place don the floor slab. They are piled in the right sequence for demoulding. After hardening of the concrete, the wall panels are erected and fixed to each other with sticking out steel wire at the

corners and T-junctions. Then the corners and T-junctions are filled with concrete. Roof anchors are fixed to the top beam and roof beams can be installed.

The corners and T-junctions receive a wire mesh after which inside and outside is stuccoed in 3 layers totaling 1,5 cm on each side. With this concept over 7,000 social houses were build in Brazil in 1982. Even after almost 30 years not a crack can be found.


Figure 2. The Climatix System.

Alternatives to the Climatex system have been developed over the years and have resulted in concepts combining the boards with steel frame structures but also with reinforced concrete poles where the boards slide in grooves. In the Malaysia and some Balkan countries the boards were applied in concepts where the boards were already in place and the rebar openings with rebar were filled on site. Only in the place where the concrete has to be poured is temporary shuttering needed. Again a very effective way to build all kinds of well insulated housing at relative low cost.

4.2 *Byggelements; a new Swedish alternative*

Independently from other alternatives Träullit in Sweden developed a roofing board of 240cmx60cmx15cm with one (Bygg element) or two (Tak element) embedded poles. Originally meant for large span roofing (240cm(8')) these reinforced boards, when placed fully vertical, are very effective for building single story houses with 10-15 cm thick walls. In situations where the insulating value of the reinforced boards is insufficient, a second layer can be added that is not reinforced but may be solid or of the sandwich type with a mineral wool inside layer. Often this second layer is fixed horizontally to reduce cold or heat bridges. The boards are fixed to the floor slab by a bolt that goes trough the pole(s) in each board.


Figure 3. Tak Elements

On top a connecting wooden beam or cast reinforced concrete ringbeam add structural strength to the required specs and provide fixing of the anchors for the roof construction. Combinations with (cold rolled) steel beams and trusses are also possible. Finishing inside and out is done by applying metal or other mesh and several layers of stucco. Water resistant on the outside and breathing lime on the inside. Alternative for the inside finishing layer can be gypsum drywall.

Both the Climatex concept and the Bygg elements are very flexible for design and allow assembly of complete walls on site or can be assembled partly prefab when applied in large projects with a lot of similar houses. Like Climatex walls, Byggelement walls can be used for insulating inside walls as well.

4.3 *Large Elements when labor is a substantial cost factor*

The Swedish architect involved in the research project of the Lund University for Passive Housing Materials, was the first to experiment with 40 cm thick walls made of solid WWCB. Because at that time this material was only available in boards measuring 240x60x15 cm, he cut blocks of 40 cm and build walls while using the blocks as large bricks.

Over a period of several years the cooperation between the WWCB factory and the architect resulted in ever larger WWCB blocks and currently the most effective size for building and insulation is a solid panel of 600cm x 260cm x 40 cm with an R value of 5,3 per square meter. Basically these large Elements are solid SIP's that under certain local conditions need additional reinforcement for additional load bearing requirements, for example when snow loads, hurricanes or earthquakes are an issue.

A building team of 3-4 and a small crane can place the walls of several houses in a single day. This makes this building concept especially interesting for countries where labor cost are

high. Because of its insulating properties at 40 cm thick the large element system is also a very attractive alternative for both cold and very warm climates as well as areas with frequent bush fires as it will not burn even after extended exposure to extreme heat. (6 hours in 1200º Celsius).

Figure 4. From foundation to turn-key delivery in less than 4 months total building time.

A number of material properties of WWC are independent of density and or thickness. The testing of these properties has been well documented by most of the EU producers. Especially accessible is the English brochure of Celenit where pages 6 to 9 show some general properties of the thinner ceiling boards. For homogeneous WWCB the figures of the product Celenit N are most compatible with the WWC as used in Large elements. As the maximum thickness given is 75 mm extrapolation of the thickness range can give some indication of likely values for LE panels ranging from 35 cm till 60 cm thickness. See: http://www.celenit.it/performance.asp and http://www.celenit.it/characteristics.asp

For practical reasons the low density WWC should not be included in construction calculations as this in general requires that the material needs to be certified for load bearing properties. For calculating constructions where the WWC is the insulator the calculation should always be based on the structural strength of the wooden, steel or concrete skeleton. That way the restrictions for use in most types of constructions is circumvented while the limited added strength of the WWC material give some added strength above the calculated values for the load bearing structure.

Figure 5. LE's ready for shipment.

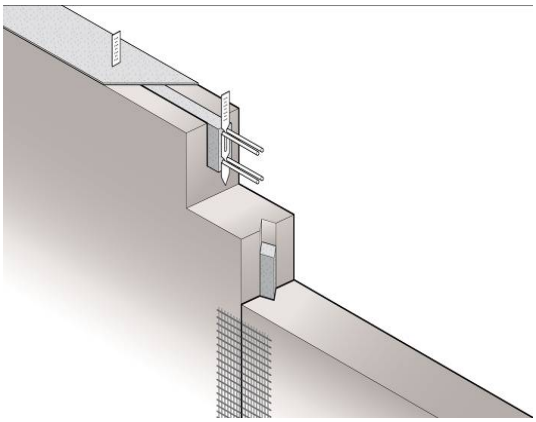

Figure 6. Principle of construction.

4.4 *Construction with Large Elements when labor is a substantial cost factor*

Due to the low weight of the wall elements one can transport up to 108 metres of large wall elements on a truck with a trailer. The elements are loaded into open containers, e.g. one container on the truck and two on the trailer.

The Träullit Large Element system consists of a column/beam system of reinforced concrete that is cast on site after the elements have been mounted onto the foundation. In the joints between the large wall elements vertical V-shaped slits form a square cavity (approx. 70 x 70 mm) when the elements are mounted next to each other (Figure 6). At the crest of the large wall element the U-shaped groove (approx. 100 x 160 mm) forms the carrying (ring) beam that runs along the top of the element around the entire outer wall crest. The vertical and horizontal cavities and grooves are reinforced with steel bars and are cast on site after the elements have been

stabilised with buttresses. During the mounting the corners can be stabilised with sharpened corner braces. These ensure stability for the casting process.


Figure 7. Economic (Just-in-time) transport.


Figure 8a. Placement of LE's

Figure 8b. Placement of LE's

To get the correct cover layer of concrete around the reinforcement, rafter fastening irons are used. This is an arrow-shaped, 3 mm thick piece of sheet metal that has punched gaps for fixing the reinforcement bars and the fastening of the rafters. It is struck into the U-shaped groove of the large wall element crest. The walls are mounted with a mortar leveling on the foundation. A reinforcement bar in the joint between the large wall elements is anchored into the foundation and can be bound to the carrying (ring) beam. The load-bearing structures are the joint columns and the carrying (ring) beam. These are reinforced in order to be able to carry the appropriate loads. The large wall element itself has a compression resistance factor of 27kN per running meter. A possible bending down of the concrete beam is prevented by the large wall element that works together with the concrete ring beam.


Figure 9. Open Ring-beam.


Figure 10. Anchors in ring beam for floor.


Figure 11. Pouring of concrete.

Once the wall elements have been mounted and the beams and cavities have been cast on site, the walls have to be air tightened so that no wood wool cement remains visible. This is particularly important around windows and the crest of the building where it will be impossible to plaster after the windows and the rafters have been mounted. Beams and struts that are placed in direct contact with the outside wall must also be plastered before they are mounted. The diffusion barrier on the inside of the roof is folded double and squeezed against the exterior wall with an L-shaped sheet metal profile. Between the wall and the diffusion barrier an EPDM-rubber is fitted.

The rafters are anchored to the large wall elements by the arrow-shaped sheet metal pieces that were cast into the carrying (ring) beam. The actual amount of nails/screws needed for the anchoring of the rafters is determined by the wind load on the roof. Under each rafter a moisture proofing sheet must be placed to ensure no moisture is carried to the wood rafters. The gable

walls are anchored to the roofing with screws and plugs all the way to the concrete beam in the large wall element joints to ensure a tight fastening of the gable. If the building is more than one level, the large wall elements are placed on top of each other and the joint column runs all the way to the top of the upper carrying (ring) beam. The elements on the ground level must be mounted, reinforced and cast first before the large wall elements of the upper level can be mounted. Depending on the wind load the building must withstand (depending on location), the columns may have to be cast larger and be better reinforced to be able to ensure stability. The beam layout of a multilevel building can be made of wood or concrete. If wood is the chosen material, a strut with a cast-in threaded stainless steel bar is anchored onto the wall which the rafter can be hung into with an iron joist hanger. Concrete based rafters can be made of light-weight concrete or similar. All rafters, regardless of material, are mounted onto the inner crest of the large wall elements.

The elements are always lifted and handled by a crane and two or three construction workers that fit the elements together, buttress them, and manage the concrete casting on site. Such a work team can manage to lift down 5-6 large wall elements from the truck, fit them, and buttress them in an hour. A complete mounting with reinforcing, caulking the joints and casting on site naturally takes a longer time. On average one can complete a mounting of about two elements per hour.

Electricity fittings are simply milled into the wall since the large wall element is very easy to work with. (note: in the new fully-automated Large Element Line, an integrated CNC Centre can optionally provide all such openings for cables and piping in the plant). When all the fittings are finished the milled fittings are plastered over. After that the entire surface of the interior wall can be plastered.

Figure 12. Inner walls prior to stuccoing.

Figure 13. Ready villa (215 m2 living space).

Fastenings for e.g. kitchen cupboards and fittings are usually made with screws and plugs. The hole for the plug should be drilled a couple of millimeters smaller than what is recommended for the selected plugs. The drilling hole should be cleaned and air-proofed with e.g. mounting glue before the plug is mounted. After this the interior fittings can be mounted into place. A normal 10 millimeter plug has a vertical pulling load of 165 kilos per mounted screw. Stiffer plugs of the type that is used for lightweight concrete have a vertical pulling load of 300 kilos per mounted screw.

The Träullit large wall elements have obtained the highest fire-rating in Sweden. When tested the large wall element was subjected to a continuous fire during six hours. The temperature of the oven was 1200 degrees centigrade on the fire side of the wall, while the other side of the wall held a temperature of only 45 degrees centigrade.

Table 1. Technical Data for Träullit Large Wall Element (thickness 400 mm)

Träullit Large Wall Element (thickness 400 mm)	Technical Data
U-value	0,19 w/m² ºC
Fire rating	REI360
Heat storage capacity	250 kJ/ m² ºC
Critical RH (preliminary tests)	90 %
Air permeability	20 m³/mhPa
Bending strength	27 kPa
Load carrying strength	27 kN per running metre of wall
Density	Approx. 300 kg/m³
Fire tests on LE	6 hour fire resistance (REI 360)

4.5 *Wood Strand Cement Board / EltoBoard®, when others fail*

EltoBoard® is a relative new development by Eltomation aimed at applications that seek a structural panel that is lighter and at the same time stronger and cheaper to produce than conventional mineral bonded competitors like Cement Bonded Particle Board (CBPB), Backer Board and some of the magnesium bonded boards. Eltoboard is not affected by fire, mould, fungus or vermin, including termites. This makes EltoBoard a strong competitor for OSB in areas where OSB is currently not appreciated for stick build construction. Production wise it is a great advantage that EltoBoard can be produced on an extension of the standard Eltomation WWCB plant. Due to its green and durable properties WSCB will allow for higher market prices as its use gives a significant boost to the future value of a building.

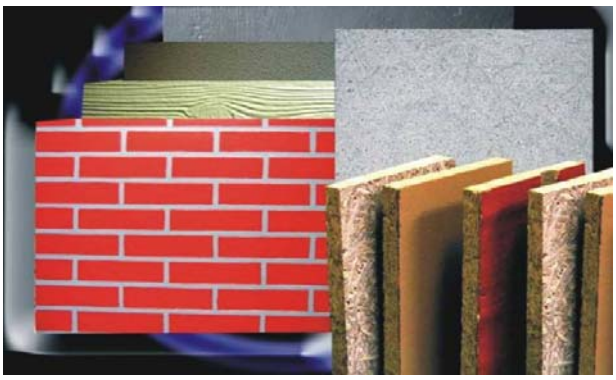

Figure 14. EltoBoard with different finishes.

Figure 15. Eltoboard before final finish.

The production of medium-density Wood Strand Cement Board (WSCB – EltoBoard) is accomplished on a standard WWCB Plant to which a special EltoBoard Press has been added, which will compress the fresh wood-cement mat to a much higher density. The result is a medium density board with structural strength (bending strength of up to approx. 20 MPa). Board dimensions are typically 60 cm wide and 240-300 cm long.

Board thicknesses range from 8 to 25 mm. Eltomation is currently also developing a production line to produce WSCB - EltoBoard as 120 cm (4') wide boards, which will allow the client to cover a broader market-range, e.g. for replacing other structural boards such as Cement Bonded Particle Board (CBPB) and Oriented Strand Board (OSB), for reasons of moisture-, fire- or insect resistance. For a detailed description of the production process of WSCB, reference is made to the IIBCC 2006 (Sao Paulo) paper of Mr. G.J. (Gerry) van Elten. This Publication is available on the website of Eltomation (www.eltomation.com) under "Publications". There you can also find a presentation of Mr. Matt Aro of the Natural Resources Research Institute, Duluth MS, USA specifically on the properties of WSCB/Eltoboard.

4.6 *Wood Strand Cement Board / EltoBoard® and Large Elements, some facts*

General: the properties, certification and working instructions of WWCB low density are well documented on the individual sites of EU producers (see Eltomation reference list) and general instructions as documented in the Leichtbauplatten-fibel. As the Large WWC Elements are implemented in load bearing walls below facts concentrate on a number of regular asked questions from potential producers, architects and project developers. Some of the facts are LE specific others are valid for all WWCB products.

A number of material properties of WWC are independent of density and or thickness. The testing of these properties has been well documented by most of our customers. Especially accessible is the English brochure of Celenit where pages 6 to 9 show some general properties of the thinner ceiling boards. For homogeneous WWCB the figures of the product Celenit N are most compatible with the WWC as used in Large elements. As the maximum thickness given is 75 mm extrapolation of the thickness range can give some indication of likely values for LE panels ranging from 35 cm till 60 cm thickness.
See http://www.celenit.it/performance.asp and http://www.celenit.it/characteristics.asp

4.7 *Certification*

For practical reasons the low density WWC should not be included in construction calculations as this in general requires that the material needs to be certified for load bearing properties. For calculating constructions where the WWC is the insulator the calculation should always be based on the structural strength of the wooden, steel or concrete skeleton. That way the restrictions for use in most types of constructions is circumvented while the limited added strength of the WWC material give some added strength above the calculated values.

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Recycled Materials for Technical-Artistic Applications obtained with Tungsten Mine Coarse Wastes

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ABSTRACT: Mining and quarrying activities in Europe produces about 55% of total industrial wastes, according to recent Eurostat data. Thus, it is desirable to find out new solutions that can contribute to reuse of such waste. In this context, a research work has been carried out regarding the study and reuse of coarse wastes of Panasqueira tungsten mine, located in Portugal. The study consisted in designing innovative polymer-based composite materials incorporating mining waste particles of different sizes having aesthetic value for potential use in technical-artistic applications. Mainly, it consisted in developing a prototype of a terrazzo tile for external use, taking into account parameters that affect aesthetic value, such color and texture and, as well verifying the fulfillment of CE marking requirements, according to current standards. Results obtained in this work point out the possibility of developing innovative solutions with added-value by reusing Panasqueira mining wastes as new recycled materials for different technical and artistic applications, such us conservation and restoration/rehabilitation of historic monuments, sculpture, decorative and architectural intervention or simply as materials for building revetments.

1 INTRODUCTION

In most European countries (EU27), according to the Eurostat, about 55% of industrial waste is produced from mining and quarrying. Mining, and as a consequence mining waste, is unevenly spread over the countries (Eurostat 2009). In Portugal the mining waste accounts for approximately 20% of the total waste accumulated.

In fact, the accumulation of waste from mining and quarry industry, over the years, leads to the formation of large deposits that apart from the potential risk of environmental pollution, causes serious landscape impacts, affecting the quality of life of local populations.

Most mining and quarrying wastes obtained from grinding of rocks, placed in deposits in specific locations/regions, can be reused in construction, particularly coarse materials, such us in asphalt pavements or concrete. However, its potential for reuse to a national scale is mainly conditioned by transport and consequently by economical aspects. As result it is desirable to find out additional solutions that can contribute to the recovery and reuse of such waste materials.

The waste from mines and quarries are likely to become raw material for industrial applications where the high value of the product does not prejudice its reuse due transport

costs, which includes, as example, processing of calcium carbonate waste for Portland cement production or using it as fertilizer for agriculture, in the specific case of marble industry.

Other added-value applications for mining and quarrying wastes are the production of compact composites, for example, from marble or quartz wastes. Compact composite materials are constituted by several sizes of particles/aggregates linked by a polymeric resin matrix. The economic value of the composites depends, primarily from its aesthetic.

It is an innovative approach to reuse mining waste materials, as was proposed in a recent study consisting in the development of new applications for architectural, technical-sculptural and restoration process, using wastes of Macael Region, Spain. These new applications, consisting in polyester-based composites, were dependent on wastes particular texture and white color scale and values, as well as its mechanical and chemical properties (Peralbo Cano, 2007).

In this context, a research work has been carried out regarding the study and reuse of coarse wastes of Panasqueira mine, one of the most important and largest tungsten mines in the world. It was found out that due to deposit due to time in deposit mineral waste particles from Panasqueira mining suffered natural aging, becoming with a particular color and texture that gives it a highly aesthetic value.

2 TUNGSTEN MINE WASTES

2.1 *General description*

Panasqueira is an underground mine situated in central Portugal on the southern edge of the Sierra of Estrela mountain range, a natural park, near the Sierra of Açor, a protected landscape, and also near the Zezere river. Tungsten and tin have been mined in the Panasqueira area since the 1890s. During the mining process two types of mine waste are generated, coarse aggregates derived from rock blasting and waste mud conveyed by pipelines into lagoons amounting for several million tones. In the 1980's Panasqueira mining was generating of about 300 tones of coarse aggregates per day. Currently, it is still generating almost 100 tones per day. Panasqueira heaps already assumes enormous proportions, of similar size of large mountains (see Figure 1).

Figure 1 – General view of Panasqueira tungsten mine, located in Portugal (left) and partial closer view of one the main heaps of coarse wastes (right).

Wastes from Panasqueira mining have the size of coarse aggregates (on average, diameter size of 5mm to 25mm) and mud containing very fine particles (diameter size of less than 2mm).

Coarse mining waste particles are constituted by a major percentage of greywacke schist and about 10% of white quartz. Immediately after being extracted and deposited, coarse waste particles present a light gray color, typical of schist rocks. However, due to time and exposure to natural environmental conditions, its color gradually changes to ocher color, i.e. a tone iron color.

2.2 *Composition and properties*

Typical chemical composition of wastes is presented in Table 1. Composition was determined, in several samples of waste mud, by energy dispersive spectrometry (SEM/EDS). It consists mainly of silica and alumina with smaller percentage of iron and potassium, and minor constituents.

Table 1. Chemical composition of mud waste (%)

SiO_2	Na_2O	Al_2O_3	Fe_2O_3	K_2O	TiO_2	Other minor oxides
68.54	1.14	18.27	5.64	5.24	1.17	-

Table 2 presents physical and mechanical properties of coarse wastes. Particle shapes were characterized on the basis of EN933-3 and EN933-4 for concrete aggregates. Particles maximum and minimum dimensions were determined accordingly to EN933-1 and EN12620. Mechanical and physical properties were determined by EN1097-2, EN1097-3, EN1097-6 and BS812-110. From the results obtained it is evident that waste coarse particles present good properties, equivalent to those found in standard good quality granite aggregates.

Table 2. Physical and mechanical properties of coarse waste particles

Flakiness índex	FI = 27,7
Shape índex	SI = 53,2
Maximum dimension	D = 25,4 mm
Minimum dimension	d = 1,19 mm
Loose bulk density	2,79 g/cm^3
Water absorption	0,2%
Resistance to fragmentation (Los Angeles)	19,2%
Aggregate crushing value	16,5%

It was also found out that some waste mud deposits might contain undesirable constituents, such as heavy metals (Cu, Zn, Mn), arsenic and sulfur, representing a potential risk of environmental pollution. However, waste mud was not considered in this study. It has been object to a depth investigation regarding of its interest for the development of geopolymeric binders (Torgal et al., 2008).

3 EXPERIMENTAL STUDY

The experimental study consisted in developing polymer-based composite materials incorporating tungsten mining coarse wastes, as obtained directly from one of the several heaps of Panasqueira mine.

3.1 *Mix formulation*

Composites were produced using a polyester resin considering its low cost and ease of use at ambient temperatures. Polyester resin presents ideal properties for most industrial and technical-artistic applications. Polyester has good surface hardness and stiffness, good compressive, tension and shear strength, withstanding relatively well high and low temperatures. It suffers slight deterioration when submitted to atmospheric agents and additionally it is a low density material (Peralbo Cano, 2007).

Initially, as part of this investigation, different formulations of composite wastes were studied in laboratory. Thus, several diverse mix compositions having different sizes of coarse wastes, resulting in various prototypes were evaluated (Antunes, 2009). Later, was decided to use the wastes in its natural state, as found in heaps, although its particle size distribution pre-

sents discontinuity. Optimal resin content was based on a balance between the physical and mechanical properties of composites, i.e. resin content required for a good involvement of all particles and to provide good mechanical strength.

Moreover, a technological method was developed for the production of a terrazzo tile prototype with tungsten waste materials. It consists in a relatively simple and low cost process of two main stages, mixing and compacting in moulds, as illustrated in Figure 2. The process requires low energy and does not use water, thus being environmentally friendly.

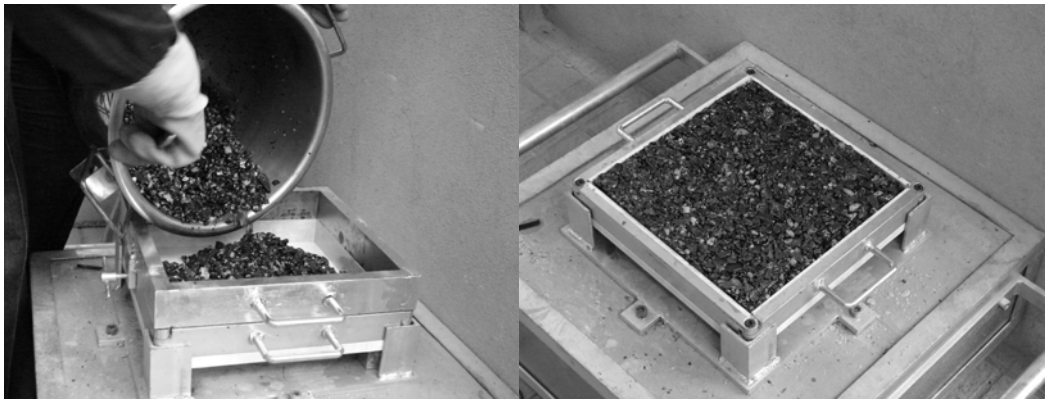

Figure 2 – Placing composite mix in moulds during the production of a terrazzo tile prototype.

3.2 *Study of waste chromatic properties*

One of the most relevant aspects of the final appearance of these polymer composites has to do with the color of waste that constitute it and with possibility in its modification.

Various studies of color are known, as well methods and instruments for color measurements, performed in various research works related to different polymer composites (mortar and concrete) for technical and artistic applications (Durán Suárez, 1996) (Corpas Iglesias et al., 2002). According to these studies, the use of colorimetric measurement instruments taking into account the existing standards, allows to determine the characteristic parameters for the manipulation and color correction of the various materials composing the mixture.

The measurement of the color of the wastes used in this type of composites was performed with a Konica Minolta spectrophotometer, model CM2500C, which has ring geometry of 45º, vertical observation, for measuring, comparison and color control. The range of wavelength of study is between 360nm and 740nm, with a rate of increase of 10nm wavelength standard observation of 2/10 degrees (CIE 1931/2º, CIE 1964/10º). To realize the color study, after measuring various parameters, chromaticity coordinates L*, a* b* were selected according to the CIE-LAB 1976 system. The measurement area for each point was 4-8mm, by using the illuminant D65.

Color measurements were made on the surface of the waste particles in its original state, i.e. as obtained after rock blasting, and in its aged state, i.e. as found in heaps. Color measurements were also carried on in particles surface after being submitted to 800ºC and 1000º in oven, for two hours. Figure 3 presents the original aspect of coarse wastes (A), the aged state (due to weathering) (B) and both states after being submitted to 800ºC (C) and to 1000ºC (D). It was observed a general darkening in wastes after being submitted to 1000ºC and as well volumetric expansion.

Regarding colorimetric values, in chromaticity diagram presented in Figure 4 are given color values corresponding to different states of wastes as shown in Figure 3. By analysis of results, it appears that the chromaticity values increase considerably when waste particles are submitted to temperature at 800ºC. In this case, there is a significant increase of red and yellow colors. By contrast, when wastes are submitted to 1000ºC temperature, decreases saturation of these two colors. In any case, brightness of waste particles decreases as it suffers aging or when submitted to temperature, in comparison to its natural state, as show in Figure 5.

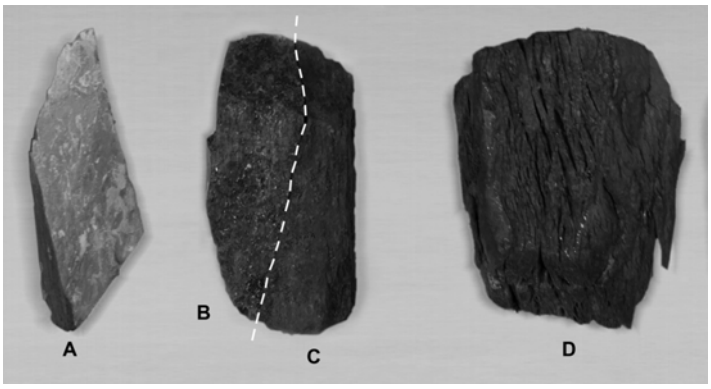

Figure 3 – Aspect of coarse wastes, (A) original state, (B) aged state, (C) submitted to 800ºC, (D) submitted to 1000ºC.

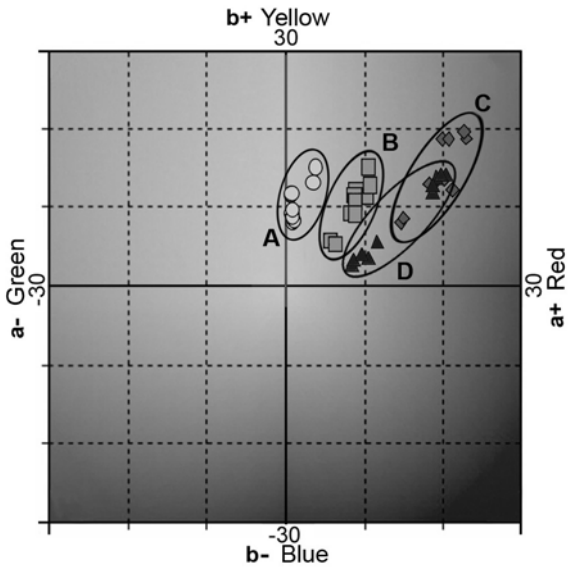

Figure 4 – Chromaticity diagrams of tungsten coarse waste.

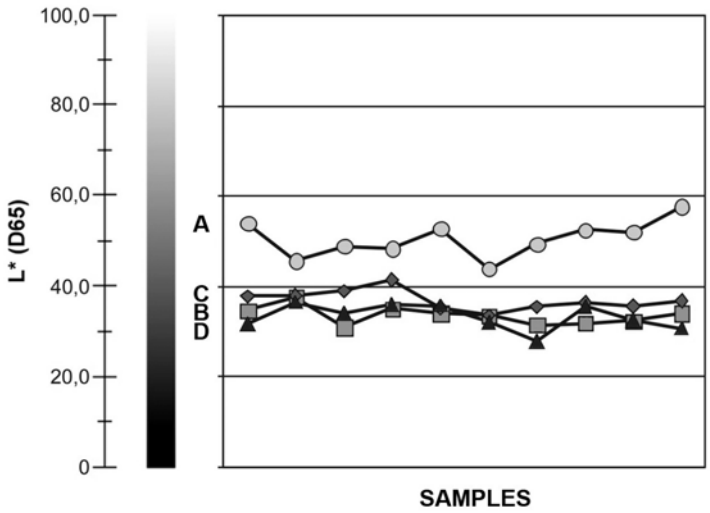

Figure 5 – Brightness diagrams of tungsten coarse waste.

Regarding colorimetric values, in chromaticity diagram presented in Figure 4 are given color values corresponding to different states of wastes as shown in Figure 3. By analysis of results, it appears that the chromaticity values increase considerably when waste particles are submitted to temperature at 800ºC. In this case, there is a significant increase of red and yellow colors. By contrast, when wastes are submitted to 1000ºC temperature, decreases saturation of these two colors. In any case, brightness of waste particles decreases as it suffers aging or when submitted to temperature, in comparison to its natural state, as show in Figure 5.

Thus, it can be conclude that despite of the characteristic color (ocher) of aged wastes as found in Panasqueira heaps, given then a good visual quality, it may be heat-treated to change its color, allowing more use possibilities in technical artistic applications, like mortars for intervention in historic heritage and many architectural applications.

3.3 *Terrazo tiles prototypes*

Taking into account its color characteristics, good physical and mechanical properties of coarse wastes, the development of terrazzo tiles for external use in architectural applications may be a viable opportunity for immediate application of these composites (Peralbo Cano et al. 2010).

Thus, in this study, unit prototypes of 30 x 30cm size and 3cm thickness were produced. Mix composition was obtained using optimal resin percentage, for minimum final cost.

In view of its technical feasibility, physical and mechanical characteristics were studied to obtain CE marking taking into account requirements of EN13748-2 standard for terrazzo tiles, specifically for outdoor use. According to EN13748-2 the following experimental tests were carried out: flexural strength, compressive strength, abrasion resistance, slip/skid resistance, weathering resistance, reaction to fire and thermal conductivity (Antunes et al. 2010).

Table 3 presents the average results obtained of CE marking requirement tests for terrazzo tile prototypes. It can be seen in Table 3 that some tests are not required for CE marking for terrazzo tiles for external use. In the list of required tests, namely flexural strength (breaking strength), wheel abrasion and Böhme abrasion tests, water absorption and freeze/thawing resistance, results obtained correspond to different CE marking labels.

Table 3. Results obtained of CE marking requirement tests, for terrazzo tile prototypes.

Test	Mean values	Class	CE marking
Breaking strength:			
flexural strength	f_{cf} = 3.0 Mpa	1	ST
compressive strength *(unnecessary test)*	f_c = 7.5 Mpa	*not applicable*	*not required*
Abrasion resistance:			
Abrasion wheel test	V_{AD} = 24,8mm	2	G
method of Böhme	$\Delta V = 3{,}90 cm^3/50cm^2$	4	I
Slip/skid resistance *(unnecessary test)*	USVR = 45	*not applicable*	satisfactory
Weathering resistance:			
water absorption	W_{ma} = 1%	2	B
freeze/thawing resistance	no weight loss	3	D
Reaction to fire *(unnecessary test)*	quality evaluation	A1fl	*not required*
Thermal conductivity *(unnecessary test)*	k = 0.479 W/mK	*not applicable*	*not required*

In the study developed, prototypes have shown a very good flexural strength and as well excellent freeze/thawing behavior. Flexural test was carried by following the methodology presented in EN12390-5 with some adaptations, using testing specimens of 4x4x16cm size, as il-

lustrated in Figure 6. The results obtained in this test were between 2.8 and 3.5 MPa which correspond to “Class 1”accordingly to EN13748-2 and “ST” as CE marking.

Compressive strength testing is considered unnecessary for CE marking, according to the EN13748-2 standard, once flexure strength represents more accurately tile breaking resistance.

Abrasion resistance was determined by both wide abrasion wheel test and method of Bhöme. Results of groove obtained in wide abrasion wheel test, vary from 21.5 to 24.8mm, showing a relatively good behavior, while in Bhöme test very good results were obtained.

Unpolished slip resistance values (slip/skip resistance) were determined by pendulum friction test, as show in figure 7. Since waste terrazo tiles present ridges and grooves on outer surface, such test in also considerer unnecessary accordingly to EN13748-2 and CE marking should indicate “satisfactory”.

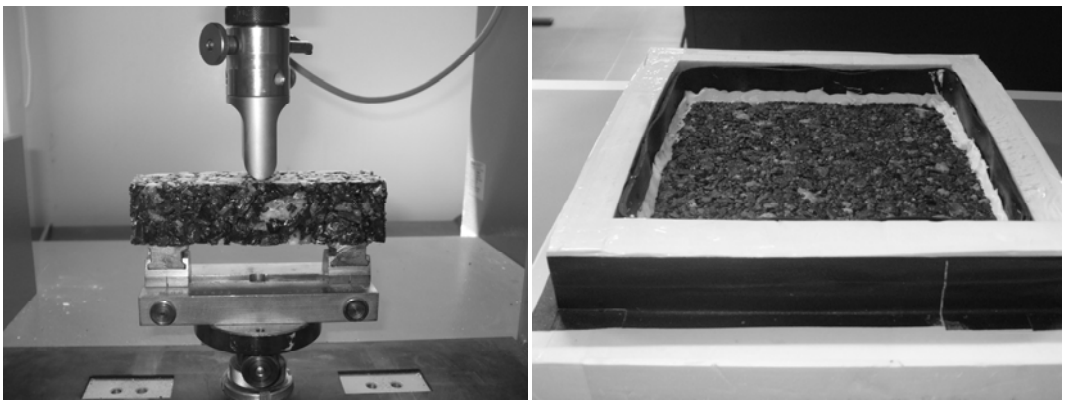

Figure 6 – Flexural test (left) and freeze/thawing test (right), carried on in tungsten waste composites.

The water absorption average value obtained was of $W_{h,24} = 0.12$ g/cm^2, and the value of absorption capacity obtained was of $W_{m,a} = 1\%$ by mass. It is a very low value which is justified by the fact that wastes are coated with polyester resin, which prevents it from absorbing water.

Freeze/thawing was carried on accordingly to EN13748-2, consisting in submitting prototypes to 28 cycles of freeze and thawing while surfaced cover by a water solution containing 3% NaCl, as illustrated in Figure 6. Prototypes resisted without any deterioration to a sequence of 28 cycles of freezing/thawing, each having the duration of 24 hours and ranging from -20ºC to 20ºC.

Figure 7 – Slip/skid resistance test (left) and non-standard evaluation of reaction to fire (right), carried on in tungsten waste composites.

Regarding fire resistance, terrazo tiles for external use are consider to be reaction to fire class "A1fl" without the need for testing according to EC Decision 96/603/EEC, as amended. However, it was found out, by carrying on a non-standard test, as shown in Figure 7, that polyester resin easily incinerated when submitted to fire, as expected.

Thus, the global results presented in Table 3, clearly show that tungsten waste composites developed in this study, fulfill CE requirements in the frame of a possible industrial production.

4 CONCLUSIONS

This research work presents and experimental study consisting in the development of polymer-based composites incorporating coarse waste particles from Panasqueira mining, one of the largest tungsten mine in the world. These composites benefit of wastes natural characteristics, particularly in visual aspect.

The study contributes to discover new added-value applications for the recovery and reuse of mining wastes in the particular case of Panasqueira mine, but also, in general, for mining and quarrying industry.

It can be concluded, from this work, that coarse waste from Panasqueira mining are adequate for reuse in technical and artistic applications due to its color and texture, namely sculpture and architecture, without being submitted to any special treatment (grinding or heat-treatment). However, color of wastes can be changed by heat-treatment and possible by other process, chemically based, for example, not yet studied.

Taking into account their mechanical and physical characteristics, it is believed that there is a potential for the use of Panasqueira aged coarse wastes as new construction polymer-based materials in technical-artistic applications, particularly as terrazzo tiles for outdoor use, fulfilling CE marking requirements.

Finally, the aim of this study is also to contribute to environmental protection, particularly for the recovery and reuse of mining waste materials in a context of a global concern to achieve sustainable development.

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Eco-Efficient Ternary Mixtures Incorporating Fly Ash and Metakaolin

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ABSTRACT: With the growing awareness of environmental problems, particularly with regard to energy efficiency and greenhouse gas emissions, the construction and the cement industry has had a prominent place, the latter being responsible for about 7% of CO_2 emissions into the atmosphere. Knowing that cement production contributes about one tone of CO_2 for every tone produced, it remains paradoxical that concrete, the product most consumed by humans, exceeded only by water, cannot find a credible, more efficient and greener replacement material for portland cement. Considering the available technological solutions, involving the energy efficiency of cement intensive production or the demand for alternative fuels for cement manufacture, a simpler solution might be the rationalization of resources by cement replacement by alternative materials. There is already a kind of concrete (high volume fly ash concrete) with very limited applications until nowadays but with intrinsically environmental advantages. However, the reduced early strength of this type of concrete is a limiting factor for its widespread usage. In this context, a study was developed in mortars with binary and ternary mixtures where significant volumes of cement were replaced by fly ash, and also, simultaneously, for another addition: metakaolin. In this paper, one present the main advantages and drawbacks of the simultaneous use of these two mineral additions which synergy may cause very interesting performance characteristics even with high volumes of cement replacement. These ternary mixtures show very promising performances, allowing large volumes of cement replacement, maintaining or improving both mechanical and durability performances. These binders could be a viable solution for obtaining an eco-efficient enhanced performance concrete for widespread usage in construction as an alternative for conventional concrete.

1 INTRODUCTION

Nowadays, the world ecosystem is constantly faced with ever-larger ecological problems associated with the emissions of CO_2. It is well known that for every tonne of portland cement produced, approximately one tonne of CO_2 is released into atmosphere, which means that the portland cement industry contributes for about 7% of the total CO_2 emissions. Also, other adverse environmental impact of portland cement production refers to the high energy consumption. After aluminium and steel, the manufacturing of portland cement is the most energy intensive process (Malhotra & Mehta (2002)).

However, the emission of CO_2 and the energy consumption are only two of the many problems we are facing nowadays. The inadequate durability of reinforced portland cement concrete structures and the increase on the volume of construction in the last few decades has resulted in a rampage of our natural resources. The availability of resources is finite and therefore we must alert the industry to take into account the sustainability of construction.

The concrete industry, due to its large size, is the ideal home for economic and safe incorporation of millions of tonnes of industrial by products such as fly ash (FA) from coal combustion

thermoelectric power plants. Therefore large scale cement replacement in concrete by FA will be highly advantageous from the standpoint of cost, economy, energy efficiency, durability, and overall ecological and environmental benefits (Malhotra & Mehta (2002)).

The worldwide production of coal combustion products is estimated to be about 1300 million tonnes per year of which at least 70% (900 million tonnes) is FA which is suitable to use as a pozzolan in concrete or other cement based products (Mehta (1999)). Unfortunately, only about 20% of the worldwide available FA is being used by the cement and concrete industry. To achieve a sustainable development of the concrete industry, the rate of the use of pozzolanic and cementitious by-products will have to be accelerated (Malhotra & Mehta (2002)). Reusing greater amounts of FA in concrete mixtures and replacing higher quantities of cement will certainly help to reduce a major problem of environmental impact. Incorporating high volumes of FA in concrete is one of the possible ways for making green concrete.

High volume fly ash concrete (HVFAC) (percentage of replacement of cement weight by fly ash greater than 50%) mechanical and durability characterization was already been evaluated (Camões (2006), Sirivivatnanon & Ho (2003), Malhotra & Mehta (2002)) and bibliography document some practical applications (Sirivivatnanon & Ho (2003), Bilodeau & Seabrook (2001), Langley (2001)) that permits to classify this kind of concrete in the field of conventional concrete. Design requirements related to mechanical characteristics will be perfectly fulfilled and with this type of concrete it will be possible to build more durable structures while contributing significantly to the construction sustainability (Camões (2006)).

According to Malhotra (2002), the following characteristics are typical for HVFAC: a minimum of 50 to 60% fly ash by mass of cementitious materials; low water content, generally less than 130 kg/m^3 of concrete; cement content not more than 200 kg/m^3 of concrete, but generally about 150 kg/m^3; low water/cementitious ratio, generally less than 0.35.

According to Malhotra & Ramezanianpour (1994) HVFAC exhibits adequate strength development characteristics both at early and later ages. However, there are other authors like Gillies (2001) reporting that some HVFAC developed lower strengths at 3 and 7 days of age but achieved higher ultimate strengths when properly cured. Furthermore, experience shows that faster construction is not always less expensive. Poor-quality concrete, with its honeycombs and many cracks, frequently requires costly repairs and results in litigation. Poorly built structures have a tendency to deteriorate faster, especially when exposed to aggressive environments. Thus, owners must pay a higher life-cycle cost.

Compressive strength values will differ depending on the materials and proportions used but one can say that typically HVFAC have 28 days strength of approximately 35 MPa and 91 days strengths of about 45 MPa (Burden (2006)). The compressive strength tests made by Camões (2006) indicate that concrete with about 35 MPa strength at 28 days can be produced using 160 kg/m^3 of cement and 400 kg/m^3 of binder content (C400) which is sufficient for the majority of the structural concrete constructions' applications. Furthermore the author said that this kind of concrete can also be used when higher strength is needed. CANMET also reports that HVFAC can be used for high strength applications (Burden (2006), Bilodeau & Seabrook (2001)).

These concretes seem to be highly durable ones once they show reduced gas and water permeability, capillary absorption, high resistance against chloride penetration, low heat of hydration and reduced drying shrinkage (Burden (2006), Camões (2006) and Malhotra & Mehta (2002)). Mehta (2004) reported that the addition of high volumes of FA in concrete reduces the water demand, improves the workability, minimizes cracking due to thermal and drying shrinkage, and enhances durability to reinforcement corrosion, sulphate attack, and alkali-silica expansion. In this type of concrete it is expected that the very low permeability of HVFAC offsets any marginal reduction in the concrete's pH due to its large quantities of mineral admixtures (Malhotra (2002), Malhotra & Mehta (2002)). However it is well known and accepted between researchers that carbonation depth increases as FA content increases (Burden (2006), Jiang, et al (2000)) because the rate at which concrete carbonates is a function of, among others, the mass of CH available for reaction (Burden (2006), Joshi & Lohtia (1997)). In fact, as the permeability of the concrete is reduced by the addition of FA, it may be expected to become harder for CO_2 to penetrate the concrete. However, FA reduces permeability by reacting with CH. This reaction reduces the amount of material available for reaction with CO_2. Thus less CO_2 has to penetrate to neutralize the concrete.

HVFAC have some drawbacks that prevent presently their widespread usage. The main potential problems associated with implementation of these concretes are: i) slower strength development along time and reduced early age strengths; ii) greater sensitivity to curing process; iii) high plastic shrinkage of this type of concrete having a very low water/binder ratio; iv) reduced carbonation resistance.

Considering the presented disadvantages the low early strength may be considered critical because can extend the period before demoulding and consequently retard the construction, which can lead to an increase of the overall costs.

In order to overcome these disadvantages, in this work one propose incorporating in concrete, adding together with a very high quantity of FA, other mineral addition that prevent or minimize these adverse factors and thus enable wider application of an eco-efficient concrete.

In contrast to portland cement, metakaolin (MtK) presents very interesting environmental properties and the good-will of their addition in concrete was already been studied and proven (Justice (2005), Badogiannisa et al (2004), Fernandes (2004), Kosmatka et al (2003)).

MtK is a highly reactive pozzolan classified as ultra-fine with an average diameter around 1-2 microns. The presence of MtK has a huge effect on the hydration of cement. When portland cement alone hydrates, typically 20-30% of the resulting paste mass is CH. However, when MtK is added, it reacts rapidly with these newly forming CH compounds to produce supplementary calcium silicate hydrate. The pozzolanic reaction of MtK is considered to be very effective and similar than silica fume. Thus, the partial replacement of cement by MtK will increase the performance of concrete either in early or at long term ages. The optimum cement replacement content is less than 20%. Some authors indicate 5% (Justice (2005)) and for Portuguese MtK Fernandes (2004) report the value 15%.

The addition of MtK results in a substantial performance improvement of the concrete, both at young and long term ages. Thus, it is expected that the cumulative addition of MtK in HVFAC can contribute for solving problems associated with reduced early age strength. However there are few references about activated HVFAC (Xiaosheng et al (2007)).

In this context an experimental study has been developed aiming the performance characterization of ternary HVFA mixtures. The tests were performed on mortar samples due to the obvious advantages that this solution presents in comparison to concrete (lesser material waste, greater ease at producing the compositions and maneuvering the molds and samples, lesser occupied space by the samples, etc.) and that usually can be summarized in a decrease of man-hours necessary to this experimental study. However this work aims to contribute for the knowledge of eco-efficient concretes and not mortars. In fact, this option was made taking into account that the mortar specimen's results may be extrapolated to estimate the performance of the corresponding concretes (Camões et al (2005), Camões (2002) and Daczko (1999)).

2 EXPERIMENTAL PROGRAM

The tested mixes are presented in Table 1. The cement (C) used was a CEM II/B-L 32.5N produced by CIMPOR which was replaced by MtK MIBAL-C, FA from Pego thermal power station or by both (FA + MtK) simultaneously. The binder content is considered the sum of cement and mineral additions used (B = C + FA + MtK), W represents the water added and SP the superplasticizer. A commercial available 3th generation copolymer SP was used.

Table 1. Studied mortar mixtures.

Mix	Name	Materials						
		B [kg/m^3]	C [%]	MtK [%]	FA [%]	M [kg]	W/B [-]	SP [%B]
I	PATTERN	484	100	0	0	1457.9	0.55	0
II	10%MtK	484	90	10	0	1449.1	0.55	1.5
III	20%FA	484	80	0	20	1422.8	0.55	0
IV	40%FA	484	60	0	40	1387.6	0.55	0
V	60%FA	484	40	0	60	1352.5	0.55	0
VI	10%MtK+20%FA	484	70	10	20	1414.0	0.55	0
VII	10%MtK+40%FA	484	50	10	40	1378.8	0.55	0.4
VIII	10%MtK+60%FA	484	30	10	60	1343.6	0.55	1.5

In order to evaluate the mortar's behavior in fresh state one submit it to flow table test according to EN 1015-3 (2004). At the hardened state the mechanical behavior was evaluated through flexural and compressive strength tests (EN 196-1 (2005)). For flexural tests, series of 3 specimens with 40x40x160 mm^3 for each age of testing (3, 7, 14, 21, 28 and 90 days) were used. Consequently, compressive strength was obtained from 6 40x40x(±80) mm^3 specimens.

The durability performance was evaluated through chloride migration (LNEC E463 (2005)) and water absorption by capillarity tests (EN 1015-18 (2002)). Chloride migration tests were done in 3 specimens of 50 mm height and 100 mm of diameter at 28 and 90 days of age. Water absorption by capillarity was carried out using 3 cubic samples with 50 mm of edge at 7, 14, 21, 28 and 90 days of age. The reading period was carried out between regular intervals decreasing with time until a 90 days period was reached. To determine the capillary absorption coefficient only the first 4 hours were considered.

3 MINERAL ADDITIONS

3.1 *Metakaolin*

MtK is a pozzonalic addition and derives from the thermal activation of kaolin clay at about 750/800ºC. The methakaolin used was extracted from Barqueiros, Portugal, located in the Barcelos Council and named Mibal-C. This deposit in Barcelos is of sedimentary nature with brute reserves estimated in millions of tons (Pinto (2004)). In Table 2 one can see its main properties.

Table 2. Properties of the used metakaolin, MIBAL – C (Pinto (2004)).

Characteristic		MIBAL - C
Particle Dimension [%]	< 30 µm	99 ± 3
	< 10 µm	93 ± 5
	< 5 µm	82 ± 5
	< 2 µm	68 ± 6
Chemical Composition [%]	SiO_2	47.0
	Al_2O_3	37.1
	Fe_2O_3	1.3
	K_2O	2
	Na_2O	0.2
	MgO	0.15
	TiO_2	0.3
	CaO	0.1

Characteristic		MIBAL - C
Unburnt	Loss on ignition [%]	12.75
Humidity [%]	Initial	32 ± 3
	Granules	18 ± 2
	After drying	< 2
After drying parameters	Burnout	0.09
	Flexural resistance (110ºC) [MPa]	2.45 ± 0.49
	After burnout flexural resistance [MPa]	13 ± 3
	Water absorption [%]	10 ± 2
Others	Density [g/cm^3]	2.4 – 2.7
	Suspension's pH	6 – 9

Table 3. Properties of the used fly ash, PEGOP (Camões (2006)).

Carachteristic		PEGOP	Carachteristic	PEGOP
Chemical composition	LOI [%]	7.30	*Cl^-* [%]	0.00
	SiO_2 [%]	60.87	*free CaO* [%]	0.00
	Al_2O_3 [%]	20.40	*Na_2O* [%]	0.55
	Fe_2O_3 [%]	7.82	*K_2O* [%]	1.92
	total CaO [%]	2.72	*P_2O_5* [%]	1,14
	MgO [%]	1.40	*TiO_2* [%]	1.29
	SO_3 [%]	0.22	*Total SiO_2+Al_2O_3+Fe_2O_3* [%]	89.09
Physical properties	Density [kg/cm^3]	2360	*Fineness > 45 µm* [%]	27.30
	Blaine's specific surface [m^2/kg]	387.9	*Humidity* [%]	0.16
			Water demand	0.297

3.2 *Fly ash*

The FA used was produced by Pego Power Station located in Portugal, with an average loss on ignition (LOI) which varied between about 6% and 9%. These high LOI values belong to the upper class (category C) established by EN 450:2005 or may exceed the proposed limit. How-

ever, studies have shown that, at least for this FA, the high LOI is not impeditive of its use on concretes (Camões (2006), Camões et al (2003) and Camões et al (2002)). Table 3 shows the main properties of the FA used.

4 EXPERIMENTAL RESULTS AND DISCUSSION

4.1 *Workability*

The flow tests used to assess the workability of the mixes provided the results shown in Fig. 1.

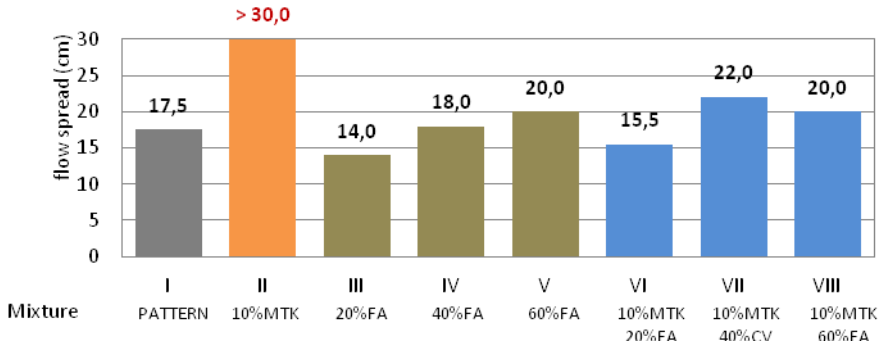


Figure 1. Flow table test results.

These test results has provided some atypical values as SP was used only in some mixes (II, VII and VIII). The usage of this admixture was due to difficulties in the mixing process when MtK was used once, as it is known, its presence makes the mixtures less workable (Pinto (2004)). On the contrary, incorporating larger quantities of FA originates higher workability. In practice one can say that the synergic effect of these two additions complement each other as FA provide a mitigating effect of this disadvantage of using MtK.

4.2 *Mechanical strength*

In Fig. 2 one can see the evolution of compressive and flexural strength along time. These values were obtained from 3 to 90 days of age. The flexural test results present greater sensitivity than compressive strength tests maybe because of the effect of sample's imperfection that affects more the flexural than the compressive strength.

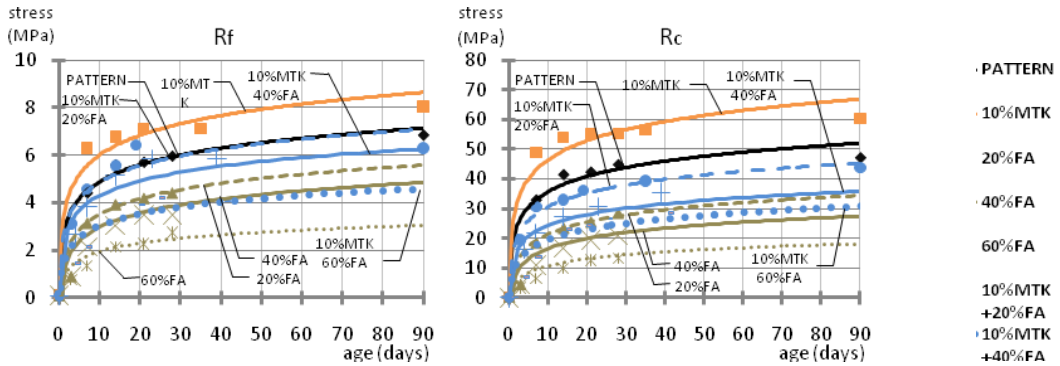


Figure 2. Mechanical strength test results.

Observing Fig. 2 one can see an already known effect of cement replacement by FA: the delay on the strength development and for these HVFA mixes the drastically reduction at early strength. This effect is due to the reduced availability of calcium hydroxide (derived from cement hydration) to react with FA and because it is a very slow chemical reaction.

Contrasting to FA, MtK magnifies both flexural and compressive strength even in early ages, and for all FA content tested. Unlike FA, MtK reacts very quickly with calcium hydroxide being the responsible for the high early age strength obtained. At a later phase, as FA slowly reacts

with calcium hydroxide, FA controls the long term strength development. In Fig. 3 this fact is well demonstrated as it can be observed that with 10% of MtK addition in the ternary mixtures the compressive strength of the binary mixtures (with just cement and FA) has been substantially ameliorated. It is also known that the greater compactness is associated with a higher strength, which may indicate that the mixtures showing better performance will be more compact, and from this perspective, MtK being a much more thinner and reactive material may have a predominant effect.

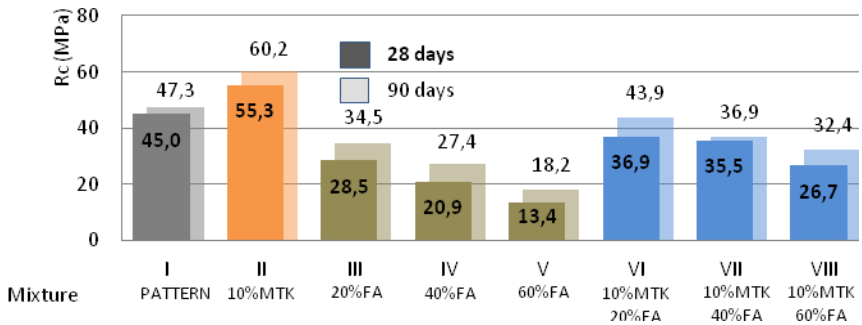


Figure 3. Compressive strength (R_c) at 28 e 90 days of age.

4.3 *Durability indicators*

In Fig. 4 one can see the coefficient of chloride diffusion obtained from rapid migration tests.

Analyzing the results achieved it's possible to observe that all mixtures made with mineral additions presented better performance than the standard one. This effect was already expected hence FA fix chloride ions. According to Camões (2002) a first part is chemically bonded and is incorporated in the cement hydration products. Another part is physically fixed and is absorbed by micro-pores surface. Just a third part called "free chlorides" is free to move and is responsible for steel reinforcement corrosion. Also the increase in the aluminates provided by the presence of FA in the binder is expected to be responsible for better performance (Camões (2002)) once they reacts chemically with chloride ions and reduce the free chloride content.

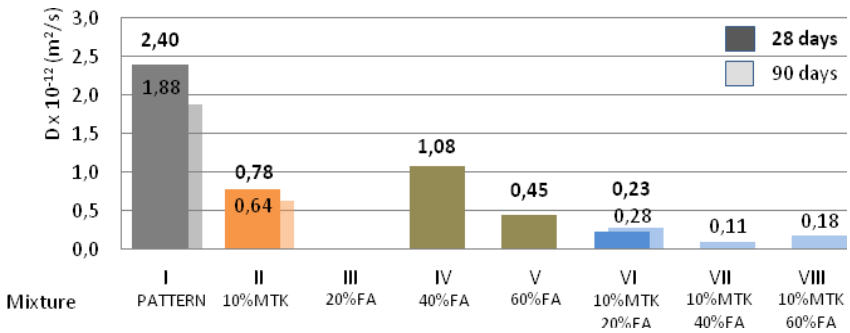


Figure 4. Coefficient of chloride diffusion (D) at 28 e 90 days of age.

The obtained results showed the high potential of the addition of 10% of MtK and all the ternary mixes showed enhanced performance than the FA binary ones due to the presence of MtK.

With respect to results of coefficient of capillary absorption at 28 days (Fig. 5) one can verify that it reaches higher values for standard mixture. The inclusion of FA increases the mixture's performance but higher FA contents leads to worst behavior. When 60% of cement replaced by FA was reached its coefficient of capillary absorption was similar to the standard mix. The FA addition should work almost as filler once the pozzolanic reactions were apparently very slow. Being MtK a much thinner and reactive material than FA its addition causes good performance due to filler effect and high pozzolanic activity. Its presence in the mixture decreases the size of the bigger pores and provides more compact and therefore less permeable mixtures. Thus ternary mixtures present much lower coefficients of capillary absorption than binary ones. This

synergetic effect of MtK combined with FA results in much more efficient mixtures. Nevertheless, mix VIII must be referred once its capillary absorption was significantly enhanced when compared to the other HVFA mixture tested (mix V), which was similar than the standard one.

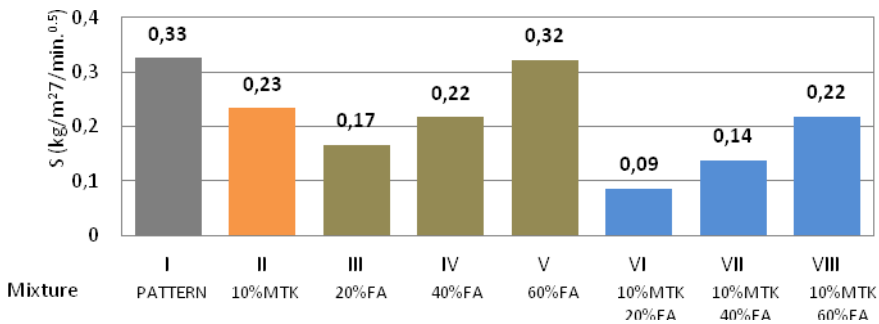


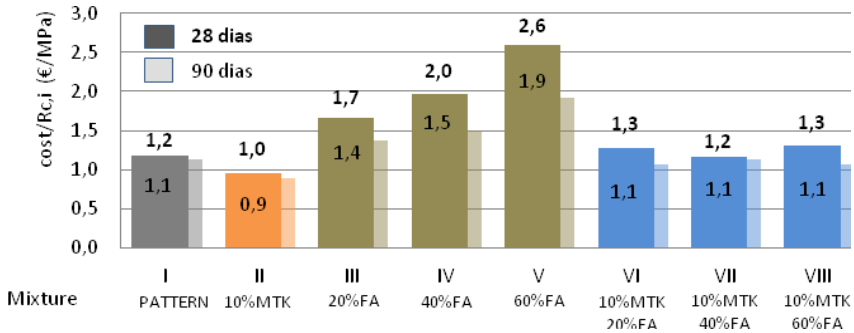
Figure 5. Coefficient of capillary absorption (S) at 28 days of age.

4.4 *Cost analysis*

For the mortar's cost only the raw material prices have been considered discarding the indirect costs. Anyways it is known that cement prices is nowadays competitive and that future additions will also have to be. For this study one have considered a value nearly 4 times lower than cement's for the price of FA and for the MtK price a value identical to the cement's. The price of sand (M) was adopted based on commercial values.

The cost/benefit ratio based on compressive strength is shown in Fig. 6. It is known that the cost of mixtures with FA is lower than the standard ones (Reis (2009) and Camões (2002)) but it is expected that HVFAC present a weak cost/benefit ratio based on compressive strength at least at early ages. This aspect is noted in Fig. 6 but interestingly one can verify that MtK corrects all the binary mixtures leading to a cost/(compressive strength) ratio similar than the standard mix.

It should be pointed out that the cost/benefit ratio here presented is the most onerous for the tested mixtures. However if one consider the results obtained in the durability indicators, the situation reverses itself and the ratios cost/benefit are undoubtedly advantageous for high volumes of cement replacements.



Material	(€/kg)
C	0.08
MtK	0.08
FA	0.02
M	0.01
W	0

Figure 6. Cost/benefit analysis based on compressive strength at 28 and 90 days of age.

5 CONCLUSIONS

Based on the obtained results one can conclude that it's possible to produce an eco-efficient HVFAC incorporating a reduced percentage of MtK capable of contributing for a decrease in the environmental impacts associated to concrete consumption. This kind of concrete presents durability or mechanical performances as good as or even better than conventional concretes even at early ages. MtK acts as a FA mechanical performance regulator. This effect is more pronounced at early ages preventing the great disadvantage of using HVFAC. This way incorporating additional MtK in HVFAC even when the pozzolanic additions have slow reactivity, seems to be a valid way for the widespread usage of this kind of eco-efficient concrete.

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Spent Catalyst Cracking Waste: pozzolanic activity and its influence on cement paste and mortars properties

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ABSTRACT: Industry wastes used as a supplementary or mineral addition in cementitious materials have always become "by-products" and not wastes. These by-products when incorporated into cements diminish the environment impact, reduce the cement consumption and improve several properties on fresh and hardened mortars and concretes. Spent catalyst cracking waste (SCCW) produced at petroleum industries is a by-product that can be used as a mineral addition in cements. Researches had been attained and results showed that it has pozzolanic characteristics. The study of this by-product is recent and its influence on the cementitious materials could be more understanding. The aim of this work was to verify SCCW influence on properties of fresh paste, such as setting time, temperature evolution during setting and the consistency of mortars. Pastes and mortars studied were produced with natural and grounded SCCW (30% cement replacement by mass). Results showed that SCCW, when used as supplementary material in cement, affect the workability, reduces setting time, increasing the kinetics reaction and mortars consistency.

1 INTRODUCTION

Inorganic materials that take part in the hydration reactions of Portland cement have been used as supplementary cementing materials. These inorganic materials are called mineral additions and could be classified as pozzolanic or latent hydraulic materials. Pozzolanic materials have high SiO_2 and Al_2O_3 content, they have reactivity, and their mixture with water and CaO produce a new compound called calcium silicate hydrate (C-S-H). In this way, they act as hydraulic cements, improving several fresh and hardened properties on cement materials Taylor 1997.

Natural and artificial mineral addition, such as fly ashes, silica fume, blast furnace slag, steel slag, volcanic ashes, diatomaceous earth, rice husk ash, have been used as pozzolanic materials (Taylor 1997) (Dal Molin 2005) (Mehta & Monteiro 2008).

Most of mineral additions used as supplementary cementing materials are wastes from industry and offer environmental, economic and technological advantages such as (i) reduce the natural resource mining; (ii) prevention of disposal problems; (iii) reduce the energetic coast of Portland cement production and (iv) improve the properties of cementitious materials (Taylor 1997) (Dal Molin 2005) (Mehta & Monteiro 2008) (Payá et al. 1999).

Conversion processes at a refinery are used to increase the quantity and the quality of the end product (gasoline). Various conversion processes are used and the most common is to crack the high molecular-weight into smaller. Catalyst cracking is the most important and the Spent Catalyst Cracking (FCC) is by far the most widely used.

The waste generated from this process is a problem for the petroleum industry. This waste is sent to the cement industry to be used in clinker production because of the silica oxide in its chemical composition. Its waste is classified as inert material from the environmental point of

view, and the quantity is significant. Furimsky reported that about 400,000 tons were produced annually (Pacewska et al. 1988).

Fluid catalytic cracking waste (SCCW) is an inorganic material that could be used as a mineral addition on cementicious materials. This material has pozzolanic caracteristics (Payá et al. 1999) as similar as silica fume and fly ash (Pacewska et al. 1988). Studies about chemical, physical and mechanical properties on mortars containing SCCW as supplementary cementing materials have been done by several authors (Payá et al. 1999) (Pacewska et al. 1988) (Payá et al. 2001) (Velásquez, 2002) (Payá et al. 2003a) (Payá et al. 2003b).

The aim of this work was to contribute to these studies observing the influence of SCCW on fresh mortars properties. The properties evaluated are the mortars workability by consistency measured by initial flow, setting times and the temperature evolution during setting of pastes.

2 SPENT CATALYST CRACKING WASTE (SCCW)

Fluid Catalytic Cracking waste (SCCW) is a residue from naphtha cracking process in the petroleum refineries industry. SCCW consists, basically, of silicates and aluminates compounds with opened atomic structure (zeolite type) and high specific surface, which could be responsible for the high pozzolanic material activity (Payá et al. 1999) (Velásquez, 2002) (Payá et al. 2003a).

SCCW presents a spherical morphology when observed by Scanning Electron Microscopy (SEM). These spherical particles, with 0,1 to 30 μm of diameter, has a porous appearance with internal caves and connected channels. Specific gravity value for SCCW is about 2450 kg/m^3 (Payá et al. 1999) (Velásquez, 2002) (Payá et al. 2003a). Porous structure of the SCCW is responsible for speeding up the kinetic cement hydration reactions when used as a mineral addition on cementicious materials. They act as nucleation points for precipitation of hydrate products, providing pozzolanic characteristics to this material (Velásquez, 2002).

When finely grounded, SCCW presents particles with irregular shape, less than 2 μm in diameter and porous structure, that increase their reactivity and its specific gravity ranged from 2450 kg/m^3 to 2510 kg/m^3 (Payá et al. 1999) (Payá et al. 2003b).

Pacewska et al. (1988) studied the influence of SCCW on hydration of cement paste. The use of SCCW accelerated considerably the hydration process with a strongly exothermic process, making cement paste sets much more rapidly.

The pozzolanic activity of SCCW was studied by Payá et al. (2001) on mortars produced with grounded SCCW. They concluded that in the first ages the material did not show pozzolanic activity. The initial action of grounded SCCW was restricted to act as filler, an inert addition. The increase of compressive strength occurred after 7 days of age, and with the obtained results it could be considered as a pozzolanic mineral addition.

Payá et al. (1999) had shown the workability reduction on mortars produced with SCCW and grounded SCCW. The studied mortars showed a significant relation with the reference mortar; however, there were not differences in results with SCCW and with grounded SCCW. It suggested that the effect of SCCW used on mortars workability is recurrent, much more, for the internal structure of the SCCW than the material fineness.

3 EXPERIMENTAL PROGRAM

3.1 *Materials*

Materials used in this experimental work were: high initial strength Portland cement (named CPV ARI RS), natural SCCW (SCCWn), grounded SCCW (SCCWg) and water.

The SCCW source was from Paulínia city petroleum refinery (São Paulo State, Brazil). The color of material was slightly grey. A laboratory ball mill was used to obtain SCCWg.

Natural and grounded SCCW were used as a cement replacement by mass (30%) and mixtures used 0,53 water/cement or water/cement+SCCW ratio (water/binder ratio).

Specific gravity and fineness on 75 μm sieve opening were determined.

Morphologies from natural SCCW (SCCWn) and grounded SCCW (SCCWg) were obtained by scanning electron microscopy (SEM-LV JSM 5900) at National Laboratory of Synchrotron

Light (LNLS), equipped by X-ray diffraction energy dispersive microanalysis (SEM-EDS).

3.2 *Mix design*

Pastes were produced with cement, SCCW (natural and grounded) and water. All pastes had the same mixing proportions and they were 1: 0,53 (1 part of cement: 0,53 part of water/binder ratio), in mass (Table 1).

Table 1. Pastes mix proportions

Prepared Pastes – 1:0,53 (in mass)				
Mixtures	Cement (g)	SCCWn (g)	SCCWg (g)	Water/binder ratio (g/g)
P1	1500	0	0	0,53
P2	1050	450	0	0,53
P3	1050	0	450	0,53

Mortars were cast with cement, SCCW (natural and grounded) and natural sand. All mortars had the same mixing proportions and they were 1: 3: 0,53 (1 part of cement: 3 parts of natural sand: 0,53 parts of water/binder ratio), in mass (Table 2).

Fresh mortar was prepared using a 5 liters countercurrent pan-type mixer. At first, cement and SCCW powder (previously mixed) were mixed with the mixing water. After that, further mixing was done with the addition of natural sand. The mixing operation was completed in 5 minutes.

Table 2. Mortars mix proportions

Prepared Mortars – 1:3:0,53 (in mass)					
Mixtures	Cement (g)	SCCWn(g) (g)	SCCWg (g)	Natural sand (g)	Water/binder ratio (g/g)
M1	1500	0	0	4500	0,53
M2	1050	450	0	4500	0,53
M3	1050	0	450	4500	0,53

3.3 *Text methods*

In order to evaluate the characteristics of each mixture, it was prepared pastes and mortars to perform tests in fresh state (Figure 1).

In fresh pastes it was evaluated setting times by Vicat needle. Temperature evolution during setting was also determined using a semi-adiabatic recipient. Three thermocouples were used to measure pastes temperatures. They were connected to a datalogger Testo 177 which registered the temperatures.

In fresh mortars the workability was measured by the initial flow in a flow table.

Each property was measured in three samples of every paste and mortar, and the arithmetic mean of the results calculated.

4 RESULTS AND DISCUSSION

4.1 *SCCW Characteristics*

Morphologies from SCCWn and SCCWg were obtained with a scanning electron microscopy (SEM-LV JSM 5900), and an elementary composition with a X-ray diffraction dispersive energy microanalysis (SEM-EDS). Figures 2 and 3 show the particles of SCCWn and of SCCWg, respectively.

Natural SCCW (SCCWn) particles were spherical and their diameter ranging from 40 μm to

150 μm (Figure 2a). These particles showed a roughness on their surface (Figure 2b). After grinding SCCWg particles changed their shape. These grounded particles showing angular and spherical ones. Their diameter ranged from 25 μm to 75 μm (Figure 3a). Some particles had a very porous structure showing many internal channels (Figure 3b).

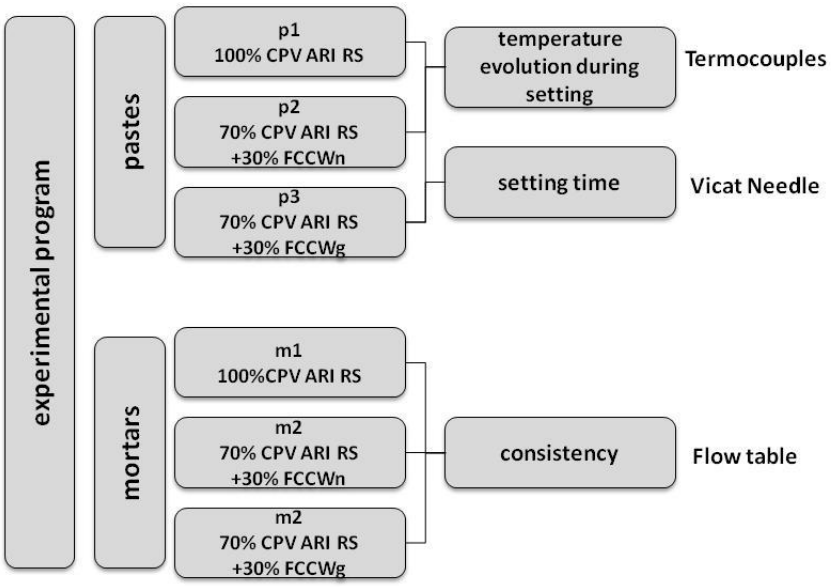

Figure 1. Experimental Program

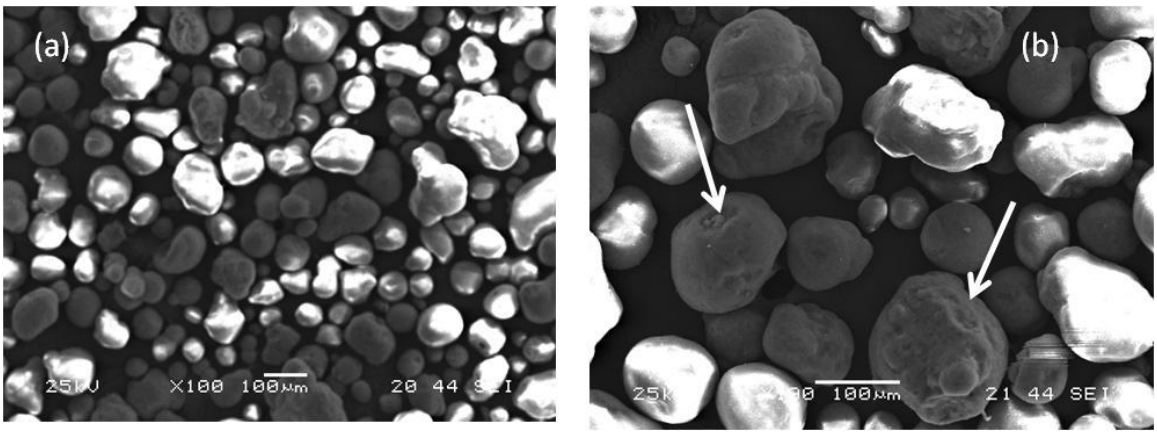

Figure 2. SEM images of SCCWn: (a) spherical and (b) roughness surface

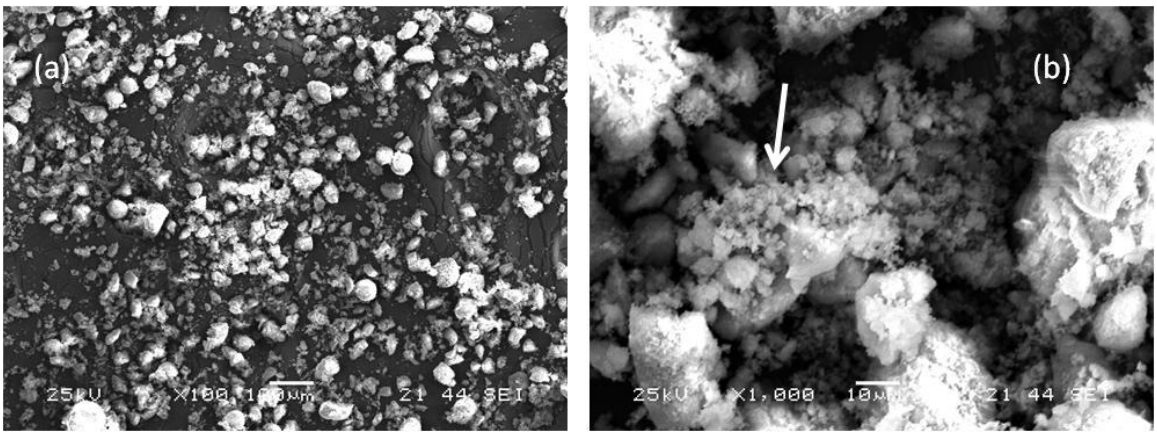

Figure 3. SEM images of SCCWg: (a) irregular shape and (b) porous morphology

In order to evaluate its composition, both natural and grounded SCCW were analyzed by EDS. The results are observed on Figure 4 and Table 3. Specific gravity and fineness are presented on Table 4.

The chemical nature showed the major presence of silicates and aluminates compounds in SCCWn and SCCWg. This can explain the pozzolanic performance of this waste.

Table 3 – EDS chemical elementary composition

Material	EDS chemical elementary composition (%)				
	O	Al	Si	Fe	Au
SCCWn	41	23	25	0	8
SCCWg	52,07	13,86	14,25	0	0

Table 4 – Physical properties measured from SCCWn and SCCWg

Material	Physical properties	
	specific gravity (kg/m^3)	fineness (%) (material retained - 75 μm)
SCCWn	2713	37,7
SCCWg	2697	1,08

SCCWn and SCCWg have (i) the same chemical nature, Si an Al and (ii) the same particle appearance as the materials used by Payá et al. (1999). Therefore they have significative difference on size and specific gravity. Values were greater than values (2450 kg/m^3 untill 2510 kg/m^3) reported on their research.

4.2 *Mortar consistency*

The summary of the results obtained in terms of mortar initial flow are presented in Table 5. Figure 5 show mortar spreading on flow table.

Table 5 – Initial flow results of mortars

Mixtures	M1	M2	M3
Initial flow value (mm)	209	142	146

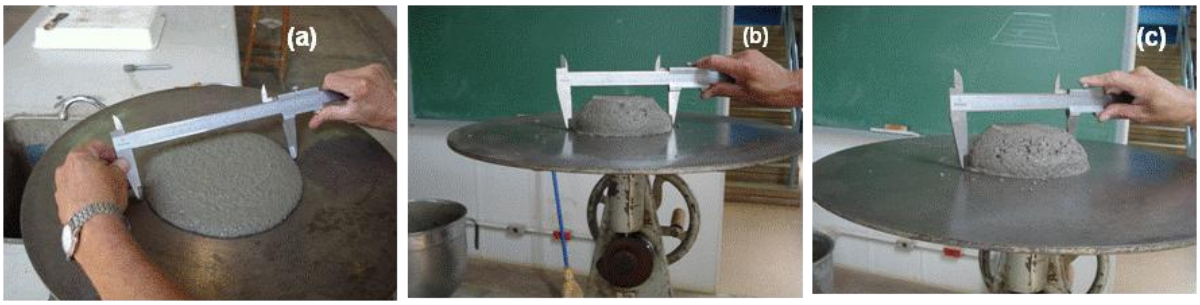

Figure 5 – Mortars spreading by flow table test: (a) M1 – 100% CPV ARI RS; (b) M2 – 70% CPV ARI RS +30%SCCWn and (c) M3 - 70% CPV ARI RS + 30%SCCWg

Initial flow mortars produced by SCCW (M2 and M3) were lower than mortar produced only CPV ARI RS (M1). There were a significant reduction on workability properties. The particle roughness from natural and grounded SCCW can be responsible for this reduction Payá et al. (1999). There were no significant difference on initial flow resulting from mortars produced with both SCCWn and SCCWg.

4.3 *Setting times*

Setting times measured by Vicat needle are presented on Table 6.

Natural and grounded SCCW accelerated initial and final setting times of pastes. The same result was obtained by Pacewska et al. (1988). There were no significant difference on initial setting from pastes produced by SCCWn and SCCWg; and a slightly difference between final setting from SCCWn and SCCWg. The grounded of SCCW accelerated final setting.

Table 6 – Setting times results

Setting times	Pastes		
	P1	P2	P3
Initial setting (h:min)	4:00	1:00	1:10
Final setting (h:min)	7:00	4:30	3:30

4.4 *Semi-adiabatic temperature evolution*

Data from temperature evolution of pastes with and without SCCW are shown on Figures 6 to 8. Temperatures were measured by a datalogger which registered the values with time.

The vertical lines on figures represent the setting times measured by Vicat needle.

From these Figures it is observed that SCCWn and SCCWg accelerated the hydration reaction with a high exothermic process. Cement pastes with SCCW addition (P2 and P3) quickly had it initial setting times (around one hour). The hydration process continuous rapidly, and final setting is reached after 4:30 hours (P2) and 3:30 hours (P3).

Relatively to reference results (reference paste, with no addition) (Figure 6), which had its initial setting at 4:10 hours, both pastes P1 (Figure 7) and paste P2 (Figure 8), at this time, reached their final setting.

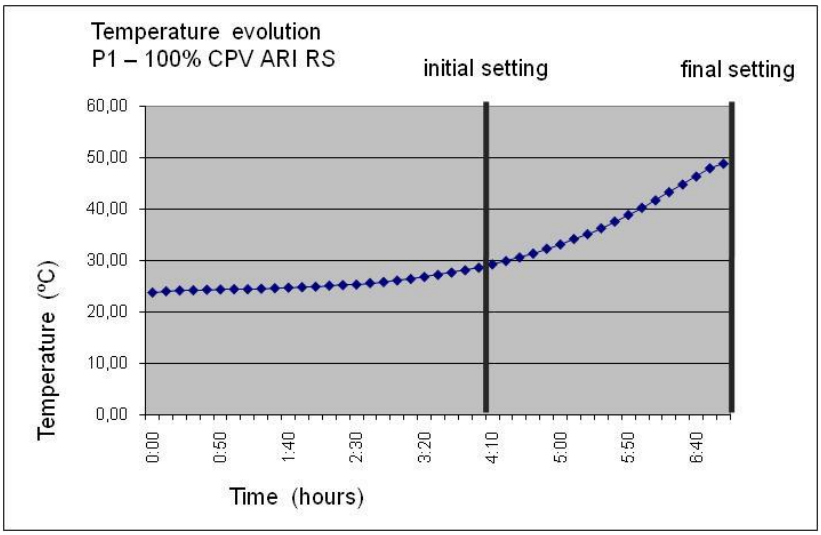

Figure 6. Semi-adiabatic temperature evolution from pastes P1 – 100% CPV ARI RS

The same behavior of pastes with SCCW have been observed by Pacewska; Wilinâska e Kubissa Pacewska et al. 1988. It can be explained by a typical behavior from the kinetic reactions when mineral additions with pozzolanic characteristics are used with cement products Velásquez, 2002.

4.5 *Pozzolanic activity of SCCW*

Pozzolanic activity index (PAI) is measured in mortars according to Brazilian Standards. It is measured by the ratio between compressive strength results from mortars produced with the

pozzolanic material and reference mortar (without pozzolan). The result must be higher than 0.75.

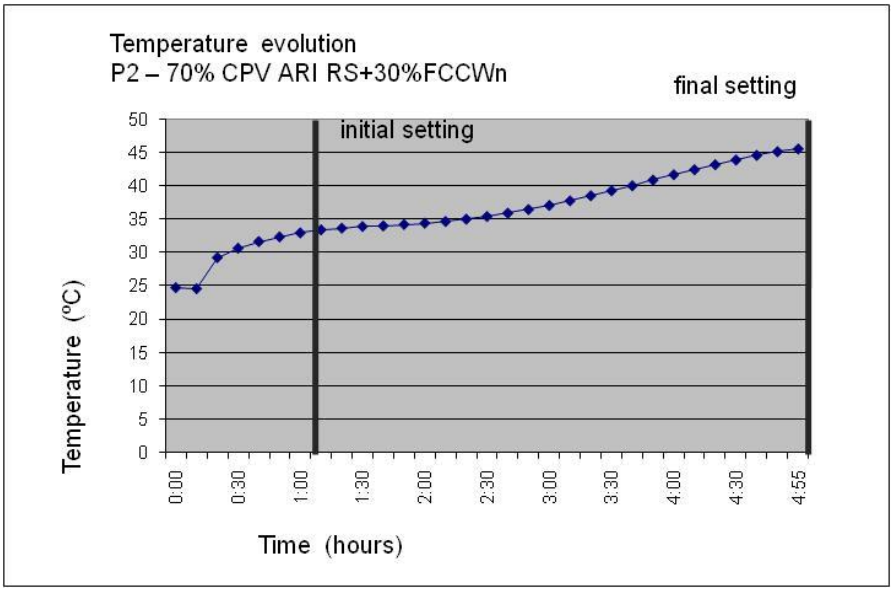

Figure 7– Temperature evolution from pastes P2 – 70% CPV ARI RS+30%SCCWn

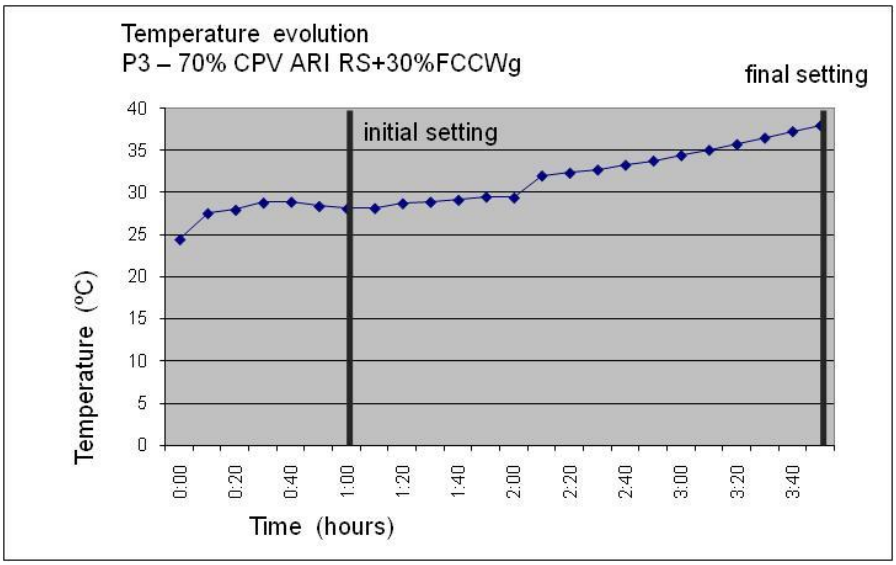

Figure 8. Temperature evolution from pastes P3 – 70% CPV ARI RS+30%SCCWg

Table 7 show the results of pozzolanic activity with cement for both natural and grounded SCCW.

Table 7 – Pozzolanic activity

SCCW	Pozzolan Activity Index (PAI) (%)
SCCW natural	67,3
SCCW grounded	81,5

5 CONCLUSIONS

The results obtained on this experimental study from pastes and mortars properties with 30% cement replacement (by mass) to SCCWn and SCCWg, enable us to conclude:

- SCCWn and SCCWg accelerated reactions of pastes with a high heat of hydration;
- Cement pastes produced with SCCWn and SCCWg quickly have initial and final setting times;
- Mortars initial flow with SCCWn and SCCWg were lower than reference mortars. There were no significant difference between mortars produced with both SCCWn and SCCWg;
- SCCW showed to be a good pozzolanic material.
- The pastes and mortar workability were affected with SCCW addition. Low values from consistency, quickly won for setting times and the accelerated hydration kinetic reactions, that could be observed on pastes and mortars produced with SCCW, reduce the material workability.

ACKNOWLEDGEMENTS

The authors would like to thank the Laboratory of Binders and Wastes - FEC/UNICAMP for the support on physical and mechanical tests, and the Brazilian Synchrotron Light Laboratory – LNLS for the support on SEM observations.

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Formulation of Efficient Silicate Disperse Paints

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ABSTRACT: Was investigated silicate disperse paints by way of changing the main components of the quantities and adding of hydrophobic additives.
It was found that addition 2% of the hydrophobic additives, such as emulsions of aminosiloxan, aminosilan or silicon resin, considerably improved the hydrophobic properties of silicate dispersion paint coatings. Furthermore, treating dry coating surface with liquid repellent increases the hydrophobic properties of coatings. Abrasive resistance of silicate dispersion coatings and the traction grows with increasing of the amount of liquid glass, while wet scrub resistance of coatings can be improved by increasing the amount of polymer dispersions in formulations. However, adding more 7.5% polymer dispersion significantly decreases the water vapour permeability of coating. The amount of liquid glass has no significant effect on the water vapour permeability of coating.
On the basis of the results, special silicate dispersion paints were developed with an exceptionally high feature of high water resistance, high mechanical resistance, good cleanability, especially good water vapour permeability or cost-effectiveveness. Also, the paper presents the testing results of physical and mechanical properties of industrially produced special silicate dispersion paints coatings.

1 INTRODUCTION

Building facade external thermal insulation systems (ETICS) have recently been widely used in construction in Lithuania. ETICS are the simplest and most reliable methods of conserving energy for buildings over the long time. ETICS are used for renovation of existing buildings and it is necessary to ensure a long term service life of thermal insulation. Therefore the main factor of desired durability of ETICS is a high protective features of finishing coatings. Special requirements are established for the finishing coatings of such systems: they have to be waterproof, resistant to atmospheric effects, chemically aggressive agents, bond well with the base and be highly permeable to water vapour and gas (Ramanauskas and Stankevičius, 2000). Such requirements are largely met by mineral silicate paint coats, but they are too permeable to water, are not elastic and strong enough (Miniotaitė and Stankevičius, 2001). In addition, once prepared for use, paints are unstable and have to be used up fast (Weinmann, 1986).

Liquid potassium glass modified with polymer dispersions and with additives added produces much more stable silicate/dispersive paint that can be stored for an extended period of time (Daunoravičius et al. 2008). However, universal paints of usually simplified formulation that are designed for common use fall short of meeting today's needs. Although general-purpose paints have quite good technical and decorative properties, such as colour, covering, normal drying time, their coatings usually do not have any exclusive properties, particularly higher waterproofness levels and increased permeability to water vapour. Other important

physical mechanical and performance characteristics include resistance to wet scrubbing, friction, contamination, scratching, etc.

On the other hand, the technology of paint makes it very difficult or even impossible to produce a universal paint with very good technical and performance properties. While some properties are improved, others inevitably worsen. For instance, if decorative properties get better, the mechanical ones worsen, and improvement of waterproofness may lead to lower permeability to vapour, etc. Therefore, the main goal was to create paints with a certain well-defined special property, without making other indicators much worse. The main requirement of being environmentally friendly has to be in any case.

The previous thesis (Daunorovičius et Al. 2009) set thresholds for the quantitative proportions of the main components of paint ensuring appropriate technological parameters of paint, stability of stored paint and the quality of the coat. In addition, it was presumed that if the quantities of individual components were modified within the established limits, the main technological properties of paint and the performance characteristics of its coat, such as permeability to water and vapour, mechanical strength of a dry and wet coat, the strength of its adhesion to the base, could be changed significantly. Waterproofness can be boosted by the addition of various hydrophobic additives or their treatment with water-repelling liquids (Wagner, 1995).

This thesis is focused on correction of paint formulations within the set limits, selection and testing of hydrophobic additives to identify the effects of the quantity of the main components and the variety and quantity of additives on the properties of paint coats.

The purpose of the thesis is to create paints with different special properties by changing the quantities of the main components of base (universal) silicate dispersion paints and using hydrophobic additives, and to carry out laboratory and production tests on the paints.

The tests performed correspond to global paint industry development tendencies, i.e. a decrease in the quantity of organic components, an increase in the quantity of non-organic substances and growth of the demand for special paints.

2 MATERIALS AND METHODS

To make the paint, we used industrial liquid potassium glass *Trasol KE-K* with a density of 1.24 g/cm^3 and a silicate module of 3.86. Such liquid glass was modified with styrene/acryl polymer dispersion *Finndisp A 11* with a particle size of 0.19 µm and a pH of 7.5–8.5, with the minimum film forming temperature being +14 ^{o}C and a non-volatile particle content of 48%.

The characteristics of non-organic pigments that are resistant to alkali and light are presented in Table 1, and those of the micro-fillings used are provided in Table 2.

Table 1. Pigments used in paint and their characteristics

Name	Chemical formulation	Colour	Average particle size, µm
Red iron oxide (hematite)	Fe_2O_3 (under 95 %)	Dark red	0.17
Yellow iron oxide	Fe_2O_3 (<84 %)	Yellow	0.7
Chromium oxide	Cr_2O_3	Green	0.30
Iron black (magnetite)	Fe_3O_4	Black	0.20
Titan white	TiO_2 (rutile)	White	0.10

Table 2. Micro-fillings and their characteristics

Micro-filling	Chemical formula	Particle shape	Average particle size, µm
Talcum	$3MgO{\cdot}4SiO_2{\cdot}H_2O$	Lamellar	10
Calcite	$CaCO_3$	Ball	6
Calcite	$CaCO_3$	Ball	10
Ground ceramics	Al, Si oxides	Ball	40
Chalk	$CaCO_3$	Ball	30

To prepare the paint, the following additives were used to ensure the right technological properties of the paint and technical characteristics of painting: liquid glass stabilisers, viscosity

modifiers, thickening agents, dispergators, counter-foamers and emulsifiers. These additives were not tested and their quantities were chosen based on the manufacturers' recommendations.

The water permeability of paint coatings was identified on the basis of LST EN ISO 7783-2:2002 using mortar board samples. 200 µm thick coatings formed on the boards were hardened for 14 days at a temperature of +21°C, ±2°C and relative air humidity of 60%, ±10%. Later, the samples were tightly attached to glasses with water. The glasses were placed into the test chamber with controlled temperature and humidity. At certain intervals, the sample glasses would be weighed to calculate the density of vapour passing through the paint coating according to LST EN ISO 7783-2.

The resistance of paint coatings to abrasion was identified on the basis of LST EN ISO 7784-2:2006 using a Taber device (Picture 1) and 10 mm concrete panel samples with paint coatings applied and hardened in the same manner.

Picture 1. Identifying paint coating resistance to abrasion using a Taber device on the left and establishing resistance of paint coating to wet scrubbing using a Braive Instruments device on the right.

Coating resistance to wet scrubbing: 200 µm thick paint coatings were formed on window pane lamellas and then hardened for 14 days at a temperature of +21°C, ±2°C and relative air humidity of 60%, ±10%. After that, the coatings were tested using a Braive Instruments device (Picture 1) on the basis of the standard methodology as defined by LST EN ISO 11998:2006.

Water permeability was established on the basis of LST EN 1062-3:2008 using 3 cm thick 225 cm^2 standard concrete panels with 200 µm paint coatings formed on them, which were hardened for 14 days at a temperature of +21°C, ±2°C and relative air humidity of 60%, ±10%.

Strength of adhesion when tearing paint coatings off concrete panels was identified under LST EN 1504:2004 using a CONTROLS device 58-C0215/T. The test paint was applied on dry standard concrete panels in a 240 µm layer and then hardened for 14 days at a temperature of +21°C, ±2°C and relative air humidity of 60%, ±10%.

Resistance to atmospheric effects: coatings were artificially aged in a QUV/ spray machine with UVA 340 bulbs. The test cycle consisted of 5 hours of irradiation and 12 minutes of watering. 200 µm thick paint coatings were formed on glass lamellas. The samples were inspected once every 20 cycles. Before an inspection, the coatings were washed using a soft sponge and warm water (water temperature would be below +30°C) and then left to dry. Inspections can usually identify the following defects in the coatings: peeling, cracking, gaps, bubbles, chalking, contamination and discolouration. Chalking is the emission of easily removable particles on the coating surface after one or several of its components, normally the binding agent, breaks down. Chalking products can be removed from the coating using a duct tape. Chalking products that stuck to the tape were checked against a contrast base. The level of chalking and other abrasions in the coating was assessed on the basis of the benchmark pictures and benchmark scales provided in LST EN ISO 4628.

3 RESULTS

The quantities of the main paint components were selected based on the above [6] assump-

tions of optimising silicate dispersion paints, i.e. by making the following quantitative proportions: a proportion of pigment and filling mass of 1:3.3, a total proportion of liquid glass and polymeric dispersion hard substance mass and the total filling and pigment mass of 1:3.5, a percentage ratio of the mass of fine (5 µm) to coarse (10 µm) fillings of 57:43.

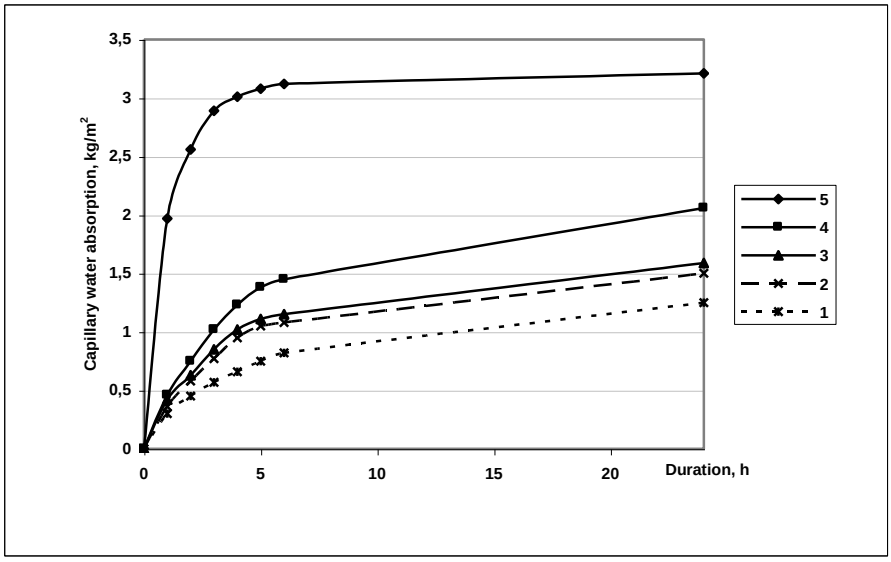
The formulation of paint that matches the above ratios as well as the properties of the hardened coating is presented in Table 3.

Table 3. Test silicate dispersion paint formulation and the properties of the paint

Pant component	Quantity, % of mass	Coating properties
Water	20.5	
Liquid glass	28	
Polymeric dispersion *Finndisp A 11*	6	
Carbonate filling, 5 µm	16	Vapour permeability: 214 g/m^2 per day;
Carbonate filling, 10 µm	12	Capillary water absorption: 1.59 kg/m^2 (per day);
Talcum	5	Resistance to wet scrubbing: 4,800 cycles;
TiO_2	10	Resistance to abrasion: 29.8 mg/100 revs
Dispergator	0.3	Strength of bond with concrete: 2.4 MPa
Stabiliser 1	0.2	Chalking grade: 2
Stabiliser 2	0.1	
Thickening agent	0.1	
Anti-foamer	0.3	
Emulsifier	1.0	
Viscosity modifier	0.5	

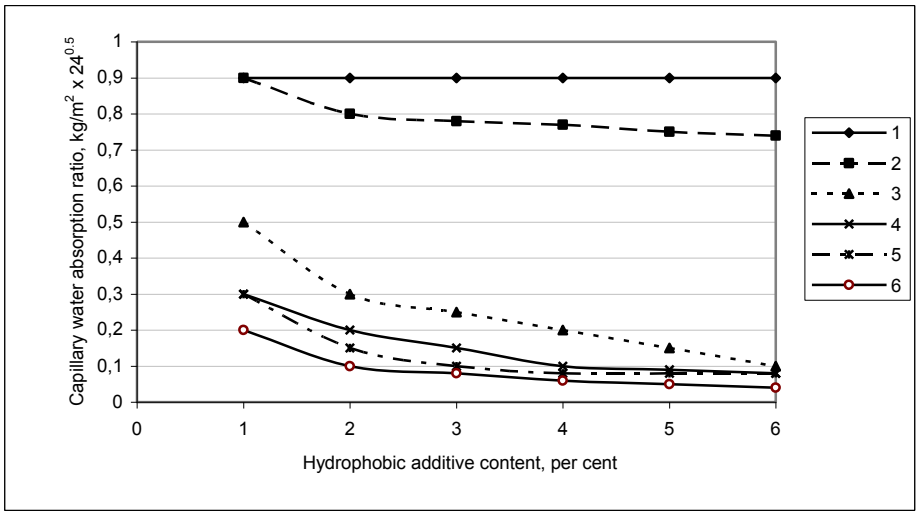
This is a universal, quite cost-effective paint with good technological, technical and performance properties. However, it also has shortcoming, with high water permeability being the most important one.

Silicon organic compounds were used to make the paint hydrophobic. There are many types of silicon hydrophobic materials, depending on the length of alkyl groups adjoining the Si component. As shown by the data presented in Picture 2, the most effective paint additives are aminosilane and aminosiloxane emulsions as well as silicon resin emulsion. Hardened coatings can also be made hydrophobic by applying hydrophobic liquids on the outside. However, this method produces slightly inferior results.



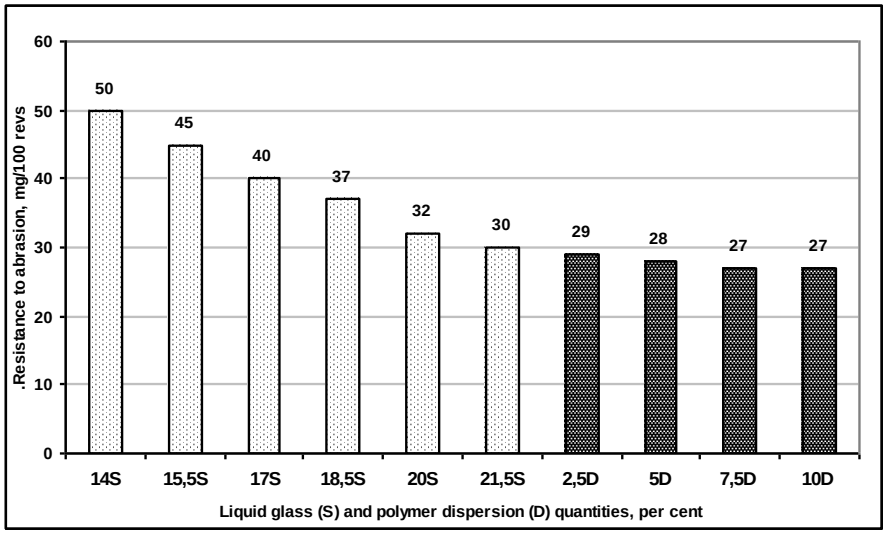
Picture 2. Dependence of the capillary water absorption indicator in paint coatings on the type of the hydrophobic agent and the method of hydrophobic treatment: *1* – 1.5 per cent aminosiloxane emulsion added to the paint; *2* – 1.5 per cent silicone resin emulsion added to the paint; *3* – 1.5 per cent aminosilane emulsion added; *4* – hardened coating treated with hydrophobic liquid; *5* – coating without hydrophobic treatment

As the quantity of the hydrophobic additive increases (Picture 3) its hydrophobic effect becomes relatively smaller and therefore the most effective content of such additive is 2 per cent of the total mass of the paint.

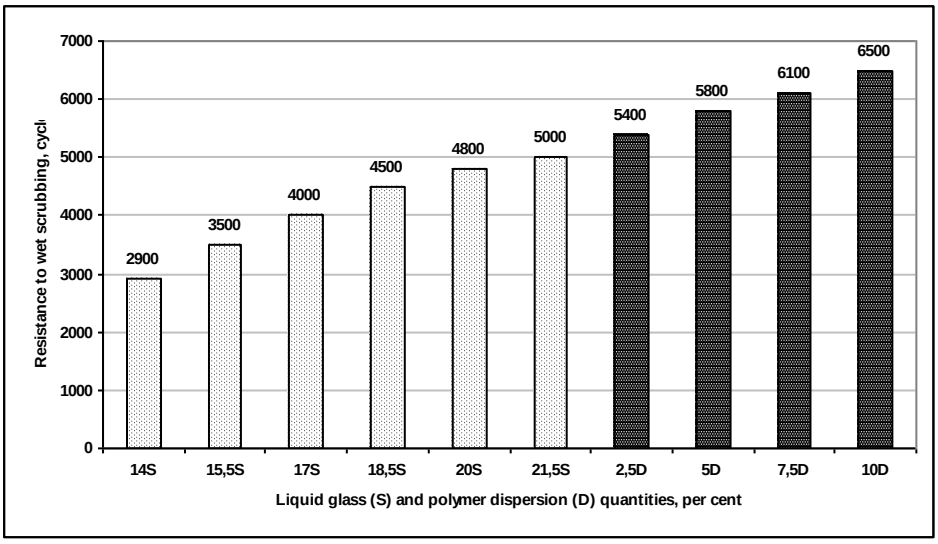


Picture 3. Dependence of the capillary water absorption indicator in test paint coatings on the type of the hydrophobic agent and the method of hydrophobic treatment: *1* – aluminium stearate; *2* – silicone oil emulsion; *3* – silicone resin emulsion 1; *4* – silicone resin emulsion 2; *5* – aminosilane emulsion; *6* – aminosiloxane emulsion

The strength of dry boats was assessed through their resistance to abrasion. The results indicate that resistance to abrasion depends to some extent on the quantitative ratio between the liquid glass and the fillings and pigments (Picture 4). By increasing the liquid glass content from 14 per cent to 21.5 per cent, the loss of the coating mass to abrasion can be brought down by 40 per cent. Whereas modifying dispersion could even reduce resistance of dry coatings to abrasion a little.

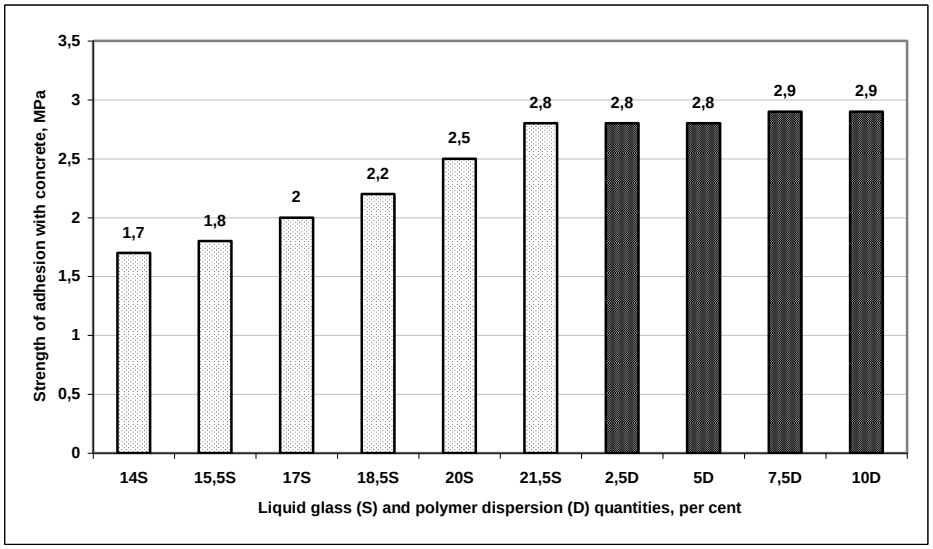


Picture 4. Dependence of paint coating resistance to abrasion on the content of liquid glass and modifying dispersion added to paints with 21.5 per cent liquid glass content



Picture 5. Dependence of paint coating resistance to wet scrubbing on the content of liquid glass and modifying emulsion added to paint with 21.5 per cent liquid glass content

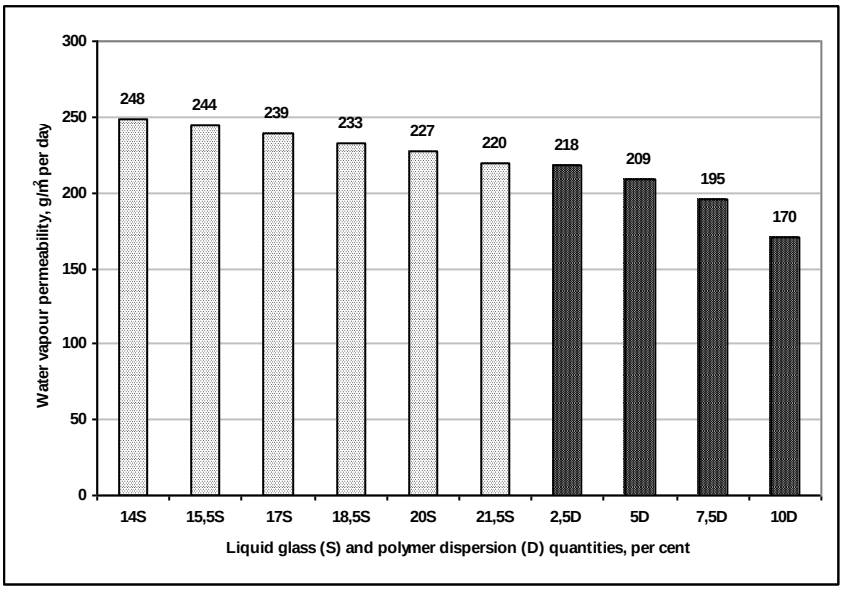
The results of the strength of coating adhesion to concrete by tearing are shown in Picture 6. Apparently, this indicator depends on the content of the binding agent used in the paint, i.e. liquid glass the most. If the content of liquid glass in paint is raised from 14 per cent to 21.5 per cent, the strength of paint-to-concrete cohesion goes up to 65 per cent. Whereas addition of modifying polymer emulsion (dark columns) will only slightly increase the strength of cohesion with the base.



Picture 6. Dependence of the strength of paint coating adhesion to concrete by tearing on the content of liquid glass and polymer dispersion added to paint with 21.5 per cent liquid glass content

The results of the tests of dependence of vapour permeability on the content of the binding agent, i.e. liquid glass and the modifying agent, i.e. polymer dispersion is shown in Picture 7.

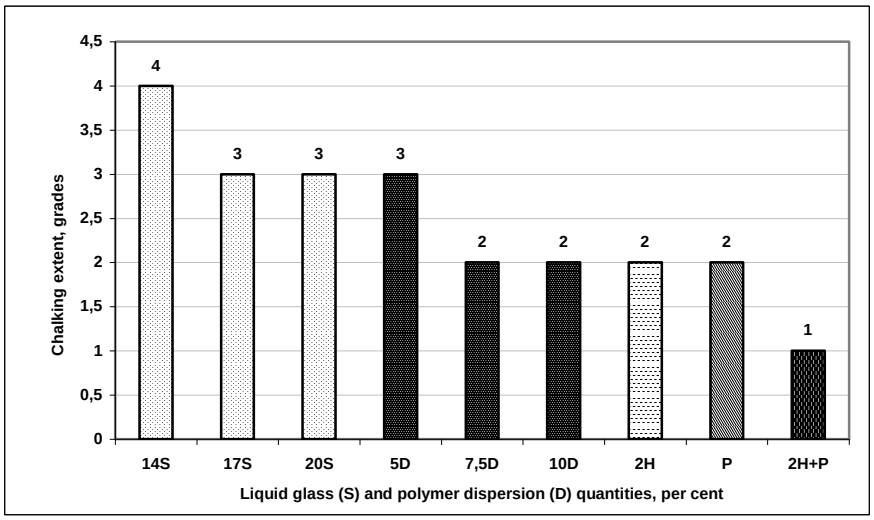
Paint coating vapour permeability does not depend on the content of the binding agent a lot. As the content of liquid glass in the paint increases, vapour permeability deteriorates slightly. However vapour permeability of coatings can be reduced further (by roughly 20 per cent) through the addition of polymer emulsion, especially when its content in paint is increased to 10 per cent.



Picture 7. Dependence of paint coating vapour permeability on the content of liquid glass and polymer dispersion added to paint with 21.5 per cent liquid glass content

Changes in the resistance of coatings to wet scrubbing are of a similar nature. Given a larger amount of liquid glass, resistance to wet scrubbing increases to 70%. Given a larger amount of dispersion, it increases to 25% (Pic. 5).

Paint coating resistance to atmospheric impacts was identified through accelerated ageing using a QUV-spray machine. The chalking of the coatings and other visual changes were assessed after a certain amount of test cycles. The extent of coating chalking after 100 test cycles is shown in Picture 8.



Picture 8. Dependence of the extent of paint coating chalking on the content of liquid glass, polymer dispersion added to paint with 20 per cent liquid glass content and the method of hydrophobic treatment (H – by adding the hydrophobic agent to paint with 20 per cent liquid glass and 7.5 per cent dispersion content; P – by treating hardened coating surface with silicon liquid; H+P – by adding the additive and treating the hardened surface)

It can be seen that after accelerated ageing trials, coatings with higher liquid glass content chalk less. A similar tendency is observed when the polymer dispersion content goes up to 7.5 per cent. The extent of chalking can be brought down by another grade by treating paint coatings hydrophobically in an integrated way. No other visual defects were observed in paint coatings in the process of accelerated ageing.

Given the above dependencies of formulations and properties, the formulations of silicate dispersion paint could be adjusted accordingly to change the coating properties and come up with paint with certain special properties.

The aforementioned trials determined dependencies between the content of core components or additives in paint and the properties of the paint. On that basis, the base formulation of silicate dispersion paint was adjusted in a focused way, producing paint with certain special properties. The development of the formulation of such paint was based on an assumption that in order to produce paint with the necessary special property one has to increase (reduce) the content of the component that affects it to the maximum extent possible. Such adjustment can only be done within well-defined limits, maintaining rational quantitative ratios of all the core components of paint.

By changing the content of the core components of paint and by using extra additives, several types of special silicate dispersion paint were produced, each with a certain particularly distinctive property like hydrophobia, resistance to mechanical impacts or atmospheric effects, extremely high water vapour permeability.

On top of that, lab tests of paint established that an increase in the content of fillings and thickeners in paint produces a thicker layer that does not run off vertical surfaces and levels out small surface irregularities. An increase in the content of the binding agent and hydrophobic treatment of paint will produce a paint that is more resistant to dirt and washing. A cost-efficient paint that still possesses decent properties can be produced by reducing the content of the binding agent and adding cheaper fillings.

The resultant special paint (Table 4) was manufactured. The paint was made using an industrial-grade paint mixer by adding the components in the following way: first the water, the dispergator, the stabiliser, some of the anti-foamer and the thickening agent were added together and mixed for 30 minutes. Then followed the titanium dioxide, the fillings and the concoction was mixed for 60 minutes. Eventually, the dispersion, the remaining portion of the anti-foaming agent, the viscosity modifier and the emulsifier were added and the stirring continued for another 30 minutes. The liquid glass was added at the end of the technological process, followed by another 15 minutes of mixing. When making the paint in a ball mill, the components should be added in a more or less the same manner as above. However, in that case the components can be added in two stages, stage two involving the addition of the liquid glass, the dispersion, part of the anti-foamer, the viscosity modifier and the emulsifier. For the first stage, the mixing should continue for 2.5 hours, and for another 30 minutes once all of the components have been added.

Table 4. Formulation of special silicate dispersion paints

Component	Paint formulation marker						
	SDB	SDH	SDD	SDP	SDG	SDS	SDE
Water	20.5	20	19.5	17	22	21.5	26.5
Liquid glass	28	27	**31.0**	30.5	27	26	25
Polymer dispersion	6	7	6	**8**	**4**	6	5
Pigment (titanium dioxide)	10	8.5	8	8	5	5	5
Pigment (iron oxide)	-	-	-	-	-	**6**	-
Talcum	5	5	5	5	5	5	8
Carbonate filling (large particles)	12	12	12	12	12	12	5
Carbonate filling (fine particles)	16	16	16	16	16	16	8
Cheaper filling (ceramics, chalk)	-	-	-	-	**6**	-	**15**
Stabiliser 1	0.2	0.2	0.2	0.2	0.3	0.2	0.3
Stabiliser 2	0.1	0.1	0.1	0.1	-	0.1	-
Dispergator	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Thickener	0.1	0.1	0.1	0.1	0.6	0.1	0.1
Viscosity modifier	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Anti-foamer	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Emulsifier	1	1	1	1	1	1	1
Hydrophobic agent	-	**2**	-	**1**	-	-	-

Paint formulation marker legent: SDB – base (universal) formulation; SDH – waterproof paint; SDD – abrasion-resistant paint; SDP – washing-resistant paint; SDG – paint with high level of water permeability; SDS – coloured paint; SDE – cost-efficient paint.

Component content that determines a certain special property of the paint is given in grey. The testing results of physical and mechanical properties of industrially produced special silicate dispersion paints coatings presented in Table 5.

Table 5. Properties of special silicate dispersion paint

Indicator	Paint formulation marker						
	SDB	SDH	SDD	SDP	SDG	SDS	SDE
Vapour permeability, g/m^2 per day	214	203	220	218	**296**	225	248
Capillary water absorption, kg/m^2	1.59	**0.95**	1.32	1.18	2.20	2.10	2.35
Resistance to wet scrubbing, cycle	4800	6000	6400	**6800**	4400	4800	4200
Resistance to abrasion, mg/100 revs	29.8	29.4	**15.0**	18.4	28.5	29.4	31.6
Strength of cohesion with concrete, MPa	2.4	2.2	2.8	2.7	1.9	2.0	1.7
Chalking, grade	2	2	2	2	4	3	4
Colour	White	White	White	White	White	**Misc.**	White
Production price, LTL (manufacturer's data)	211	241	219	225	178	215	**156**

Indicator of the special property of the paint is given in grey.

4 CONCLUSIONS

Water permeability of coatings can be reduced two or more times by adding 2 per cent of hydrophobic additives (silicones) to the paint and by treating hardened coatings with hydrophobic liquids. The extent of chalking of coatings with hydrophobic treatment drops by two grades. Coatings with hydrophobic treatment are resistant to wet scrubbing by 20 to 25 per cent. The strength of silicate dispersion paint coatings is determined by liquid glass. With its content increasing from 14 per cent to 21.5 per cent, coating resistance to abrasion goes up by 40 per cent, the strength of cohesion with the base improves up to 65 per cent, and the paint becomes 70 per cent more resistant to wet scrubbing. Modifying polymer dispersion affects the strength of coatings to a much smaller extent. However, it makes coatings considerably (up to 20 per cent) more resistant to wet scrubbing. Besides, the addition of 7 per cent dispersion drops the level of coating chalking by one grade.

Vapour permeability of silicate dispersion paint coatings decreases the most (by up to 23 per cent) when the content of polymer dispersion is increased above 7 per cent. Hydrophobic treatment of coatings does not affect vapour permeability in any significant way. When the liquid glass content is raised from 14 per cent to 21.5 per cent, vapour permeability drops a little (by up to 12 per cent).

Paint with one single exceptionally well-distinguished property of the coat, like hydrophobia, resistance to mechanical impacts, resistance to washing, water vapour permeability can be produced by increasing (reducing) the content of the component that determines that property, or through the addition of additives. An addition of 2 per cent of hydrophobic agent produced highly waterproof (0.95 kg/m^2) paint, when the liquid glass content was raised to 31.0 per cent, the paint became resistant to abrasion (15.0 mg/100 revs), and when the polymer dispersion content was increased up 8 per cent, the washing-resistant properties of the paint improved up to 6,800 cycles. Paint with better water vapour permeability qualities (296 g/m^2·per day) was produced by dropping the liquid glass content to 27 per cent and that of polymer dispersion to 4 per cent. On top of that, 6 per cent of mineral pigment added resulted in coloured paint, and by adding 15 per cent of cheaper filling the paint became more cost-efficient.

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Iron, Steel and Stainless Steel, from the Point of Eco-Efficient Materials and Technologies

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ABSTRACT: Iron, steel and stainless steel are from the same origin, just having different features due to the other substances added to their micro structures to get different kind of materials. All have same basic in the meaning of reactions under action. With other additional materials, they differ.
When small amounts of carbon is added to iron, which is a heavy, ductile, magnetic, metallic element, steel is produced as an alloy of iron. When chromium is added to steel, stainless steel is produced.
To create eco-friendly space which is healthy and comfortable, by having a balance between ecological integrity and economic viability, it is aimed to use eco-efficient materials as iron, steel and stainless steel and technologies, related with these materials.
In the paper, the eco-efficiency features and technologies of these three materials will be described through the built examples.

1 INTRODUCTION

Since the beginning of the history, for iron is a cheap material and easy to have it from earth, it is being used during the all civilizations, in pig iron, cast iron and wrought iron as a very strong building material. Then with the addition of carbon and other metals to iron in some amounts, and due to the producing technologies, some common alloys of steel are produced easily with a mass production. With the resistance to corrosion, stainless steel gains a long service life, while steel creates lots of opportunities with advantages in design and in construction of buildings and bridges. Also there is a high quality in innovative and environmental-friendly solutions in details of designs for sustainable design development.

Not only the most effective features of these three materials as recyclable and reusable, but also richly produced spaces by using iron, steel and stainless steel as eco-efficient materials and energy saving technologies, the solutions will always have long life service in their best value for all.

In this paper, especially, the eco-efficiency, which is based on the concept of producing more goods and services while getting fewer from the resources and letting less waste and pollution out, of the building materials, which are iron, steel and stainless steel will be described through the built examples.

2 ECO-EFFICIENCY

There is a vocabulary which describes concepts which are related to sustainability and global environmental changes. Eco-efficiency is one of the terms, which defines the overarching philosophical and scientific concepts, in a way toward sustainability. Other terms which are complementary, are such as green building, building assessment, ecological design, life-cycle

assessment, life-cycle costing, high-performance building, and charette. They articulate special techniques in the assessment and in applying the principles of sustainability to the built environment.

The concept of eco-efficiency, which is defined by the World Business Council on Sustainable Development, WBCSD, in 1992, covers environmental impacts, and costs as a factor to calculate the business efficiency. The term eco-efficiency is considered to describe the delivery of competitively priced goods and services that answer human needs and make better quality of life, while reducing ecological impacts and resource intensity throughout the product's life cycles, to a defined level suitable with the Earth's carrying capacity.

There are 7 elements of eco-efficiency, defined by WBCSD, which are: to reduce the material requirements of goods and services, to reduce the energy intensity of goods and services, to reduce toxic dispersion, to enhance materials recyclability, to maximize sustainable use of renewable resources, extending product durability, to increase the service intensity of goods ad services.

Furthermore, dematerialization, closing production loops, service extension, and functional extension are four aspects of eco-efficiency which make it an important strategic element in today's economy.

Also there are ways to achieve eco-efficiency gains. These ways are; optimized processes which mean to move from costly end-of-pipe solutions to approaches, preventing pollution at first; waste recycling which is to use the by-products and wastes of one industry as raw materials and resources for another, to create zero waste; eco-innovation which is to manufacture "smarter" by using new knowledge to make old products be more resource-efficient in producing and in using; new services, which are to lease products rather than selling them, to change companies' perceptions, by spurring a shift to product durability and recycling; and networks and virtual organizations, to share the resources to increase the effective use of physical values.

As a summary, eco-efficiency defines most of the main basic principles supporting the concept of sustainable development (Kibert, 2005).

3 MATERIALS

We use iron and steel for well over millennium in engineering achievements. All are based on ferrous alloys for processing machinery and equipment. An engineer may explain these alloys as a group of materials rooted on the iron-carbon system, letting a wide range of useful properties take place, which can be formed into complex shapes.

Definitions in dictionary, are written that steels are alloys of iron and carbon. The group which is based on the iron-carbon system contains the strongest materials in absolute terms.

Iron is also one of the ferromagnetic elements which are four. Articles that are attracted to a magnet, can be made of iron or steel.

Depending on carbon content and heat treatment, stainless steel can be defined in four different types, such as ferritic, austenitic, martensitic and precipitation hardening. Stainless steel is a non-magnetic material (Weidmann, Lewis, Reid, 1990).

4 IRON

Iron ore, which is the fourth plentiful element in the earth, is a chemical compound of iron with other elements, such as oxygen, silicon, sulphur or carbon. Also there are lots of coke in the earth. In steelmaking, mostly very pure, also called as "rich", iron-oxygen compounds are used as iron ore. To get hot metal or molten iron, in a liquid state, the iron is produced from a blast furnace. If it is in solid state, its name is pig iron. The reason of calling s pig iron is, in past, it was cast into shapes, similar to piglets. Big amount of iron ore is mined in areas far from the center and to extract iron ore needs disruption which is small(IISI, 2004&eurofer, 1995).

Iron is a very important metal. There are lots of article made of iron (Branley, Pella, Urban, 1972). Since the industrial revolution started around 1850, iron is used in construction more than it was used in past.

Picture 1. The Eiffel Tower (photo, taken by Y.K.Aktuglu, Sept. 2010).

Iron's great landmark in architecture is Gustav Eiffel's tall structure, the Eiffel Tower, 300m in height, was built in 1889 for Paris Exposition. He used so many iron sections in small dimension to get the bigger one. The tower was constructed in 2 years. It was a prefabrication product which was riveted in site (Blanc, McEvoy, Plank, 1993). Also Eiffel did tests for the wind loads. And still the Eiffel Tower , is a very popular place to visit, not only its architectural and structural solutions, but also from the balconies of the tower, the views of Paris are very special.

The scheme of the Tower design is very simple. While four inclined trusses are going to the top in vertical, 3 rings in horizontal, at first level balcony, then at second level balcony, and finally at the third and the top balcony, held these four legs to produce the stability for the whole structure. The lattice trusses let the wind flow through the leg structure without giving any damage to the Tower, unless its small displays at the top, when it is very windy. Also through the inclined legs from ground to the second, there are inclined-elevators in 2-storeys.

In the construction of structural elements, the small sections are preferred to have a more free design level and also a more economical level is achieved from the point of selection of elements while composing the huge standing landmark.

Its construction technology, used for Eiffel Tower, can be learned from the printed materials, is an advanced one at its era.

5 STEEL

Steel which is made of steel scrap, iron ore and coke, can be made by using an electric arc furnace or a basic oxygen furnace. And more or less 50 % of steel produced in the world is gotten from recycled scrap. Then there is no waste steel, produced in the production process.

In embodied energy (EE), which means that it is all the energy needed to extract and transport materials and produce an outcome. A building's EE is a total definition of the EE of all the materials used in the construction of the building. For steel structures are slim structures with thinner columns, comparison with other materials, then less material will mean less embodied energy (eurofer, 1995).

Normally, steel is known as an alloy of iron and carbon. Steel could be produced by melting pig iron and blowing air or oxygen through the metal, melted. At the moment, carbon is added to produce steel. And also when other metals, eg. manganese or vanadium will be added, the steel with special properties will be produced. In this way, steel can be prepared with properties such as flexible or stainless or brittle (Branley, Pella, Urban, 1972).

There are more than 10000 different steel grades, which are based on different chemical compositions and microstructures, and they can be composed in lots of shapes, sizes or finishes.

Because of this variety, steel is a major foundation of our technological developments (IISI, 2004).

Picture 2. The Centre Pompidou, with a 60m width in narrow side (photo, taken by Y.K.Aktuglu, Sept. 2010).

Centre Pompidou, was designed by Richard Rogers and Renzo Piano, and opened in 1977 for public service as a cultural center. Its magnificently spanned trusses for 48m., gerberettes , cantilevered for 6m., circular hollow section columns, with a diameter 850mm, full with water for fire protection, bracings, etc. are important parts of the whole building in construction with steel. As a house for modern art museum, Centre Pompidou is also very important landmark with steel. In the entrance level, a floor plan which is free-from columns is a very good example what it means to build with steel. The need for a volume in 2 floors height, can be easily arranged inside and outside of the museum building and cultural centre. The trusses let all mechanical instruments be installed into their places.

Picture 3. The Centre Pompidou, from the pool side (photo, taken by Y.K.Aktuglu, Sept. 2010).

The design of the bracings which stabilize the Centre, also helps the view to be transparent and light through the wires, going vertical and in diagonal. The A-bracings connect the trusses, in a height of 2.5m., in three points, from the ends and mid of the trusses, through the floor height which is 4.5m. In the picture 3, these A-bracings at the end of the trusses are seen through the total height of the Pompidou Centre.

6 STAINLESS STEEL

Stainless steel which is an alloy of steel, chromium, and sometimes nickel and other metals, has perfect resistance to corrosion, and is also aesthetic, hygienic, easy to maintain and recyclable (Arcelor).

Stainless steel which is an interesting material, has unusual combination of features, as being a ductile material, means tough and durable and no need for surface protection against

corrosion. Stainless steel can be called as a symbol of strength and quality (Blanc, McEvoy, Plank, 1993).

Some stainless steels have very important mechanical properties, such as, they can be hardened to ultra-high strength levels, and still with remaining ductility, they may be formable, and also they have an ability to absorb energy (IISI, 2004).

Even though, to produce stainless steel is possible from iron ore, generally it is produced from scrap carbon steel or scrap stainless steel. By using the scrap, the energy which is needed to produce new material, in terms of embodied energy, decreases, and it makes waste and production emissions, including carbon dioxide, reduce. And there are other essential environmental benefits (Baddoo, Burgan, Ogden, 1997).

Picture 4. Science and Industry Museum, Parc de la Villette (photo, taken by Y.K.Aktuglu, Sept. 2010).

Parc de la Villette is a very important constructed environment with its science and industry museum, geode, and other entertainment buildings around. Science and Industry Museum has a huge volume for not only exhibitions but also for flowers and visitors. Its greenhouses is constructed with stainless steel cables and huge glass panes to construct a cubical composition, 32m*32m*8m in dimension. Museum is opened in !986. During the period till now, it gives a service as it did in its first days in opening, in architectural manner with having reflections through stainless steel and glass. To carry the huge glass panes, in 2m*2m.gridal form, tension bars in stainless steel carries all loads in safety till ground level. These architecturally designed huge windows let the sunshine be in to enlighten inner deep spaces including the atrium of the museum in an ecological manner. For stainless steel is a non-corrosion material, this helps the maintenance of the building to cost less.

The Serres, the glass facade elements, of Science, Technology and Industry Museum, were designed by Rice, Francis, Ritchie, RFR, fromUK, in both architectural manner and also in structural manner. The elevation of each Serre, which all metallic components are constructed from stainless steel, esp. grade 1.4401(316), has a frame as 32m.*32m.

The framework, supporting the Serres, is fabricated from stainless steel in tubular forms, on a gridal pattern of 8m.*8m. These framework is connected with the main building by 2 high concrete cylinders, 24m. in height. and they are clad in 1.5mm. polished stainless steel sheet.

For wind bracings, there are stainless steel nodes, which were cast to connect the tubular members, soid tie rods and tubular struts.

For cable truss, which is the only supporting system for the glass in horizontal, there are two single strand stainless steel cables, which are 12.7mm. in diameter and made of 19 wires with turnbuckles and fork ends for getting tension and for fixing.

And also there is a stainless steel four hole glass fixing in H form, composed of three castings, which is the other components of the glass suspension system.

This is an example of using stainless steel in structure and glazing fixings(Baddoo, Burgan, Ogden, 1997).

Picture 5. Geode, Parc de la Villette (photo, taken by Y.K.Aktuglu, Sept. 2010).

The Geode, which you can watch a movie in 360 degrees, inside a dome, cladded by stainless steel over a frame with circular hollow sections, is opened in 1985. Its shinning view, as a brilliant ball over water, from Science and Industry Museum, represents an enough meaning what stainless steel means in construction as a building material.

The cladding of the Geode, is a mosaic of 6433 doubly-curved triangular plates, in stainless steel with a grade of 1.4401(316). The planes have a thickness as 1.5mm and have an edge of the triangular form as 1.2m. in length.

The spherical form by mirror polished stainless steel plates is managed according to the final required radius of 18m. and 4 of these plates are arranged onto aluminium framing beneath (Baddoo, Burgan, Ogden, 1997).

7 CONCLUSION

It may be easily defined that, iron as the raw material, as the main metal to produce all, steel and stainless steel as alloys, adds its identity to other produced outcomes. When we count the abilities of iron in construction as a building material, we may count additional lines about steel and stainless steel because of other substances, they are in the same composition. For iron is a recyclable material. Then steel is, too and stainless steel is, too.

Eiffel Tower, since 1889, Pompidou Centre, since 1977, Science and Industry Museum, since 1986, and Geode, since 1985, are all for public use. In every built example, a more advanced construction technology is used, starting 1889 till the last example with their patents. In every building, first the ecological changes are taken care to have a more eco-friendly environment to decrease the expenditure of the managing costs.

As a conclusion, it may be underlined that in building with iron, steel and stainless steel, the buildings will be more effective comparing to the other building materials, through these three built examples.

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Technical visits to all built examples in the years, written down under the photographs.

Earth material and buildings: sustainable constructions techniques

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ABSTRACT: The experimental studies conducted by on the subject at the Dipartimento di Costruzioni e Restauro of the University of Florence want to expand and deepen the knowledge about the earthen building material to rationalize the way of using it.
The aim is to demonstrate on scientific bases earth's mechanical characteristics and, even with the use of additives preferably eco-friendly, to optimize the performances of durability and strength in order to achieve a standard of quality guaranteed.

1 INTRODUCTION

Recent years have seen the emergence of renewed interest in earthen architecture in national and international fields. Such changed attitude is the result of the recent considerations of eco-social-economical character, that induced to debate the model of modern development founded upon elevated energy consumption and consequent high levels of pollution and environmental damage, in favour of a low environmental impact and sustainable development. Such ecological and social-economic issues have led to reconsidering the possibility of using traditional building materials in modern constructions. Earth responds very well to the request for environmental sustainability: it's natural, healthy and renewable. These properties make earth an interesting material despite its low-ranking position on the scale of structural materials, at least from the point of view of mechanical performance.
All technologically advanced countries have set forth standards and codes defining the characteristics and expected usage limitations of construction materials and the buildings in which they are employed. Earth appears to be amongst the very poorest for use in constructions, in the sense that it exhibits extremely low values of the relevant mechanical parameters. However, this fact does not mean that it is necessarily inadequate for the construction of new buildings, or that existing earthen buildings are insufficiently safe or reliable.
In Italy earth was used as building material until 1950. Earthen buildings are still present in important amounts in some Italian regions. Sardinia is a significant example because there many people still live in secure earthen buildings and there are also some important buildings (town hall, church) made of earth.
These reasons have motivated research on the subject at the Dipartimento di Costruzioni e Restauro of the University of Florence, whose specific focus has been the mechanical performance of earthen building materials in order to achieve a standard of quality guaranteed.
To better understand the conduct of the material over time, some tests were performed on adobes taken from existing buildings.

Tests were carried out also on models of adobe walls and arches in order to study the behaviour of earthen structures.
Particular attention has been paid to assessing the effects that the addition of stabilizing substances to earth would have on such material's mechanical properties, stability, durability and resistance to weathering. The experimental studies considered various traditional additives, not always eco-friendly, and some new fully biodegradable natural additives so that in the future will be possible to improve the mechanical properties and durability of the material earth without changing its sustainable nature.

2 EXPERIMENTAL ANALYSES

The research has been conducted in a heterogeneous way: earth samples for the experimental studies have been taken from different Italian regions where the presence of earthen architecture is traditional (Calabria, Sardinia, Tuscany) and from different sites of the same region.

Table 1. Mineralogical composition of fine components.

	Quartz	K-feldspar	Didymolite	Calcite	Clayey minerals
Calabria 1	34	3	/	/	63
Calabria 2	25	6	6	5	58
Calabria 3	16	5	10	13	56
Calabria 4	24	9	9	/	58
Calabria 5	42	3	/	/	55
Calabria 6	26	7	/	/	67
Calabria 7	18	2	/	/	80
Sardinia 1	29	19	7	14	31
Sardinia 2	37	9	9		45
Sardinia 3	13	10	6	29	58
Tuscany 1	76	8	14	/	2

Table 2. Mineralogical composition of clay minerals.

	Kaolinite	Illite smectite	Smectite	Chlorite	Chlorite vermiculite
Calabria 1	20	/	/	10	20
Calabria 2	20	/	/	15	10
Calabria 3	30	15	15	15	/
Calabria 4	40	/	/	/	/
Calabria 5	50	/	/	/	/
Calabria 6	45	/	/	5	/
Calabria 7	45	15	/	/	/
Sardinia 1	20	/	45	/	/
Sardinia 2	20	/	/	/	15
Sardinia 3	5	/	85	/	/
Tuscany 1	30	/	/	/	20

Table 3. Consistency limits.

	Wl %	Wp %	Ip %	Ws %
Calabria 1	38	22.4	15.6	
Calabria 2	31	23	8	
Calabria 3	37	28	9	
Calabria 4	26	17	9	21.35
Calabria 5	25.2	15.04	10.16	
Calabria 6	34.5	26	8.5	17
Calabria 7	39	30	9	14
Sardinia 1	44	22.92	21.08	50.02
Sardinia 2	34.2	14.7	19.5	41.49
Sardinia 3	37.2	19.81	17.39	44.34
Sardinia 4	48.93	23.88	25.05	15.72
Sardinia 5	49.31	25	24.31	17.84
Sardinia 6	50.8	26.3	24.5	18.9
Sardinia 7	39	22	17	26
Tuscany 1	19	14	5	21

To verify the difference between all types of earth, physical analysis have been conducted on each sample. These identification tests include diffractometry of fine components, granulometry and determination of the consistency limits.
Diffractometry studies, carried out by the Florence CNR "Centro di studi sul deperimento e metodi di conservazione delle opere d'arte", were performed by X-ray and calcimetry. The results are presented in Tables 1-2.
Granulometric determinations were conducted by dry method following ASTM D421. The objective of this analysis is to classify, according to fixed classes of size, the particles that constitute the sample in order to determine the percentage distribution according to size.
The consistency limits are the water content that determines the transition of earth from solid to liquid and plastic state. The consistency limits determination was carried out following ASTM D4318 standard. The bulk density was determined according to ASTM D854 for thin earth samples and to BS 1377 Test6(A) for medium earth ones.
The values of consistency limits and bulk density are shown in Table 3.

3 MECHANICAL ANALYSES

As no standards exist for testing procedures on earth material and elements in Italy, it was deemed best to follow those normally adopted for conventional building materials.
The earth samples were used to prepare cubic specimens for uniaxial compression tests and, in some cases, prisms for three points bending tests. All the tests were performed in a quasi-static process with a device able to proceed with controlled displacements.
The mixtures were made by mixing earth with a percentage of water, calculated from the weight of the earth, appropriate for an easily workable mix.
With the ultimate aim of evaluating the carrying capacity of the material, the results of the experimental tests were used to calculate compressive strength, determined as the ratio between the peak load and the area of the specimen face in the contact with the test plates, compressive elastic modulus, determined in the branch of equilibrium path that could reasonably be considered linear, kinematic ductility, determined as the ratio between the displacement corresponding to the peak load and that at the end of the linear segment, and available kinematic ductility, cal-

culated as the ratio of the displacement measured at the ultimate load (conventionally established) and the displacement corresponding to the peak load (Tab. 4).

Table 4. Mechanical parameters.

	Mixtures	Number of test samples	E (MPa)	σr (MPa)	μc	μcd
Calabria 1	water 15%	3	230.90	1.838	3.524	2.973
Calabria 2	water 20%	6	93.69	1.474	1.306	1.440
Calabria 3	water 30%	10	224.33	2.418	1.907	2.822
Calabria 5	water 22%	13	242.08	2.405	1.472	1.586
Sardinia 1	water 44%	5	445.99	4.720	1.407	2.433
Sardinia 2	water 34%	5	924.08	8.395	1.327	1.956
Sardinia 3	water 37%	5	832.68	6.777	1.278	2.530
Sardinia 6	water 35%	5	269.78	2.431	2.190	7.005
Sardinia 7	water 33%	4	999.22	6.899	1.333	2.824
Tuscany 1	water 6%	12	4.03	0.026	1.101	2.208
Tuscany 1	compacted 0.60 MPa	6	43.25	3.815	1.097	2.113
Tuscany 1	compacted 0.88 MPa	6	27.46	3.354	1.165	2.006

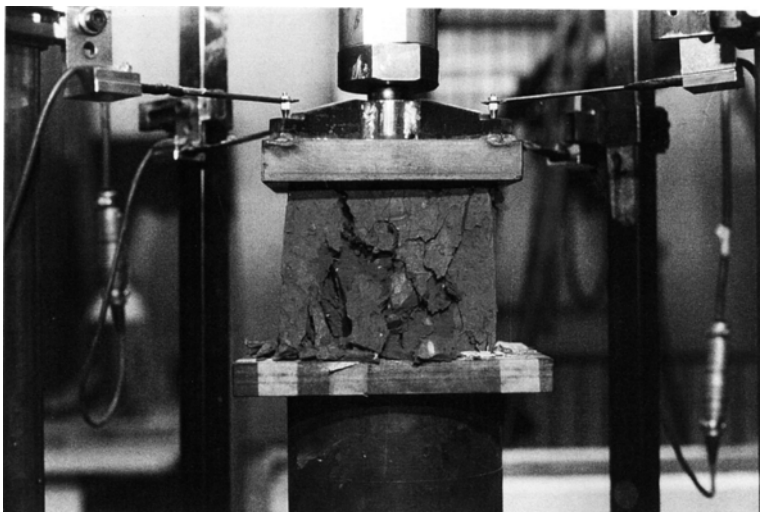

Figure 1. Uniaxial compression tests.

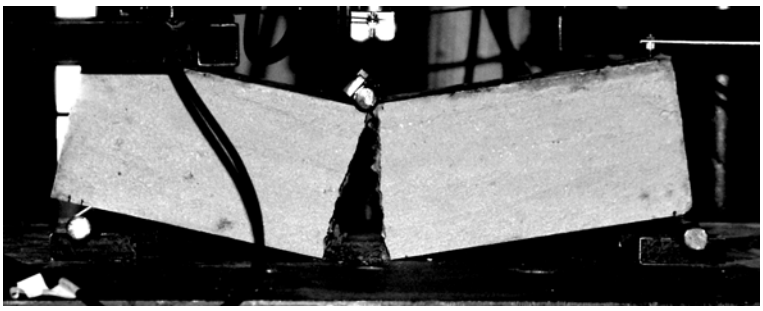

Figure 2. Three points bending tests.

4 MECHANICAL ANALYSES ON EXISTING ADOBES

To have an adequate knowledge of the earth materials' change in performance over time, uniaxial compression tests were also performed on adobes taken from existing buildings and cut into cubic specimens. The test results are shown in Table 5.

Table 5. Mechanical parameters of adobes taken from existing buildings.

	Mixtures	Number of test samples	E (MPa)	σr (MPa)	μc	μcd
Calabria adobe 1		2	54.67	0.423	2.159	2.132
Calabria adobe 2		2	43.17	0.624	1.624	3.394
Calabria adobe 3		2	32.79	0.701	1.180	2.448
Calabria adobe 4		2	21.71	0.766	1.444	6.082
Calabria adobe 5		3	583.48	9.379	1.348	5.883
Calabria adobe 6		2	54.67	0.423	2.159	2.132
Calabria adobe 6 (remixed)	water 15%	3	126.6	1.096	2.132	4.391
Calabria adobe 7		2	36.66	0.624	1.624	3.394
Calabria adobe 7 (remixed)	water 15%	3	146.3	1.173	1.754	6.656
Calabria adobe 8		2	30.44	0.691	1.180	2.448
Calabria adobe 8 (remixed)	water 15%	3	82.9	0.319	5.013	3.653
Calabria adobe 9		2	16.73	0.463	1.681	2.421
Calabria adobe 9 (remixed)	water 15%	3	195.45	1.385	1.984	6.290
Calabria adobe 10		2	28.85	0.766	1.444	6.082
Calabria adobe 10 (remixed)	water 15%	3	261.74	2.392	2.825	3.018
Calabria adobe 11		2	5.24	0.232	1.290	2.173
Calabria adobe 11 (remixed)	water 15%	3	99.21	0.694	2.616	3.634
Calabria adobe 12 (remixed)		3	227.42	1.519	4.105	2.650
Calabria adobe 14		2	109.46	0.768	1.844	2.235

5 ADDITIVES

Particular attention has been focused to assessing the effects that the addition of stabilizing substances has on the performances of the material.
Stabilization is often used in earthen building materials' tradition to improve, even significantly, the physical-chemical and mechanical characteristics of earth system.
The objectives to be asked are to limit volume changes and to increase mechanical properties, stability, durability and resistance to weathering.

Straw is the most common and traditional additive used to increase water resistance and improve cohesion within the clay particles. It was noted that the straw affects the mechanical properties with a improvement of shear strength, while the compressive strength not increases significantly.
Lime is used to increase cohesion between clay grains and it reduces the plasticity index.
The stabilization with Portland cement improves the cohesion of the grains and therefore increases the resistance of the material. It also reduces the sensitivity to water, limiting swelling and shrinkage moisture. This additive improves considerably the quality of the land but is a non natural product. This interferes with the natural features of sustainability and low environmental impact of earthen buildings.

Table 6. Tested mixtures: mechanical parameters.

	Mixtures	Number of test samples	E (MPa)	sr (MPa)	mc	mcd
Calabria 2	water 25%, gypsum plaster 10%	6	101.28	1.852	1.312	1.489
Calabria 2	water 25%, gypsum plaster 15%	6	243.14	2.163	1.179	2.021
Calabria 2	water 30%, gypsum plaster 25%	6	157.05	1.497	1.307	2.185
Calabria 4	water 33%, straw	10	133.81	1.945	2.059	1.798
Calabria 6	straw, lime 6%	5	104.74	1.213	4.425	2.028
Calabria 6	straw, Portland cement 6%	5	137.29	1.834	1.607	1.866
Calabria 7	straw, lime 6%	5	73.77	1.341	1.351	1.660
Calabria 7	Straw, Portland cement 6%	5	99.85	1.789	1.346	1.650
Sardinia 1	water 44%, straw 1%	5	347.06	3.908	1.341	2.080
Sardinia 1	water 22%, prickly pear juice 22%	5	336.62	3.685	1.165	2.276
Sardinia 1	water 22%, prickly pear mucilage 22%	5	331.07	4.081	1.262	2.576
Sardinia 2	water 34%, straw 1%	5	551.28	5.723	1.195	2.503
Sardinia 2	water 17%, prickly pear juice 17%	5	588.01	6.212	1.130	2.303
Sardinia 2	water 17%, prickly pear mucilage 17%	5	726.35	7.496	1.113	2.359
Sardinia 3	water 37%, straw 1%	5	537.89	4.957	1.348	2.317
Sardinia 3	water 18,5%, prickly pear juice 18,5%	5	610.76	6.242	1.315	2.214
Sardinia 3	water 18,5%, prickly pear mucilage 18,5%	5	631.55	6.327	1.475	2.210
Sardinia 7	prickly pear fibers 43%	2	182.48	2.201	1.452	3.587
Sardinia 7	water 37,5%, ground prickly pear 10,4%	5	366.32	3.475	1.400	3.372
Sardinia 7	ground prickly pear 50%	7	335.45	2.946	1.416	2.948
Sardinia 7	prickly pear juice 31%	2	280.83	2.841	1.670	3.114

In this experimental study we tried to identify a completely biodegradable additive that does not change the quality of sustainability and low environmental impact which can be found in earthen material.
An additive used in this research was the prickly pear. Several mixtures, containing serum, cladode mucilage or ground plant, were tested, but none of them has increased mechanical characteristics.
Also gypsum plaster was used as a natural additive for stabilization of earth. It is characterized by a very fine grain and the ability to incorporate large quantities of water. gypsum plaster added in moderate percentage has significantly improved the mechanical properties of earth.
Table 6 presents tested mixtures' composition and the results of the uniaxial compression test.

6 WATER RESISTANCE TEST

One of the main limitations of earth is its limited capacity for water resistance.
Immersion tests were conducted to test the water resistance for mixtures of earth with additives and without them.
The test was carried out by performing several cycles of immersion for a period of 5 minutes by placing the specimens in a bath full of water so that they could remain submerged for at least 5 cm. The dives were interspersed by a drying under infra-red lamps lasting 55 minutes.
Were subjected to this test mixtures-only mixes the ground and mixed with straw, plaster, prickly pear, lime and Portland cement as additives.
All additives tested gave results in increasing water resistance. In particular, a considerable increase was made by prickly pear mucilage and plaster as eco-compatible additives, and by lime and Portland cement as not eco-friendly additives.

Figure 3. Comparison between mixtures with gypsum plaster and mixtures without any additive after 6 cycles of immersion.

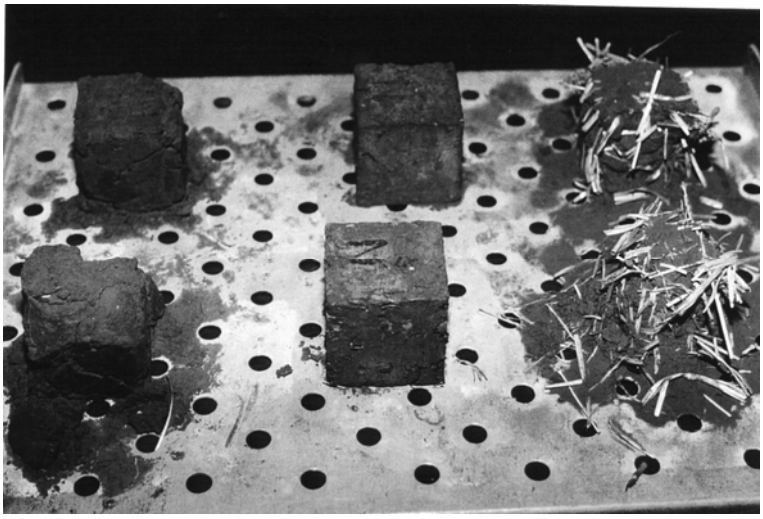
Figure 4. Comparison mixtures with straw, prickly pear juice and prickly pear mucilage after 6 cycles of immersion.

7 CONCLUSIONS

These experimental studies were directed towards researching fo a fully biodegradable natural additive for earthen material to optimize its performances of durability and strength and to achieve a standard of quality guaranteed.
Prickly pear increased water resistance but proved not good as additive for mechanical improvement.
Gypsum plaster, instead, was used successfully: it gave good results in increasing both mechanical characteristics and water resistance, without significantly altering the appearance and color of the material. Furthermore gypsum is fully biodegradable and natural and it's even used to improve the quality of agricultural land for some crops.

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Properties of Geopolymeric Artificial Aggregates obtained from Tungsten Mine Waste Mud, for Wastewater Treatment Processes

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ABSTRACT: This study investigates whether waste-based geopolymeric artificial (WGA) aggregates produced from mining wastes would be suitable to be used as alternative materials for fixed-film wastewater treatment processes (FF-WWTP). In a first stage WGA aggregates with different atomic ratios of mining waste mud/Na2SiO and Na2SiO/NaOH were produced using curing temperatures of 20ºC and 130ºC and its structural stability and pH variation after immersion in water was observed during 3 months. In a second stage, compressive strength was determined in additional WGA samples cured at 20ºC and 80ºC in dry conditions. Particles of size of 1 to 2cm in diameter were therefore produced to be used as media substratum of bio filters and physical properties of the WGA materials were evaluated (bulk density, micro porosity, durability, water absorption and void ratio) and compared with other materials.

1. INTRODUCTION

Some artificial materials (e.g. light-expanded clay aggregates (LECA) and thermoplastics) have shown to be more efficient and cost-effective competitive over conventional natural materials (e.g. gravel and sand) for wastewater treatment processes (WWTP) (Metcalf &Eddy 2003, Albuquerque et al. 2009). Bed materials frequently present clogging problems whose causes are related to the variation of its properties (e.g. compressive strength, specific surface area, void fraction and porosity), the release of fine material, excess of particulate matter and suspended solids and the development of precipitates (Metcalf &Eddy 2003) leading to resistance to flow and, therefore, to the decrease in treatment.

Reutilization of wastes is of great interest of European countries, such is the case of mining wastes. In 2006, in the EU27, approximately 55% of industry's waste was produced by mining and quarrying sector, 4.9% of which was incinerated, 43,6% recovered and 51,5% deposited. (Eurotstat, 2009).

Finding new applications for alumino-silicate wastes is of particular interest since these types of minerals are the most abundant materials in Earth's crust, as the Portuguese case, where an underground tungsten mine, located in Panasqueira area, produces tonnes of wastes per day, since 1980s, resulting in deposit of several millions of tonnes of alumino-silicate waste muds. Presently, Panasqueira mine produces approximately 100 tonnes of waste per day, and research in utilization of such mining wastes to produce geopolymeric binders will contribute to reduce waste landfill site and environmental impacts (Pacheco-Torgal et al. 2009).

As a consequence, the present research deals with a novel application of mining wastes geopolymeric binder by producing WGA aggregates as new alternative and possibly more durable materials for bed of wastewater treatment process, which can also bring larger perspectives for new applications of waste mining geopolymeric binder based materials.

2. MATERIALS AND EXPERIMENTAL PROCEDURES

2.1 Structural stability control of WGA aggregates and pH alteration in water

WGA was obtained using waste mud (precursor - P) from a local tungsten mine, after a thermal treatment for 2 hours at 800ºC as suggested by Pacheco-Torgal, 2007. NaOH 10M solution (H) and a Na2SiO L60 solution (S) were used as alkaline activators.

In a first stage four mixtures of WGA having different atomic ratios of R(P/S) (4 to 5) and R(S/H) (1.25 to 5) were produced. Samples with 2x3 cm size and having an approximate shape of natural aggregates were left to cure at 20ºC for approximately 48 hours (16 samples per mixture). Half of samples were cured at 20ºC while the other half was cured at 130ºC. For the curing ages of 7, 14, 21 and 28 days, two samples of each mixture, for each curing temperature, were placed in vessels containing 1 L of water as described in Silva et al. 2010. The time of beginning of sample defragmentation and the daily pH were registered. Water in vessels were replaced each 24 h. pH observations were stopped once the values reached 7.

In a second stage, the mixture with more stable behaviour was selected for testing compressive strength in dry and wet conditions. Samples with 40x40x40 mm3 were produced in a total of 450 cubes. The samples were first submitted to an initial dry curing period of 7 days at 20ºC and approximately 40% relative humidity. Afterwards 210 units were kept at 20ºC while the other 208 units were cured at 80ºC followed by different periods of immersion in water. In Phase I, the group of 210 samples (cured at 20ºC) were immersed in water at the dry curing age of 14, 21, 28, 35, 42, 63 and 91 days (7 Series of experiments, each one including 10 samples for testing and 3 replicates for each combination). In Phase II, the 240 samples cured at 20ºC (during an initial period of 7 days in moulds) and 80ºC (after removal from moulds) were immersed in water after 7 14, 21, 28, 35, 42, 63 and 91 days dry curing dry curing ages (8 Series of experiments, each one including 10 samples for testing and 3 replicates for each combination).

After each dry curing age, a set of 7 or 8 samples of each series in each phase was selected for water immersion in separate vessels containing approximately 1 L of water during 24 hours, 7, 14, 21, 28, 35, 42, 63, and 91 days (i.e. from 1 to 13 weeks of immersion period). During the immersion period the water in the vessels was changed every two days. Three dry samples of each series were tested to evaluate the compressive strength in dry conditions. After each immersion period, samples were removed and submitted to compressive strength (i.e. compressive strength was carried out for dry conditions and for 24hours, 7, 14, 21, 28, 35, 42, 63, and 91 days after immersion in water in each Series of both Phases). Compressive strength was determined according to ASTM C 109 for testing hardened concrete.

2.2 Bulk density, micro porosity, durability, water absorption, void ratio and resistance to weathering and disintegration

After the study of structural stability, a control of WGA aggregates and pH alteration in water has been carried on to chose the mix with the best performances. Some of its properties, that are consider important for its possible application as bed materials for wastewater treatment process, were also studied.

Thus, aggregates were produced with a diameter of about 2cm (Figure 1) and the following properties were determined: bulk density, micro porosity, weathering durability, water absorption and void ratio.

Decrease in compressive strength of the WGA materials and verification of its resistance to disintegration and weathering by slake durability test, was also determined. Slake durability test is carried out in weak rocks, like shales or similar. The test is used to estimate the resistance of equidimentional shale fragments and weighing 40g to 60g each. The slake durability index correspond to the percentage of dry mass of the fragments retained by a drum of 2.0 mm (No 10) square-mesh after two cycles of oven drying and 10min of mixing in water, under the effect of deterioration and abrasion. Test results are expressed as a slake-durability index for each particular rock (I_{d1}).

In this study, two groups of WGA aggregates were tested: one comprising aggregates dried at 20ºC for 35 days and another consisting of aggregates dried at 20°C for 35 days, then immersed

for 63 days and dried again at 20°C. Before testing, both sets were dried in an oven at 105 ºC for 24 hours.

Bulk density, micro porosity, water absorption and void ratio were determined for different aggregates obtained from the following materials: expanded clay – LECA (Figure 1), pozzolana and granite (Figure 2) – and geopolymeric waste mud (Figure 1) Bulk density, water absorption (in % of dry mass) after immersion for 24 hours (WA24) of WGA aggregates was determined in accordance with EN1097-6, used for concrete aggregates. Void ratio was calculated in accordance to EN1097-3. The bulk density of expanded clay, pozzolan and granite gravel was determined using a helium pycnometer.

Figure 1. Artificial aggregates: WGA (left) and LECA (right).

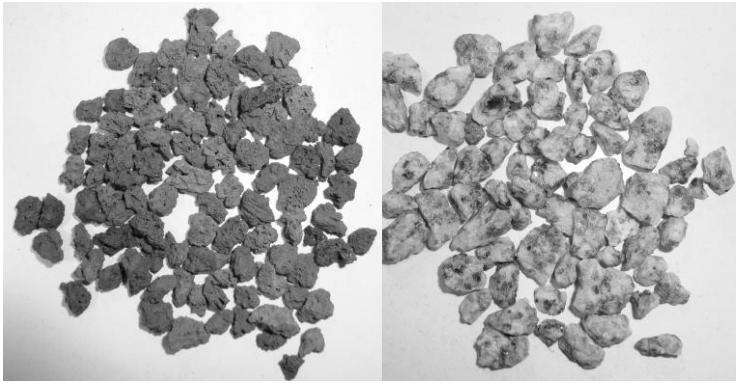

Figure 2. Natural aggregates: pozzolan (left) and granite (right).

Regarding micro porosity of different materials, it was study by mercury porosimetry. It is a well known technique that gives pore size distribution in solids, by determining the volume of mercury penetrated into the sample, which varies with increasing pressure applied. By mercury porosimetry it is possible to obtained total pore volume, material volume and density, interstitial, percent porosity, pore volume distribution by pore size and pore area. In this study, a mercury porosity model PoreSizer 9500 V1.07 (Micrometics, UAE) was utilized and samples of WGA with 35 days curing at 20°C, granite gravel, pozzolan, and granite gravel, were tested.

3. RESULTS AND DISCUSSION

3.1 Structural stability control of WGA aggregates and pH alteration in water

According to the Portuguese Law 236/98 (Water quality) the pH of treated wastewater at the discharge point should not be higher than 9. Thus, the number of days needed to obtain a pH value lower than this value was registered for all WGA aggregate samples (pH = 8 was adopted, instead of 9 to increase reliance of results in this study).

It was considered that most suitable WGA aggregates for wastewater treatment processes are the ones that quicker lower down the water pH to values below 8 and maintaining its structural stability in water. The mix that reached the objectives was mixed with the ratios of mining waste mud/Na2SiO=5 and Na2SiO/NaOH = 4 and cured at 20 °C for 35 days.

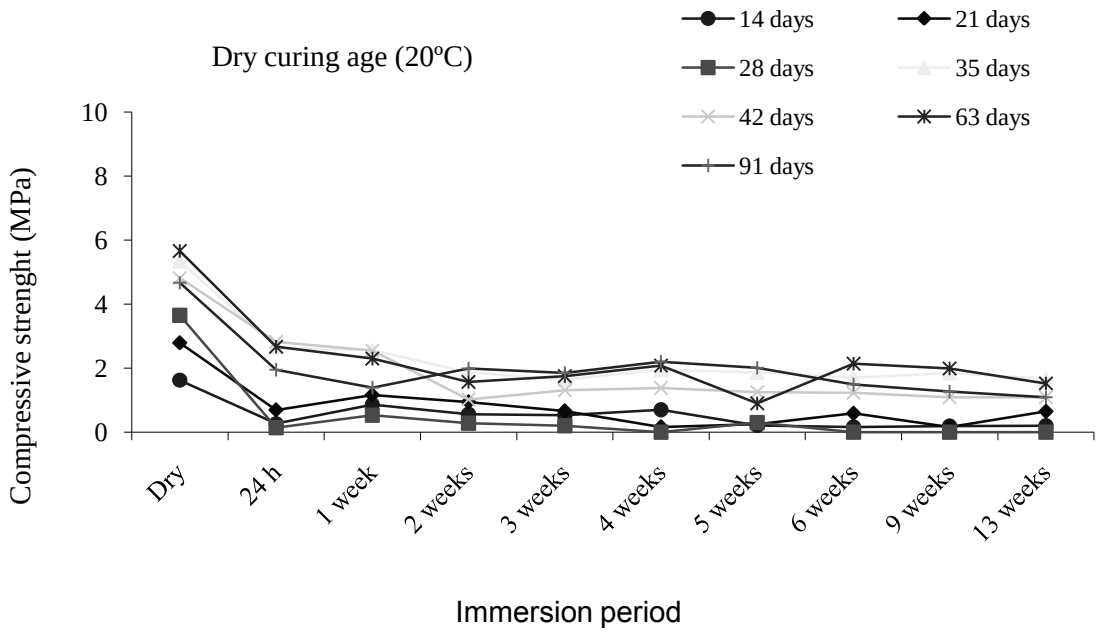

Figure 3 Compressive strength over water immersion period for curing temperature of 20ºC.

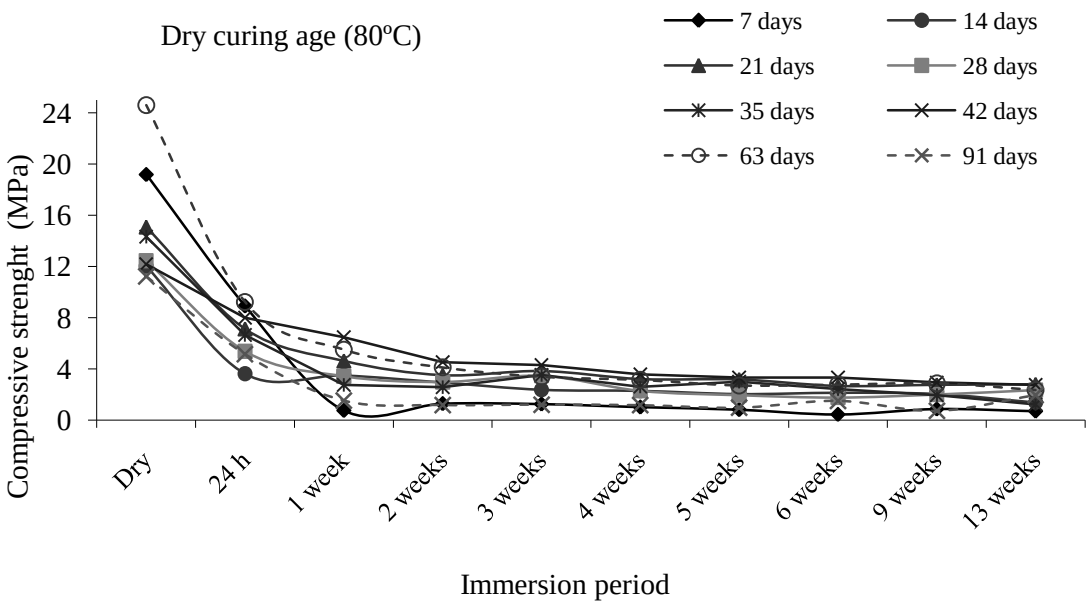

Figure 4. Compressive strength over water immersion period for curing temperature of 80ºC.

In the second stage (as referred in 2.1), regardless the curing temperature and curing age, compressive strength reduced to approximately half of initial values (dry conditions) after 24 hours of water immersion (Figures 3 and 4). The decrease in strength continued during the first 4 weeks of immersion, stabilizing most of samples after that period of time between 1 MPa and 2 MPa. In samples cured at 20ºC for longer dry curing ages (91 days) the values stabilized between 2 MPa and 3 MPa after 6 weeks of immersion. These results show that water curing

leads to a strength decrease of WGA as also observed by Kirschner et al. 2004 for alkali-activated metakaolin. Water in excess seems to have affected the hydrolysis species and, therefore, hinders polycondensation kinetics, leading to molecular destabilization of the geopolymer matrix. Additionally, alkali ions have leached out from surfaces of geopolymers leading to pH rising, which may have contributed for a slow compressive strength development.

The compressive strength after immersion stabilized around 1-2 MPa similar to the values presented by LECA (1.7 MPa), which needs high temperatures to be produced. Obviously, granite aggregates can present a high compressive strength (up to 120 MPa).

By comparing compressive strength, WGA aggregates are still advantageous over the other two materials, since are obtained from wastes (i.e. promotes the reuse of waste mud from mine activities), produced at low temperature, presenting good stability in water and not changing significantly its characteristics, are potentially more durable and, therefore, may have the same effectiveness of other materials for pollutant removal from wastewaters (not yet verified).

3.2 Bulk density, micro porosity, durability, water absorption, void and resistance to weathering and disintegration

Although water curing leads to a strength decrease of WGA, the slake-durability test in wet conditions showed that dried aggregates can be marked as “medium – high durable” and the material loss is more significant if the sample has already been immersed (table 1). When sample was already immersed and dried before the test, the proportion of retained material decreases and the rating for durability is “medium – low”.

Table 1. Slake durability index based on a single wet cycle, I_{d1} (%).

WGA	I_{d1} (%) retained material	Durability
Dry	81,9	medium – high
Dried after soaking in water	70,9	medium – low

In the table 2 and 3 are presented materials physical properties most relevant for waste water treatment processes. One can observe that LECA bulk density is lowest value, WGA and pozzolan present medium values, and granite has the highest value.

On the other hand, total pore area is highest for LECA while WGA presents a lower value than LECA and granite gravel has a much reduced total pore area. In the materials studied, higher bulk density corresponds to lower total pore area and porosity. Average pore diameter varies in the same way with bulk density.

Table 2. Materials physical properties.

Materials	Bulk Density kg/	Water absorption (%)	Void ratio (%)	Particle diameter (mm)
LECA	320	11	46	2-10
WGA	1625	20	42	10 - 20
Pozzolan	2360	14	42	3-6
Granite gravel	2640	0,4	39	5-20

Table 3. Internal porosity.

Materials	Total Pore Area (m^2/g)	Average pore diameter (Angstron)
LECA	6,370	6400
WGA	2,370	3580
Pozzolan	0,920	3470
Granite gravel	0,053	2130

Physical properties results indicate that geopolymeric aggregates presents good characteristics for use as bed material in fixed-film wastewater treatment processes.

Ongoing preliminary tests, that will be described elsewhere, have already showed that WGA particle diameters between 2 and 10mm are adequate for development of biofilm. Furthermore, since particles are of similar size the risk of clogging is lower. Thus, the percentage of void ratio is appropriate and the bulk density is not very different of other alternative materials.

LECA and WGA are the materials having higher values for total pore area and average pore diameter, which is an important parameter to obtain a good adhesion and development of biofilm, essential for pollutant removal.

4. CONCLUSIONS

The results showed that WGA presents good stability in water, does not change significantly the characteristics of water, and is durable and the compressive strength decreased over time after immersion in water, but it was still appropriate for biofilters

The bulk density, microporosity, durability, water absorption and void ratio seem to be suitable for a good adhesion and development of biofilm, essential for pollutant removal.

From an economic point of view, a WGA cured at 20ºC it is more advantageous since it presents low energy consumption and greenhouse emissions when compared to that in its expanded clay cooking reaches temperatures of 1200 º C

Additionally, the use of mining wastes to produce artificial geopolymers for FF-WWTP may bring the following advantages: production of recycled aggregates for water pollution control, minimization of environmental impacts associated to mining wastes, and reduction of land deposits of mineral wastes.

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Embodied energy optimization by innovative structural systems

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ABSTRACT: Motivated by the first oil-crisis in 1973 most countries have implemented building codes for insulation standards, resulting in a massive saving of energy for operation – heating, cooling and domestic services. Technological development in HVAC-systems and sealing methods has enabled a decrease in buildings' operational energy consumption to very low levels up to the extend known as passive-house projects. These changes have induced the relevance of widening the scope of energy saving from a former exclusive focus on operational energy in the use phase to the inclusion of embodied energy. The reduction of the embodied energy means an optimized utilization of materials and related energy during their entire life cycle.

In this respect this contribution focuses on a latest development for large span floor solutions, the "Composite Slim-Floor Beam" (CoSFB). Slim-Floor construction is characterized by integrating the principle steel beam into the floor with the advantages of low construction height as well as quick erection due to the use of prefabricated slabs. The new development, the CoSFB, combines the advantages of Slim-Floor with the ones of composite construction - stiffness, robustness, durability, easy erection and large spans - leading to high flexibility and multifunctional buildings. The span of traditional non-composite Slim-Floor Beams is limited to +/- 8m; with the CoSFB clear spans up to 14m with a beam distance of 10m and an overall construction height of only 40cm are achievable. In addition to enlarged spans and a reduced use of raw materials the CoSFB incorporates an integrated fire resistance due to the composite design. The fire resistance class R120 can be achieved without passive fire protection measures like board claddings, reactive (intumescent) fire protection systems or spray protection. Further the innovative CoSFB is ending up in less columns and larger spans and offers more flexibility in use and re-use. In addition, less construction weight leads to additional benefits as reduced column sizes, smaller foundations and less material transports to job site. In this paper the sustainable benefits of the CoSFB system are proven by design examples for typical grids (ULS and SLS design) including the verification of the vibration comfort. By explicitly presenting the gain in reduction of embodied energy consumption it is outlined, how the use of high performance materials and high quality engineering can contribute to reducing CO_2-emissions and primary energy consumption and to achieve the goals set in the Kyoto protocols.

1 LIFE CYCLE ASSESSMENT

1.1 *General*

Life cycle assessment is the analysis of the potential environmental burdens of a product or service in its production, use phase and disposal (end of life). Especially for buildings various labeling systems for the interpretation of the life-cycle assessment results in terms of ecological or even sustainable quality have been developed in the recent years [Hauke et al 2010]. They provide ratings based on the evaluation of different requirements concerning the environmental performance of the buildings. As internal benefits from an environmental assessment they promise the detection of strategic risks and environmental issues, development of sustainable products

based on environmental information (Ecodesign) and the communication with politics and authorities. As external benefits the improvement of the image due to ecological considerations, the support of environmental innovations and decrease of environmental impacts as well as the competitive advantage by inclusion of the environmental aspects are listed. Overall the investor considers the life cycle assessment of his buildings to assure a sustainable and long-term value creation and investment stability.

A full Life Cycle Assessment (LCA) is a Cradle-to-grave investigation from manufacture ('cradle') over use phase to disposal phase ('grave'), including end-of-life scenarios e.g. recycling of construction materials. All inputs and outputs are considered for all phases of the life cycle. For buildings, 50 years of design life are generally imposed - so far, it has been assumed, that ca. 80% of the energy input and emission arise in this use phase (service life).

However, motivated by the first oil-crisis in 1973, most countries have implemented building codes for insulation standards, resulting in a massive saving of energy for operation – heating, cooling and domestic services. Technological development in HVAC-systems and sealing methods has enabled a decrease in buildings' operational energy consumption to very low levels up to the extend known as passive-house projects. These changes have induced the relevance of widening the scope of energy saving from a former exclusive focus on operational energy in the use phase to the inclusion of process energy – i.e. energy for mining, processing, transportation, assembly and building site operations [Hechler 2010]. Three significant challenges evoke from this perspective:

1. Sophisticated integral building management combined with high quality cladding systems as well as optimally tailored thermal mass and minimal weight for reducing the embodied energy should be designed; for this purpose advanced, cost-effective solutions combining structural steel with concrete (ca. 10-14cm concrete slab are sufficient for passive thermal activation [corusconstruction 2010]) have already been developed. Hereby the use of high strength materials (e.g. S460 steel and higher strength concrete) should be focused on.
2. Disassembly methodologies must be developed and employed in contemporary building practice in order to enable future reuse of building parts with the lowest possible consumption of energy for transformation.
3. The understanding of buildings' structures as a capital amount of embodied energy certainly includes the existing building stock, and hereby the relevance of treating construction wastes in an upgrading process similar to the processing of virgin mining resources.

In this paper the reduction of embodied energy is focused. As LCA functional unit for comparison two slab systems have been identified: grid 1) is supposed to cover the standard grid requested by the market of today and grid 2) provides a competitive and promising outlook to on the future trend in ground floor design using the potential of the latest structural technique. The life-cycle inventories used in the LCA are listed in the following chapter to allow for neutral comprehension and reproduction of the evaluation results.

1.2 *Life-cycle inventories used in the LCA*

For the LCA, Life Cycle Inventories (LCI) are required which provide information on the materials and energy flows during their entire life. In a first step, process structures are modeled in order to have a basis for assembling data. The material and energy flows are determined as input-/output-sizes for every partial process with regard to the system boundary. By connecting all partial processes, the relations between the modules and the environment are represented, and the mass/energy balance is drawn up as the inventory of the total system. All material and energy streams which pass the system borders are listed as quantities in physical units. The data refer to the functional unit. For steel, the LCI from WorldSteel [WorldSteel 2010], for concrete the inventories provided by ECOINVENT for a standard concrete have been chosen.

Hereby the following end-of-life scenario for steel and concrete products has been used based on [Hettinger 2010]:

- 99% recovery rate for structural steel whereas 1% is lost and goes to landfill;
- 35% of reinforced concrete is directly landfilled - thus embedded rebars are also 100% landfilled;
- 65% of reinforced concrete is sorted: rebars are separated from concrete - it is assumed, that 100% of the sorted rebars are recycled;
- For concrete, it has been considered that after the sorting plant, 15% of concrete is valorised and 85% is disposed.

The Global Warming Potential impacts resulting from Life Cycle Inventories used within this study are detailed in Table 1.

Steel and concrete elements are assumed to be transported by truck only, either regular truck for steel elements and prefabricated concrete, or mixer truck for ready mixed concrete. The consumption linked to transportation is calculated taking into account partial load and empty return trips [INRETS]. Steel elements are supposed to be transported on an average distance of 1000km, and prefabricated concrete on 500km. Concerning on-site concrete, a short transport distance of 50km for the ready-mixed concrete is assumed. The origin of the different parts (cement, water granulates, etc.) has not been taken into account for the analysis.

Other information (fuel production, emissions linked to transportation, etc.) is provided by the models of the consulting group PE International [PE 2006].

Table 1. List of data and sources for steel products.

Process	LCI associated	Data source	GWP Production [kg CO_2-eq/t]
Production and recycling of steel profiles	WO-Sections – 99%	[WorldSteel 2010]	930
Production and recycling of shear studs	WO-Rebars – 99%	[WorldSteel 2010]	830
Production and recycling of steel end plates	WO-Plates – 99%	[WorldSteel 2010]	1073
Production and recycling of reinforcement	WO-Rebars – 65%	[WorldSteel 2010]	1348
Production of concrete	"Concrete, normal, at plant"	[ECOINVENT 2007]	112
	and "concrete exacting, at plant"	[ECOINVENT 2007]	135
	Linear regression for 350 kg/m3		128
Production of diesel	Diesel, at refinery	[PE / ELCD 2003]	375
Emissions - fuel combustion	truck-trailer 28-34to total / 22to payload / EURO3	[PE 2006]	3183
Separation of concrete and reinforcement	disposal, building, reinforced concrete, to sorting plant	[ECOINVENT 2002]	61
Landfill of reinforced concrete	disposal, building, reinforced concrete, to final disposal	[ECOINVENT 2002]	67
Landfill of sorted concrete	disposal, concrete, 5%water, to inert material landfill	[ECOINVENT 1995]	7
Valorization of crushed concrete	gravel, unspecified, at mine	[ECOINVENT 2001]	3

2 SUSTAINABILITY OF MODERN SLIM-FLOOR CONSTRUCTION

2.1 *Demands on modern floor systems*

Sustainability is not only of environmental nature (climate effects, wastes (= landfill), energy consumption, raw material consumption, recycling). In addition economic (life cycle costs, maintenance, value preservation, functionality, flexibility, reusability = reconstruction) and social demands (health and safety, comfort, aesthetics, urban redevelopment) are to be considered and assessed.

Consequently sustainable floors need to fulfill the demands for ecologic, economic and social sustainability [Maydl, Passer, Cresnik 2007]. Thus modern floor design is more than designing for sufficient load bearing resistance at room temperature and in fire situation only. A floor has to be also designed for today customer requirements – especially vibration comfort and heat and sound insulation. Nonetheless a floor has to be economic and cost-effective in construction due to quick erection and availability in short delivery time. The high degree of prefabrication assures further increases safety on the construction site during erection and in the final state due to quality control in the shop.

Besides modern floor design has to take into account future use. As we are normally not able to predict the future, the floor construction (and ground floor design) must be easy adaptable to future customer expectations – with this flexibility and reuse potential the investment itself becomes sustainable. Further maintenance and enhancement of e.g. installation services, should be feasible and as easy as possible.

These additional demands are requesting the design of enlarged spans and reduced column quantity in conjunction with slender slabs with few limitations for service installations. In the following chapter, a floor system is presented fulfilling all the above described criteria: the combination of slim-floor construction with composite beam design – the CoSFB. It is representing a sustainable, re-usable and economic floor system with an enormous future potential in sustainable construction.

2.2 *State-of-the-art in slim-floor construction – the CoSFB*

Slim-floor construction is characterized by the integration of a steel beam into the slab. The steel section consists of a hot rolled beam with a welded plate. To facilitate the erection, the width of the plate is larger than the flange of the hot rolled section, so the slab elements can easily be placed. The SFB (slim-floor beam) can be combined with any kind of slab. Prefabricated or partially prefabricated concrete slab fits perfectly to SFB; a safe and quick erection is assured. By using this construction system the construction thickness of the floor is reduced and thus the overall height of the building or, by keeping the building height as constant, the total quantity of floors can be increased. The technical installations (e.g. heating and cooling devices) are installed very quickly due to the absence of down standing beams. Therefore both processes are also independent in the designing phase. However, because of the small beam height, the design of a slim-floor beam is governed by the stiffness of the system and thus spans are limited.

A nice example of Slim-Floor construction is the 11000m^2 office building “Espace Pétrusse” in Luxembourg (EPL) designed by the architect Marc WERNER, built from CDC in 2006, see Figure 1 to Figure 3. The main arguments to choose the SFB solution have been: reduction of the overall building height, decrease of the foundation reaction forces (the building was built above an existing underground parking – 2 additional floors could be constructed because of the “light” system), increased erection speed (1000m^2/month) and fire resistance w/o passive protection (R90).

Fig. 1: EPL

Fig. 2: EPL – SFB and Cofradal

Fig. 3: EPL – Ground floor design

For this application, the potential to use composite action in slim-floor construction has been evaluated for the first time – although SLS design has only been focused. Based on the experience by this project it has been identified, that to increase the stiffness and fulfill the demand to large spans, a new slim-floor beam needed to be developed - the CoSFB, see Figure 4. The CoSFB combines the advantages of composite construction (stiffness, robustness, durability,

easy erectable, large spans) with the advantages of slim floor construction (low construction height, quick and safe in erection due to the use of prefabricated slabs). The aim is to assure the composite action without increasing the construction height. Therefore the use of standard shear studs welded on the upper flange is not appropriate, horizontal studs welded on the flange of the section activates not enough shear resistance. The innovative CoSFB solution, developed by ArcelorMittal in close cooperation with the University of Stuttgart/Germany, therefore uses concrete dowels to achieve a controlled shear transmission between the steel section and the concrete chord, see Fig, 4. These dowels are openings in the web penetrated by reinforced concrete. The resistance of the dowel is depending on the projection area of the compressed steel surface from the opening in the concrete chord and the 3-dimensional stress state concrete resistance activated. Concrete dowels are ductile and able to transfer 100% of the shear forces between concrete and steel without increasing the overall construction height. For the design of the dowel and further information it is references to [Hechler, Braun 2010].

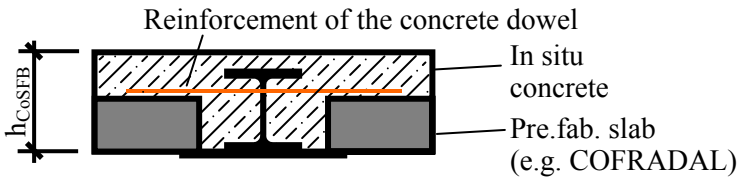


Fig. 4: Typical CoSFB section

Thanks to the increased stiffness, large span slim-floor construction is possible by respecting the deflection limitation and the vibration comfort. The typical application range for CoSFB is beam span from 8m up to 14m with a beam distance between 4m and 10m. The typical slenderness (span CoSFB / h CoSFB) of CoSFB construction is 35. Main advantages of the CoSFB construction are:

- quick and safe in erection,
- less columns and larger spans offer more flexibility in use and re-use,
- less construction weight leads to additional benefits as columns size, smaller foundations, fewer material transports to job site.

In addition CoSFB has an excellent behavior under fire conditions. The fire resistance class R120 can be achieved without passive fire protection measures (e.g. intumescent paint, spray protection or fireproof board).

CoSFB leads to an economic and flexible construction and fulfils the requirements for sustainable structures with efficient use of raw material in combination with light and slender members.

3 LIFE CYCLE ASSESSMENT OF GROUND FLOOR DESIGNS

3.1 *Introduction*

The structural performance of the CoSFB has been proven to be significantly improved compared to conventional slim-floor construction, thus leading to more economic and slender slab systems [Hechler, Braun 2010]. Further the overall flexibility completes the requested demands on economic and social sustainability. Although the environmental performance has not yet been assessed for the CoSFB system. To complete the integral sustainability assessment this paper consequently focuses on the life-cycle assessment of the CoSFB slim floor solution. As LCA functional unit for comparison two slab systems have been defined: 1) grid 8.1m x 8.1m (chapter 3.2) and 2) grid 12m x 8.1m (chapter 3.3). The grid 1) is supposed to cover the standard grid requested by the market of today. Grid 2) provides a competitive and promising outlook on the future trend in ground floor design using the potential of the latest structural technique. Grid 2) has been chosen with specific view on the demands listed in chapter 2.1.

For evaluation, results of the life-cycle assessment of the CoSFB solution are compared to results of cast in-situ flat concrete slab solutions. The related calculations for each grid and the outcome of the study are summarized in the following.

3.2 *Grid 8.10m x 8.10m*

To evaluate the environmental performance of the CoSFB + Cofradal 260 system, the Global Warming Potential (GWP = CO_2 equivalent) and the Primary Energy Consumption (PEC) for a typical 8.10m x 8.10m grid (functional unit) is calculated, see Fig. 5 and 6. The most important design results are presented in Fig. 7 (L = Beam Span; a = Beam Distance; DL = Dead Load; LL = Live Load).

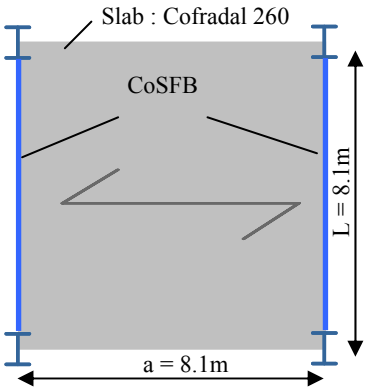
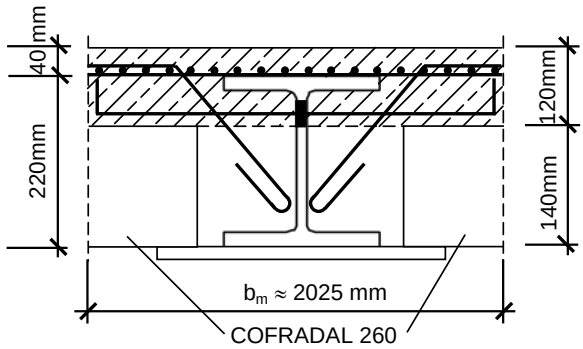
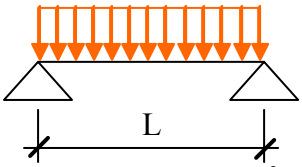


Fig. 5: Grid 8.10m x 8.10m



Steel section – HE220B, S355M + Plate 400x20, S355
In situ concrete C30/37

Fig. 6: Section CoSFB



DL slab = 2.80 kN/m^2
Additional DL = 1.70 kN/m^2
LL (cat. B) = 2.50 kN/m^2
Partition wall = 1.00 kN/m^2

Bearing Resistance, ULS: q_d = 98.5 kN/m
M_{Ed} = 810 kNm < $M_{pl,Rd,red,CoSFB}$ = 880 kNm
($M_{pl,Rd,red,SFB}$ = 350 kNm)

Deflection and natural frequency, SLS: q_k = 69.8 kN/m
$I_{y,0,CoSFB}$ = 43900 cm^4, effective width b_{eff} = L/4 ≈ 2.00 m,
Deflection δ_0 = 4.2 cm ≈ L/200,
Natural Frequency f_0 = 3.3 Hz > 3 Hz
Fire resistance of the CoSFB: R60 (w/o add. measures)

Fig. 7: Application Example – CoSFB + Cofradal 260

The GWP and PEC of the CoSFB system above is compared to a cast in-situ flat concrete slab (slab thickness 27cm + 5cm floating screed, C30/37, reinforcement ratio 41.5kg/m^2), see Fig. 8. The calculation is performed with the AMECO software [CTICM 2010]. AMECO Software calculates environmental impacts of buildings and bridges made of steel and concrete. GWP and PEC are expressed for production phase as well as for transportation and End-of-Live.

Cast in-situ flat concrete slab		CoSFB + Cofradal 260 slab	
Total volume of concrete:	21.0 m^3	Total volume of concrete:	7.55 m^3
Total mass of concrete:	50.8 to	Total mass of concrete:	18.3 to
Total mass of reinforcement:	2.85 to	Total mass of reinforcement:	1.11 to
		Total mass of the C260 sheet:	0.79 to
		Total mass of the CoSFB:	1.09 to

Life Cycle Assessment - Synthesis

Impact of ..	GWP [to Co_2-eq]	PEC* [GJ]	GWP [to CO_2-eq]	PEC* [GJ]
Production	10.04	83.82	6.99	64.46
Transport	0.26	4.840	0.17	3.260
End of Life	1.18	21.64	-0.77	-1.530
Total	11.49	110.3	6.38	66.19

Fig. 8: GWP and PEC comparison – Key figures
* Only non renewable energy mix has been taken into account.

3.3 *Grid 12.00m x 8.10m*

The CoSFB system is flexible to be combined many different slab products. This example shows the combination of CoSFB with a typical steel shuttering, the Cofraplus 220. Design results, GWP and PEC values for a 12m x 8.10m grid are given in the following.

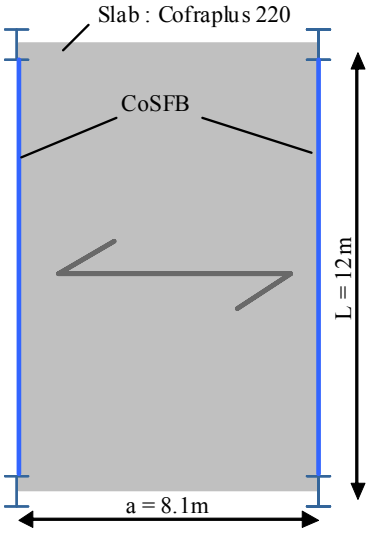
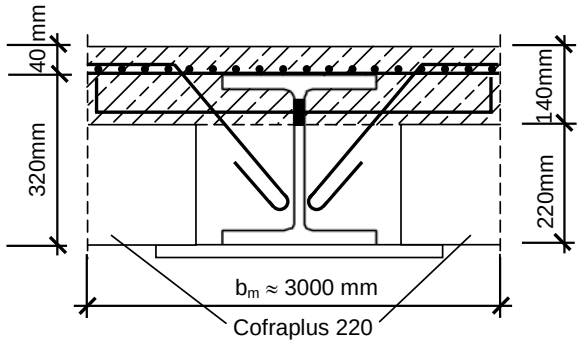
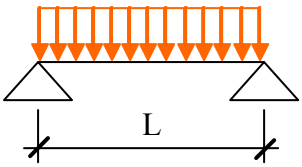


Fig. 9: Grid 12.0m x 8.10m



Steel section – HE260B, S355M + Plate 500x30, S355
In situ concrete C30/37

Fig. 10: Section CoSFB



L = 12.00 m, a = 8.10 m
DL slab = 2.80 kN/m^2
Additional DL = 1.70 kN/m^2
LL (cat. B) = 2.50 kN/m^2
Partition wall = 1.00 kN/m^2

Bearing Resistance, ULS: q_d = 116.5 kN/m
M_{Ed} = 2097 kNm < $M_{pl,Rd,red,CoSFB}$ = 2300 kNm
($M_{pl,Rd,red,SFB}$ = 910 kNm)
Deflection and vibration, SLS: q_k = 83.2 kN/m
$I_{y,0,CoSFB}$ = 162400 cm^4, effective width b_{eff} = L/4 = 3.00 m,
Deflection δ_0 – camber = 5.4 cm ≈ L/220,
Natural Frequency f_0 = 2.6 Hz < 3 Hz
⇒ check of OS-RMS$_{90}$ value [Feldmann et al 2008]
⇒ OS-RMS$_{90}$ = 2.20 < 3.20 = class D
⇒ Comfort for office use is assured!
Fire resistance of the CoSFB: R60 (w/o add. measures)

Because of a modal mass of more than 36.000 kg, the velocity and the acceleration of vibrations induced by normal walking are absolutely within the acceptable range for office use!

Fig. 11: Application Example – CoSFB + Cofradal 260

The GWP and PEC of the CoSFB system above is compared to a cast in-situ concrete slab supported by concrete beams (slab thickness 30cm, C30/37, reinforcement ratio 35kg/m^2). The calculation is performed with the AMECO software [CTICM 2010].

Cast in-situ flat concrete slab		CoSFB + Cofraplus 220 slab	
Total volume of concrete:	30.6 m^3	Total volume of concrete:	16.4 m^3
Total mass of concrete:	74.1 to	Total mass of concrete:	39.7 to
Total mass of reinforcement:	3.67 to	Total mass of reinforcement:	2.22 to
		Total mass of the C220 sheet:	1.59 to
		Total mass of the CoSFB:	2.94 to

	Life Cycle Assessment - Synthesis			
Impact of …	GWP [to Co_2-eq]	PEC* [GJ]	GWP [to CO_2-eq]	PEC* [GJ]
Production	14.04	114.3	15.09	139.8
Transport	0.50	8.482	0.26	5.910
End of Life	1.66	30.77	-1.60	-2.787
Total	16.19	153.5	13.76	142.9

Fig. 12:GWP and PEC comparison – Key figures
* Only non renewable energy mix has been taken into account.

4 ASSESSMENT RESULTS AND CONCLUSIONS

The environmental impact of CoSFB slab systems and traditional slab systems has been quantified for two grids, 8.1m x 8.1m and 12m x 8.1m. The subsequent LCA of both grids and systems clearly outlines the outstanding environmental performance of the CoSFB system hereby. Compared to the traditional concrete solution a reduction of the GWP by 40% can be achieved. Detailed cost analysis further showed, that even the costs for CoSFB slab systems are lower than for traditional slabs [Birarda et al 2011]. In fact, the combination of CoSFB with partially prefabricated slabs is a very good answer to customer needs and expectations, today and in the future. Because of ongoing discussions about the fire safety of pre-stressed hollow core slabs, they are however excluded in this assessment - even though it has to be stressed, that the CoSFB can achieve the fire resistance class R120 without passive fire protection.

Further to the reduced embodied energy in the building, steel structures are built with a high degree of prefabrication/offsite manufacture with quality control in the shop. Thus, construction sites are optimized with an enhanced safety, reduced lead times, transportation, neighborhood nuisance and environmental impact (dust, water). In design and service life the slenderness for both, columns and beams with long spans, are a major advantage for steel construction. Moreover, with slim-floor systems, shallower construction height result in either higher floor space indexes associated with less land use and/or less façade surface area achieving less heat emission and therefore reduced energy consumptions of the building. The benefit of long spans is the creation of versatile spaces capable of change over time and the adaption to user's requirements. With the CoSFB slim-floor system the construction is even able to be adapted to changes in the service installations. Further steel structures are prefabricated systems from components which incorporate an ease in maintenance and the flexibility to be extended or modified. The comfort and well-being of the user therefore depend only on the thermal design of the façade and the interior design of the floors, provided with a long-lasting aesthetics as steel is environmentally inert and a durable material. In the end-of-life phase steel structures are easy to dismantle; the steel components are either reusable or recyclable economically indefinitely without quality loss.

Overall it is concluded, that the embodied energy in the construction materials is and will be even more influencing the environmental performance of buildings. Therefore reduction on mass thus lighter buildings will generally lead to more sustainability. Here the use of high performance materials and high level of engineering is of major importance. Today and in the future, engineering will make the difference – the CoSFB herefore provides an evidence.

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Development of a Universal Scissor Component (USC) for Temporary Structures

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ABSTRACT: Structures that can adapt their shape to respond to varying circumstances, or that can be quickly and easily deployed to perform their architectural function and removed afterwards without damaging sensitive sites, are well-equipped to meet the demands of a dynamic society which embraces the concept of sustainable design.
Deployable scissor structures consist of beam elements connected by pivot joints, allowing them to be folded into a compact bundle for storage or transport. Subsequently, they are deployed, demonstrating a huge volume expansion. This process can be reversed, allowing re-use.
The purpose of this paper is to explore the development of an innovative multi-configurational Universal Scissor Component (USC) for use in mobile architectural applications. The component, single and unique, allows the design of scissor structures in a generic way. It is used to compose different geometrical configurations and can be reconfigured and re-used to meet changing requirements (cfr. Meccano toy construction system).

1 INTRODUCTION

1.1 *Transformable structures*

4D design (four-dimensional design) entails a design attitude in which *time* is explicitly included from the earliest stages of conception. So, besides the 3-dimensional space, the fourth dimension becomes a determining design parameter. The structure is transformable over time and can be described as being relocatable, reuseable, demountable; the building components can be reconfigurable, removeable, replaceable, etc. Temporary structures which have this transformational capacity, and are lightweight or easily removeable, have a lower impact on the site which makes them ecologically favourable. Generally, sustainable design can interact on one or more of three levels: (1) *material* (e.g. recycling, up-or downcycling), (2) *component* (e.g. re-use, reconfiguration), (3) *structure* (e.g. retrofitting, flexible renovation with infill).

In this research, focusing on the component level, the methods used for implementing transformation are *kit-of-parts systems* and *structural mechanisms*.

1.1.1 *Kit-of-parts systems*

This concept relies on the philosophy of designing and building like a 'meccano' system with dry, reversible connections allowing a gradual transformation of the structure over time (Figure 1). Only a few components are used as the basic building blocks, but with the possibility to compose a myriad of configurations (cfr. Lego system).

A generative dimensioning system is used as an underlying geometric grid and guarantees that existing and future components will be compatible with the system.

1.1.2 *Structural mechanisms*

With the introduction of a mechanism into a structural system, it is equipped with the ability to transform from a small, closed or stowed configuration to a much larger, open or deployed configuration (Figure 2). The obtained structures are generally referred to as deployable structures, with can transform instantaneously (Jensen, 2004).

Deployable structures are characterized by their dual functionality as load-bearing structures or mechanisms. As load-bearing structures they transfer live and dead loads. As mechanisms they provide the reversible alteration of their form (Rückert, 2000). They provide the built environment with structures which meet changing demands and can adapt to altered boundary conditions.

Although the research subject of deployable structures is relatively young, the principle of transformable objects and spaces has been applied throughout history (the Mongolian yurt, the pantographic weightlifting crane of Leonardo da Vinci…). Nowadays, the main application areas are the aerospace industry, requiring highly compactable, lightweight payload (solar arrays), and architecture, requiring either fixed-location retractable roofs for sports arenas (Wimbledon) or mobile, lightweight temporary shelters (emergency tents and recreational structures).

Generally, mobile deployable structures consist of a weather protecting membrane supported by some form of erectable structure, which is capable of easily being moved in the course of normal use and can be assembled at high speed, on unprepared sites. For this purpose, scissor structures are most effective: besides being transportable, they have the great advantage of speed and ease of erection and dismantling, while offering a huge volume expansion (De Temmerman, 2007).

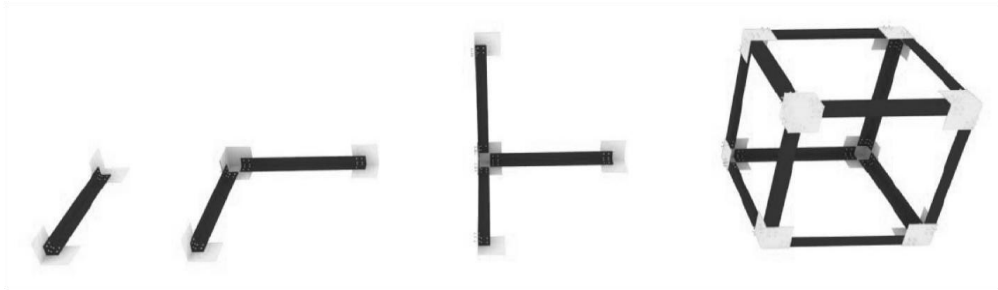

Figure 1. Example of a kit-of-parts system (© Michael Lefeber)

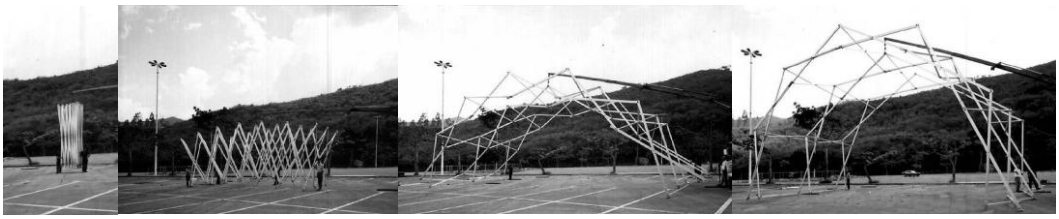

Figure 2. Example of a deployable scissor structure (© Grupo Estran)

1.2 *Innovative transformable construction system: meccano and mechanism*

In this paper, an innovative construction system for deployable scissor structures is explored, based on two levels: (i) the reuse of a *structure* and (ii) the possible reconfiguration of its constitutive *components*. While current designs of scissor systems give an 'ad hoc' solution, this research can provide a methodology for designing a unique scissor component resulting in generic structures. The designed scissor component can be used in a vast number of different configurations and can thus be re-used meeting changing requirements. In this way, the Universal Scissor Component combines the two aspects *kit-of-parts* and *structural mechanism*.

2 SCISSOR UNITS

Scissor units, also called scissor-like elements (SLE's) consist of two beams connected through a revolute joint, the intermediate hinge, allowing a relative rotation, but at the same time introducing bending moments in the beams. By connecting such SLE's at their end nodes by hinges, a grid structure is formed, which can be transformed from a compact bundle of elements to a fully deployed configuration. Finally, by adding constraints, the mechanism goes from the deployment phase to the service phase, in which it can bear loads.

Depending on the location of the intermediate joint and the shape of the beams, three main unit types can be distinguished: translational, polar and angulated units (Figure 3, 4 and 5).

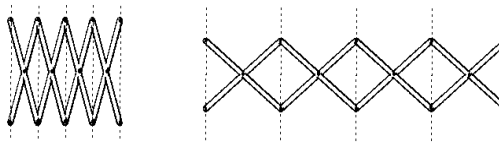

Figure 3. Translational linkage. (Alegria Mira, 2010)

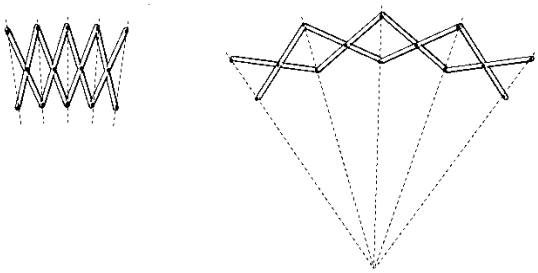

Figure 4. Scissor structure of polar units. (Alegria Mira, 2010)

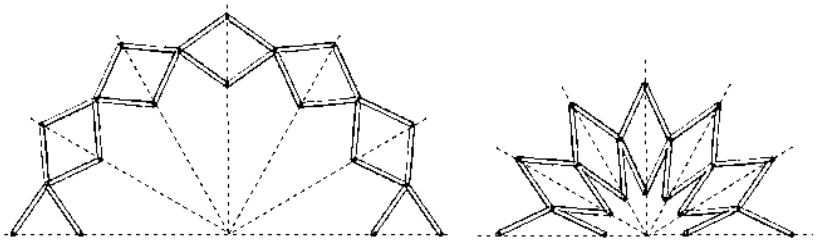

Figure 5. A radially deployable linkage consisting of angulated scissors with kinked beams. (Alegria Mira, 2010)

3 DEVELOPMENT OF A UNIVERSAL SCISSOR COMPONENT (USC)

3.1 *Configurations of the structures*

To determine the geometrical dimensions of the USC, a closer look has to be taken which configurations of structures to consider. Deployable structures with a function of a temporary shelter are expected to enclose a three-dimensional space (Escrig, 1985; Escrig & Valcarel, 1993).

3.1.1 *Barrel Vaults*

To perform an architectural function (providing weather protection) a barrel vault is a simple, but effective typology. Barrel vaults or cylindrical grids are monoclastic shapes. They can be obtained by curving one direction of an orthogonal two-way grid.

Using polar units is an effective way of introducing single curvature in an orthogonal grid as shown in Figure 6.

- direction X, or transverse direction, contains rows of identical polar units in arch formation
- direction Y, or longitudinal direction, contains parallel rows of identical translational units connecting the polar arches

Figure 6. Perspective view of a barrel vault. (Alegria Mira, 2010)

3.1.2 *Domes*

Besides the simple but effective barrel vaults, also dome geometries are considered in this research. Domes are not only architecturally and structurally viable structures, they can also serve as a geometric transition to more exotic and interesting shapes thanks to angulated elements.

To minimize distortion of two- or three-way grids over a sphere, polyhedra can be used. A selection is made of polyhedra with an equal edge length, because an identical USC in the whole global structure is the starting point. The selection results in a multitude of different geometries for the investigated architectural dome structures. The following polyhedra are considered: icosahedron, dodecahedron, icosidodecahedron, 'buckyball' (truncated icosahedron) and an adjusted rhombic triacontahedron.

A dome structure, independent from the considered polyhedron, is made deployable by substituting every edge of the polyhedron by scissor elements. For this purpose angulated scissors are implemented because of their beneficial properties, such as the ability to develop a more stabile deployment process for shapes capable of retracting towards their proper perimeter. Figure 7 shows how the adjusted rhombic triacontahedron forms the basis of a deployable dome using angulated scissors.

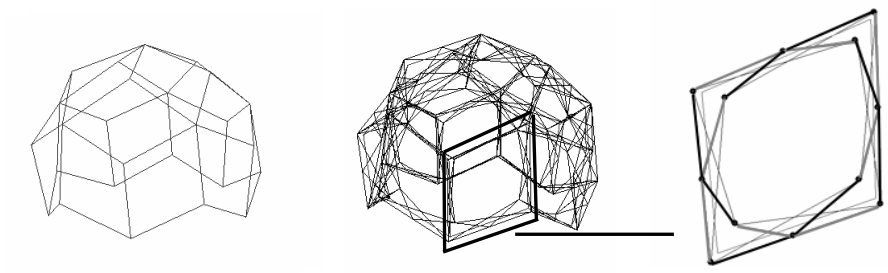

Figure 7. The adjusted rhombic triacontahedron - deployable dome structure with scissor elements – detail of edge replacement by angulated units. (Alegria Mira, 2010)

3.2 *Geometrical dimensions*

A USC will be designed with the ability to configure both barrel vaults as domes. To reach this possibility, the USC must be able to function as the three standard scissor units: translational, polar and angulated, depending on the desired end configuration.

Because hinge displacements have a dramatic influence on the structure shape, in this section decisions will be made concerning the different geometrical dimensions based on possible hinge positions. These are the dominating aspect for the geometry: because all the components are identical, i.e. the USC, the only difference between the configurations is the position of the pivot hinge.

3.2.1 *Angulated part of the component*

The angulated element is determined by the different geometrical polyhedra to form radially deployable domes. Because of the fixed geometry of the polyhedra, also the angulated part of the USC is relatively fixed. If the length of the kinked beam of an angulated scissor unit is considered as a parameter, the height is determined for a certain polyhedron (Figure 8).

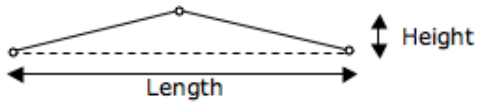

Figure 8. Parameters of an angulated beam.

A length of 2m is chosen because of the resulting range from low to high spans for multifunctional deployable structures. Moreover, a length of 2m seems to still be manageable manually. A 2m length results for each considered polyhedron in a certain height. Further, a selection is made between these different height values. The decision is based on the feasibility of the distance between the angulated intermediate hinge positions. For that reason the icosidodecahedron is excluded. Figure 9 presents the ultimate geometric dimensions for the angulated part of the USC for which six different dome structures can be built geometrically.

	Hinge position [cm]	Dome polyhedron	Elements/edge	Span Dome [m]
1	10.2	Buckyball	Double	16.9
2	16.4	Adjusted rhombic triacontahedron	Double	12.2
3	20.6	Buckyball	Single	8.5
4	28.4	Icosahedron	Double	6.2
5	33.8	Adjusted rhombic triacontahedron	Single	6.1
6	38.2	Dodecahedron	Single	5.2

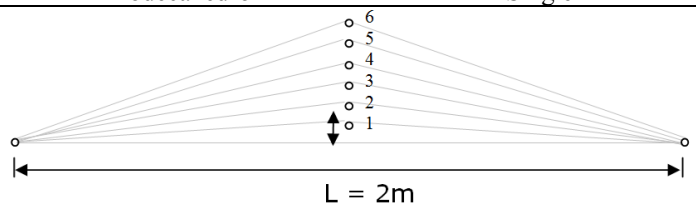

Figure 9. Ultimate geometric dimensions for the angulated part of the USC. (Alegria Mira, 2010)

3.2.2 *Translational/polar part of the component*

Compared to the relative fixed geometry of the angulated elements in the domes, the polar and translational units allow a bigger freedom in geometry choice.

A polar unit is simply obtained by moving the intermediate hinge of a translational unit away from the middle of the beams. This eccentricity of the revolute joint creates curvature when the units become deployed. A beam from a translational and polar unit can thus simply be combined into one beam with several hinge positions (Figure 10).

The length of the translational or polar beam is fixed on 2m as determined in the previous section. The parameters on which can be anticipated are the number of units and the eccentricity of the polar hinges. Configurations are investigated with a number of units from 4 to 16 to obtain a wide range of barrel vault spans and eccentricities are considered with a minimum distances of 5cm because of practical reasons.

The result is that only the eccentricities of 5cm, 10cm and 16cm have to be regard to form thirteen barrel vaults differing in span and shape (Figure 10).

	Hinge position [cm]	Number of polar units in arch of Barrel vault	Span Barrel vault [m]
1	5	U=7	8.3
		U=8	9.4
		U=9	10.5
		U=10	11.6
		U=11	12.6
		U=12	13.6
		U=13	14.6
		U=14	15.5
		U=15	16.4
		U=16	17.3
2	10	U=5	5.6
		U=6	6.5
3	16	U=4	4.1

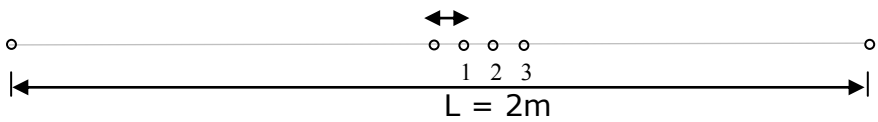

Figure 10. Ultimate geometric dimensions for the translational/polar part of the USC. (Alegria Mira, 2010)

3.3 *Geometrical shape*

In the previous section the geometrical dimensions were determined. The positions of the intermediate pivot hinges are found with the ability to compose them in such way that nineteen different architectural structures can be formed. A simple shape, easy to manufacture, is formed by connecting the hinge positions with beams. Figure 11 illustrates the designed Universal Scissor Component with the different elements.

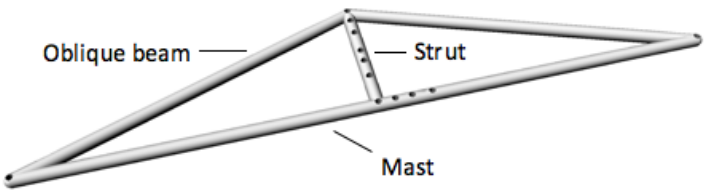

Figure 11. Universal Scissor Component. (Alegria Mira, 2010)

3.4 *Deployment*

Not only do the hinge positions determine the ultimate shape of the deployable structure, they also have an impact on the deployment behaviour which differs between barrel vaults and domes. In case of the barrel vaults, the deployment has a 2D character: the transformation proceeds automatically in the transversal and longitudinal direction, as shown in Figure 12. For the domes, the deployment transforms radially. While deploying the geometrical shape stays constant, only a variation in span in noticed (Figure 13).

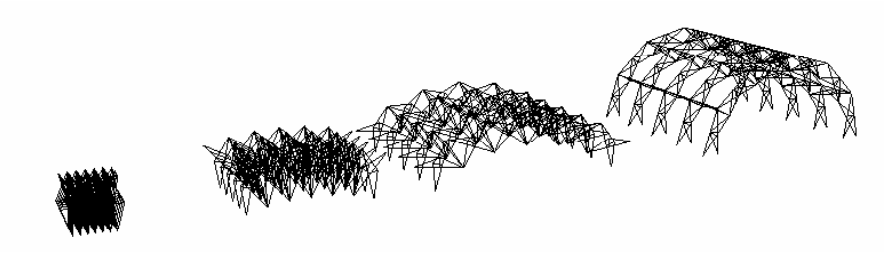

Figure 12. Barrel vault with USC's in four deployment configurations. (Alegria Mira, 2010)

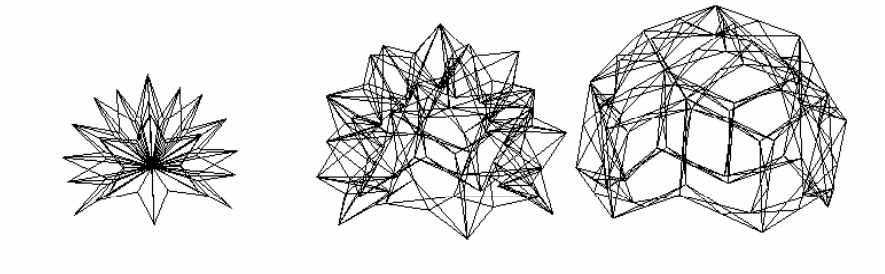

Figure 13. Deployable dome based on the adjusted rhombic triacontahedron from a fully closed to an open configuration. (Alegria Mira, 2010)

4 CONCLUSIONS

The aim of the work was to develop an innovative construction system based on a Universal Scissor Component (USC) for deployable structures and to propose different concepts leading to architecturally and structurally viable solutions for mobile applications.

Based on different configurations of structures - barrel vaults and domes - decisions were made about the geometrical dimensions and the shape of the component. Considering feasible hinge positions, the design process resulted in a USC capable of configuring nineteen different architectural structures with specific deployment behaviour (Figure 14). The USC is the unique component in all the proposed configurations, the only difference is the position of the pivot hinge, thus making re-use and adaptability relatively easy.

Based on a preliminary structural analysis, relative small sections have been found (maximum 51mm), compared to the covered area, proving the preliminary feasibility of these types of constructions. But it is to be expected that nearly all of the USC beams are over-dimensioned.

In previous research it is stated that traditional scissor elements show a low to medium structural efficiency due to existing bending moments (Hanaor & Levy, 2001). A first structural calculation has proven that the designed USC rather excludes bending moments, thus increasing the structural efficiency of the structure.

Further research and a detailed analysis are required to optimise this construction system in terms of weight-per-covered-area-ratio and material- and energy use. Deployable structures have become increasingly popular, but few have been realised successfully. Further work can consist of a better understanding of the design parameters and the related allowable tolerances and imperfections, in order to respect the architectural function of the structure and to guarantee a successful deployment and folding. Their further development calls for research into fundamental issues regarding the shape of the constitutive elements, the connections, the membrane, the deployment behaviour, and the structural performance, both during and after the transformation process. The proposed concept makes re-use and adaptability possible: it is well equipped to meet the demands of a rapidly changing society while embracing the concept of sustainable design.

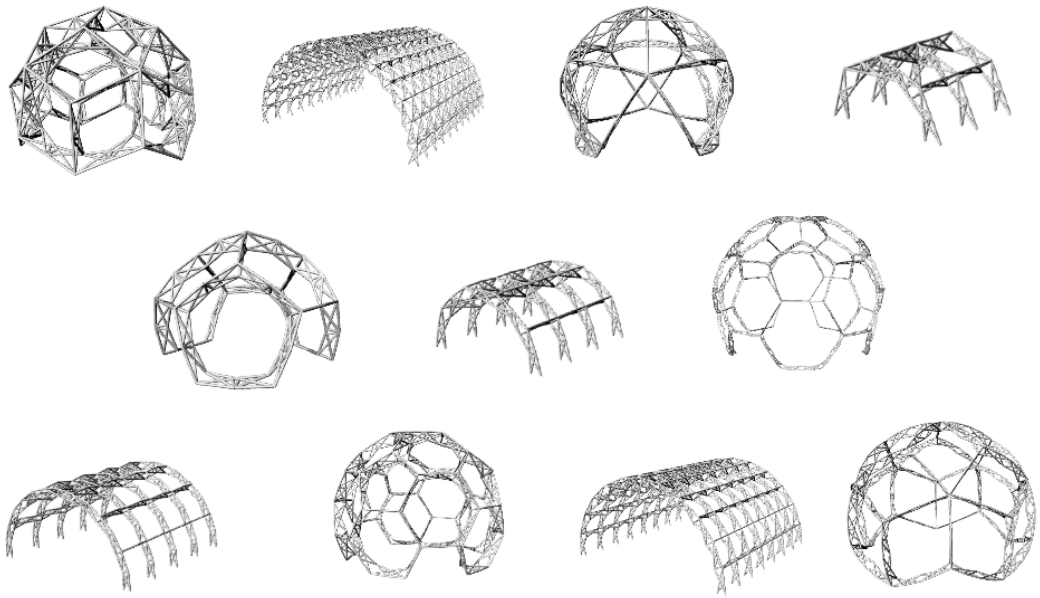

Figure 14. Selection of the possible deployable structures composed of the Universal Scissor Component.

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Aiming at Sustainability through Multi-layering for the Cyprus News Agency Building Proposal

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ABSTRACT: The present paper analyses the design proposal for the new building of the Cyprus News Agency. In terms of sustainability, of major importance was the interactive development of the spatial configuration and the façade elements design according to the natural ventilation of the interior and the external sun-protection systems applied. In the latter case the glass façade of the newsroom of the building is sun-protected through a double mesh layer of steel elements. Horizontally the layers form a filigree "curtain" with openings that are defined parametrically as to the visual interconnections from the inside to the outside and vice versa. The environmental analysis of the space refers to the natural lighting and the thermal comfort of the users. The design example clarifies the methodology of interdisciplinary integrated design, whereas architecture, morphology, construction and bioclimatic design are interrelated from an early design stage to achieve innovation in materials and systems.

1 INTRODUCTION

Public buildings are in general representative for respective developments achieved within the organizations, the public and the society. They constitute often landmarks, whose architecture reveals the identity of their functional disposition, aims and information processing models. As such the architectural designs aim at fulfilling the requirements of contemporary extroverted and transparent processes of operation on one side and environmentally sensitive developments of the interior spaces and the final built-up products within the urban fabric on the other side. On this line the architectural design may be pursued within an interdisciplinary context of development, whereas the building morphology, the structure and construction and the energy efficiency are equally important design parameters, investigated interactively from early design stages, and through the different scales of design. The introduction of bioclimatic and environmentally friendly design principles to the design in an interdisciplinary integrated context is believed by the authors to be a promising model of development for the achievement of high-quality and sustainable technology driven design projects.

The present paper analyses the design proposal developed by an interdisciplinary architectural engineering team, for the new building of the Cyprus News Agency. The building is composed of four main functional sections – entrance area, multi-purpose room, administration spaces and unified newsroom – of in total around 1600 m^2. The proposed design follows the brief requirements set by the respective European Competition in 2010, while a strong emphasis was set in the environmental building qualities. The architectural composition enhances at first place through a discrete functional disposition of the spaces, physical, visual and acoustic interactions within the interior, as well as with the exterior. Bioclimatic design considerations influenced to a high degree the development of the building morphology and the functional configuration in the interior. In addition, the construction design of the building envelope was developed interactively under consideration of the thermal comfort in the interior spaces and the visual correlations with the exte-

rior. The present paper emphasizes the last mentioned points of development, demonstrating the environmentally driven building design direction followed on one side and the design driven technological developments achieved in the building façade design on the other side.

2 ARCHITECTURAL DESIGN

2.1 *Design criteria*

The proposed architectural morphology is perceived as an expression of the social and organizational structure of the building. It is characterized by a functional and aesthetic simplicity that enhances physical, visual and acoustic interactions and differentiations within the interior and the external environment. Based on the organizational structure and the operational system of the Cyprus News Agency, the design reflects the differing and discrete functional sections of the building, promoting and expanding at the same time its social identity. In this frame the spatial sections of the building remain identifiable, but within a unified building complex, in aesthetical and functional terms. Architectural design operations, such as the relations between movement and pause, individual and collective spaces, transparent, semi-transparent and massive surfaces and different levels aim at the internal unification of the workers and the functions, preserving also their individuality and autonomy, when necessary.

2.2 *Functional Disposition*

The organizational structure of the design is reflected through the compositional development of the building in four functional sections. Each section houses a specific part of the functional program, supports the autonomous functionality of the spaces within and preserves the unity of the building as a whole, as shown in Figure 1. On the east, the spatial section of information "production" (unified newsroom) is placed, on the west, the section of information "presentation and dissemination" (multipurpose room), and on the north, the individual offices of the organization. A "corridor" comprises a significant element of the design, acting as spatial axis that engages, divides and unifies movements and programming elements, Figure 2. The circulation zone ensures free visual correlations between all main functional sections and preserves in parallel the physical and acoustic isolation of the spaces, when functionally required.

At the primary functional level, the entrance hall of the building is included (+0.50 m). The orientation towards the outer entrance area is signalized by the cantilever of the multipurpose room from above. Directly connected to the entrance hall is the main working space of the building, the unified newsroom (±0.00). The space is elevated as autonomous compositional element with a metal mesh envelope of its transparent skin, allowing for visual correlations with the surrounding external environment and preserving at the same time its privacy. It is gradually revealed in its parts throughout the visitors' route along the longitudinal ramp on the south and the free-standing staircase in the entrance hall that leads to the multipurpose room. The unified newsroom follows an open-plan configuration in support of the visual and physical communication in larger scale – global integration. In parallel the creation of local relationships within the working environment is proposed, so that micro-environments may be initiated by smaller numbers of em-

Figure 1. South-west and north-west perspective view of the building.

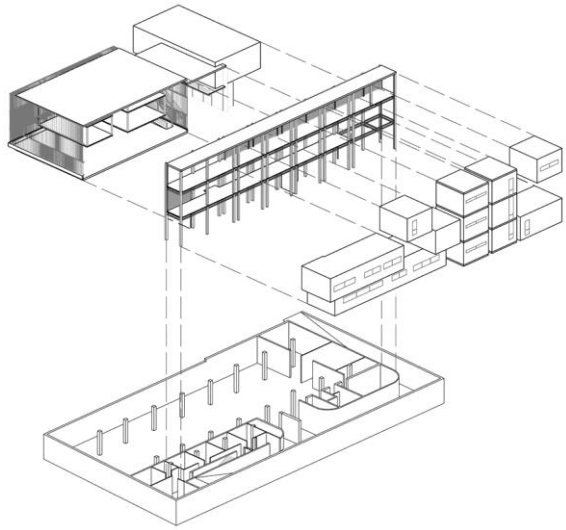

Figure 2. Blow-up of the building components.

ployees. The offices of the chief-editors, the supporting staff and the news writers are directly connected to the editors' central space. At a higher level within the newsroom space, the meeting spaces of the centre, library and conference room, are arranged.

A free-standing steel staircase in the entrance hall leads the visitors to the multipurpose room level (+4.00). Along the staircase, the metal mesh on the east and the transparent façade on the south allow for indirect visual correlations with the unified newsroom and the external spaces respectively. The multipurpose room is elevated morphologically as autonomous compositional element, with its south part cantilevering above the entrance area. Digital information elements, integrated within the semi-transparent façade, enhance the identity of the particular building part, as one of information presentation and dissemination.

The office spaces are developed along the north side of the plot; at the intermediate level with the directorate- (+4.00) and at the upper level with the administration section (+7.50). In responding to the requirement of possible gradual expandability of the building, the spaces are developed in individual functional units. This enables an independent operation of the sections within the common building volume, as well as spatial and structural flexibility in their divisions.

The underground level houses archive- and storage rooms, the computing section, the operation centre of the building and a number of parking places for the visitors.

3 STRUCTURE

The architectural design was developed in an integrated context as regards the structural and construction design of the building. The structure and the construction elements and materials applied aim in parallel at the enhancement of the architectural concept, initially developed, as well as at the achievement of the required static and seismic behavior of the system.

The underground spaces of the building are supported on reinforced concrete shear walls and conventional frames. The structure of the building above ground consists exclusively of steel members. The primary structure consists of three-storey frames, placed in the transverse direction along the main circulation zone. The multi-storey frames with openings of 2.5 m are placed in coupled pairs in the longitudinal axis at axial distances of 5.0 m. The spatial frames of the modular office units are fixed connected to the primary multi-storey frames. Diagonals are added within the cantilever planes of 5.0 m length. On the south side of the building the primary columns of the structure are connected over horizontal frame structures at the respective slabs- and roof levels to the multi-storey frames, at a distance of 10.0 m. The structure of the multipurpose room consists of a horizontal Vierendeel tube that is supported on the primary columns at the entrance area. The height of the Vierendeel beams equals to the storey height of 3.5 m. The spans of

the system account to 8.20 m and 14.60 m in the two directions respectively. The horizontal connecting planes of the Vierendeel beams, slab and roof of the space, consist of trusses for achieving the required diaphragm.

4 CONSTRUCTION- AND BIOCLIMATIC DESIGN

The construction- and bioclimatic design of the building was pursued on the basis of the morphological architectural development and the typological configuration of the spaces, following an environmentally sensitive approach. The overall comfort of the users is also supported with the development of the building envelope, as regards construction design requirements, orientations and sun-protection elements applied.

The compact form of the main functional spaces, having large users' capacities contributes positively to the achievement of the required thermal comfort conditions in the interior. The shadow diagrams prove the positive effect of the building as to the seasonal environmental benefits, Figure 3. Additionally, as shown in Figure 4, the functional disposition of the building is developed along the east-west axis, in the prevailing wind direction of the area. The main circulation zone with south orientation acts as intermediate buffer-zone for the control of the interior temperature, as well as wind-tunnel for the achievement of natural cross ventilation of the internal adjacent spaces. The multipurpose room temperature and ventilation are supported on technical systems.

The sun-protection of the transparent façade is determined according to the internal functions, through application of three systems. On this line, the multipurpose room is enveloped with a semi-transparent glass façade and an integrated digital information system. The entrance hall- and the main circulation zone façade, in all cases with south orientation, consist of double glasses of low U-values in the interior, horizontal sun-protection elements of 15.0 cm depth in the intermediate spaces and single glasses in the exterior (Trombe effect). The particular double façade system enables solar energy collection during the daytime and the absorption of warm air for the heat transfer from the interior to the exterior.

The transparent façade of the unified newsroom in all three orientations is equipped with an external couple of mesh layers, consisting of steel bars with diameter of 5.0 mm, Figure 5. The mesh layers are placed from the glass façade, at a distance of 1.0 m on the south and 25.0 cm on the east and west. Both layers are divided in three zones over the height of the building (10.50 m). The internal layer consists of a geometrically defined constant perpendicular mesh with openings of 3.0 cm (primary sun-protection element). The external layer is composed of vertical bars of variable horizontal distances, from 3.0 cm to 15.0 cm. The distances were defined parametrically as to the visual interconnections from the inside to the outside and vice versa (primary visual connection element).

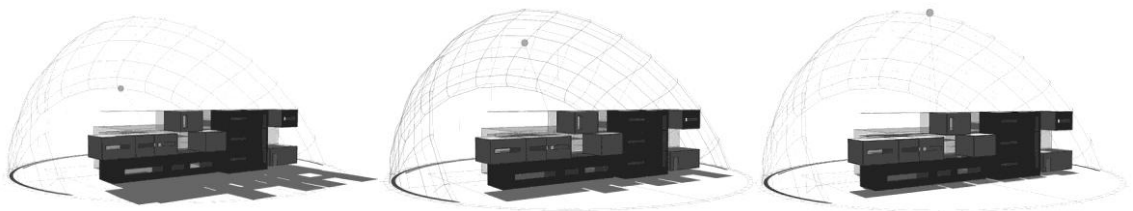

Figure 3. Building shadows diagrams for winter, spring and summer.

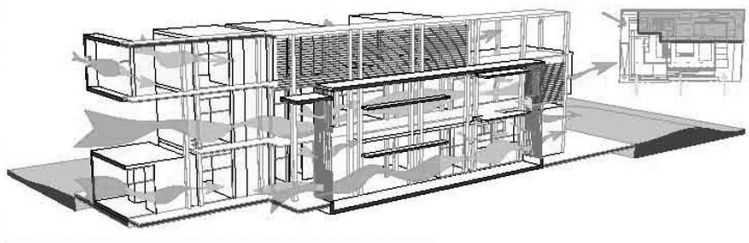

Figure 4. Natural ventilation concept in longitudinal building section.

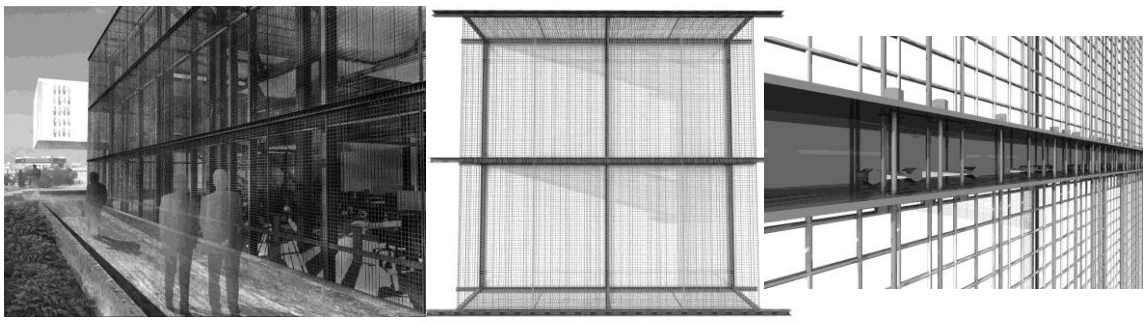

Figure 5. South-east perspective view of the unified newsroom façade with double steel mesh layer.

The construction design of the elements favors simple connections, standardization and flexibility on site. Main construction elements are steel profiles, positioned at the zones' division levels. The profiles support both mesh layers. The external vertical steel bars are fixed within the provided long holes of the profiles, according to their prescribed horizontal distances.

5 ENVIRONMENTAL ANALYSIS OF NEWSROOM

Solar radiation impinging upon external building surfaces is considered to be an important source of heat gain, whereas at the same time it is also the provider of buildings' natural illumination. Therefore an acceptable compromise solution between these two parameters needs to be found at the design stage. The benefits of natural day-light in the building are considerably more substantial as they encompass throughout the whole year. However the parameter of passive heat gains are also of major importance, especially under summer-dominant conditions, and may also be satisfied by the proper building geometry and orientation. The building can be designed to perform efficiently by combining effective glazing, solar exposure, and shading into the building form. This efficiency can also be enhanced by variations in the placement of interior spaces and by the use of integrated sun-protection systems (Alvarez et al., 2000). The shading system which is introduced in the proposed design consists of a rectangular steel mesh of round steel profiles with constant geometry (primary element for sun-protection) and of vertical steel bars, placed in variable distances along the horizontal axis (primary element for visual correlation). This design aims at satisfying both, the natural lighting needs, as well as the controlled levels of solar exposure in terms of passive heat gains.

The effect of the passive design strategies of the proposed building was obtained by using the Ecotect software (Autodesk Ecotect Analysis, 2011). Ecotect offers a vast range of modeling features in order to determine how fundamental criteria, such as solar, thermal, shading, lighting, and airflow, affect the building performance in the conceptual and detailed phases of design. This capability to forecast better the building performance over time equips architects and engineers to deliver more energy efficient and sustainable building designs. Ecotect is a concept-to-detail sustainable design analysis solution with architect-designed tools that helped measure the impact of environmental factors on the buildings performance.

5.1 *Solar Exposure and Daylight Levels*

Solar control is the main design strategy for glazed elements. Heat gain control involves the manipulation of the geometric, solar and thermal properties of all the building elements. The hourly solar exposure of the transparent, south oriented, sun protected façade was determined by employing the Ecotect „Solar Exposure" tool, using the five minute time step calculation. The task of calculating the total cumulative solar radiation incident on the investigated façade was achieved by adding up the direct and diffuse solar availability at each segment and then multiplying by both the surface incidence layer and the overshadowing and reflections layer. The resulting incident stereoscopic radiation map showed not only where in the sky the majority of incident so-

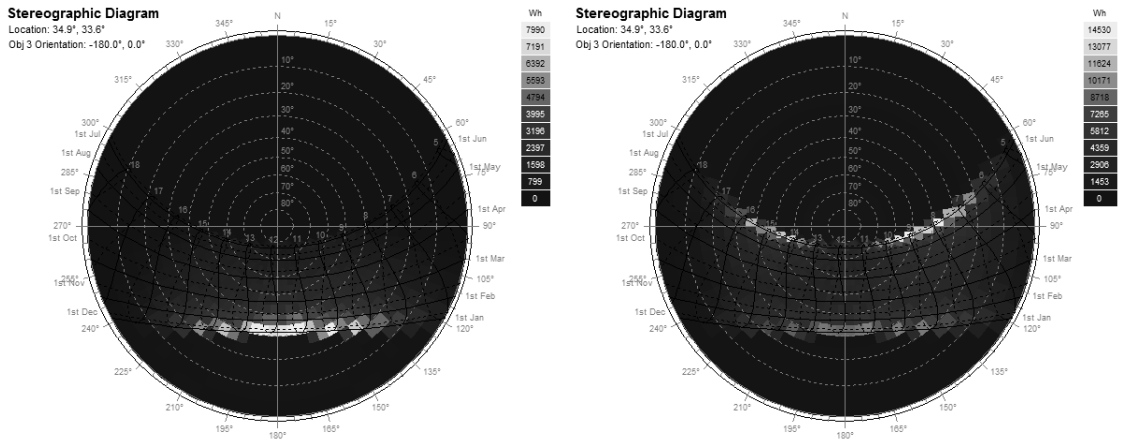

Figure 6. South Stereoscopic diagram of annual average hourly cumulative solar exposure of the examined façade with (left) and without (right) the proposed sun protection system.

lar radiation is coming from, but also when this occurs, since it is mapped onto a sun-path diagram. Figure 6 illustrates the stereoscopic diagrams of the calculation results regarding the annual average hourly cumulative solar exposure of the examined façade with and without the proposed sun protection system. The use of the proposed sun protection system does not reduce the levels of the passive solar exposure of the façade during winter. The magnitude of the solar exposure seems also to remain constant during summer. However the stereoscopic diagram of the unprotected façade reveals that the solar energy, collected by the investigated surface in summer is twice as much compared to the corresponding case with the integrated sun protection system.

The calculation of the daylight levels in the newsroom was also performed by simulating the effect of the proposed sun protection system. Since the luminous efficacy of the direct sunlight is much greater than that of the most commonly used electric alternatives, it was of importance to verify that the daylight levels in the building during the summer were not significantly reduced due to the use of the double layer shading frame. The lighting analysis in Figure 7 shows that the daylight levels at 21st of June, 12:00 in the newsroom are kept quite high, whereas no use of an additional light source was required. The results provided by the solar exposure and daylight analysis reveal that the proposed integrated shading system offers an optimum solution in terms of satisfactory lighting levels during the summer and high passive heat gains during winter.

5.2 *Heat gain control and thermal comfort in newsroom*

Figure 8 displays the hourly temperature patterns (X-axis) on a temperature/time (Y-axis) graph. In order to specifically determine the impact of several climatic factors on the temperature pattern of spaces, the outside air temperature, solar radiation and wind speed are also illustrated in this graph as dashed lines. The vertical axis on the right-hand side shows the solar radiation. The

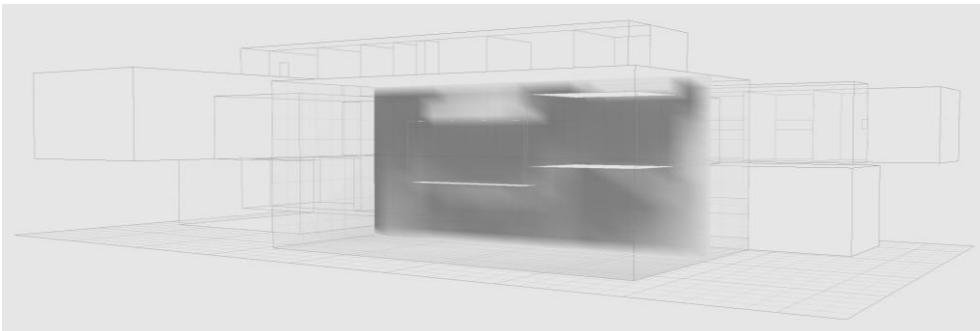

Figure 7. Lighting levels within the sun-protected newsroom, for June 21st, 12:00.

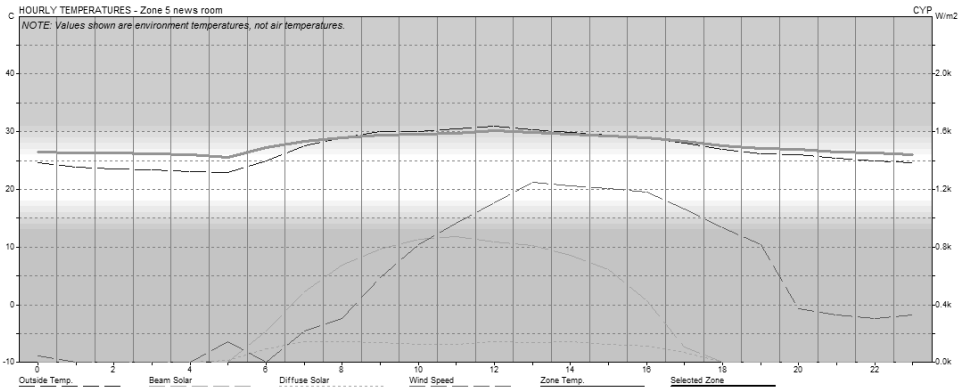

Figure 8. Hourly temperature pattern of internal and external temperatures, solar radiation and wind speed for June 21st, 12:00.

most important information of this simulation is the comparison between the temperature fluctuations of the newsroom and the corresponding changes of the environment temperature. The internal temperature remains reasonably stable throughout the day, and it is only rising slowly during the midday to around 28°C. The overall rate of change in the internal temperature and the differential against the peak outdoor temperature suggests the moderating effects of thermal mass of the building. This was expected since the building was intended to be constructed mainly with prefabricated metal components. Also looking at the solar radiation line, the noticeable rise between 8:00 am and 3:00 pm is not directly associated with a corresponding pattern in internal temperature. Additionally the fact that the sudden rise (early in the morning) and fall (late at night) of the solar radiation is also not associated with a remarkable increase or decrease of the internal temperature, suggests that the east- and west-facing side of the newsroom are well protected and that the shading design should not be revised. The minor internal temperature fluctuations are also shown in Figure 9, where the temperature levels within the newsroom with the use of the proposed sun protection system for June 21st, 12:00 is shown. This simulation shows that the temperature levels within the room are kept quasi constant, whereas no major temperature gradients are observed. As far as the pattern of the wind magnitude is concerned, it does not noticeably have any effect on the internal temperatures; therefore it is unlike that the wind behavior is expected to have any important impact on the internal conditions of the building (Ecotect Community, 2010).

The reflection of the analysis of environmental variables like dry bulb temperature, relative humidity, air movement and radiation as they effect human perception and response, were also obtained with the use of a psychrometric chart. Psychrometrics uses thermodynamic properties to analyze conditions and processes involving moist air (ASHRAE, 2009). Figure 10 illustrates, by means of a psychrometric chart, a graphic representation of the state and condition of the air in the newsroom at any particular time throughout the year, by neglecting the use of any HVAC system in the space. Based on these results it is obvious that the thermal conditions in the newsroom, especially during the summer, are close to the thermal comfort area. Therefore the proper choice

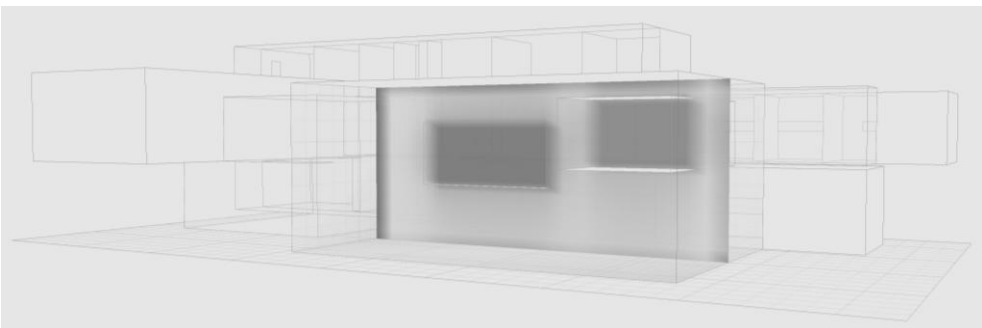

Figure 9. Temperature levels within the sun-protected newsroom, for June 21st, 12:00.

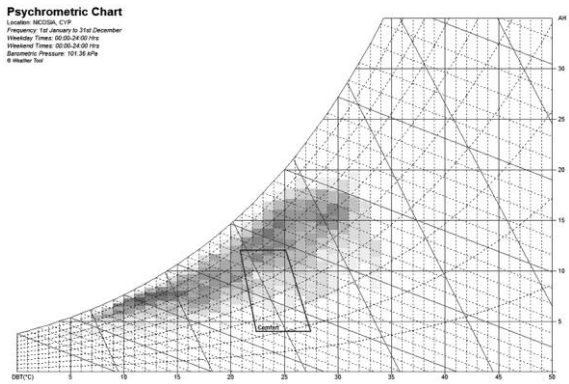

Figure 10. Thermal Conditions of non-conditioned newsroom, plotted on the Psychrometric Chart.

of the materials as well as the integrated bioclimatic design of the building results to the reduction of the cooling and heating loads which would have been needed to be achieved by mechanical means (HVAC units) for the establishment of acceptable dry bulb temperatures and relative humidity in the interior space.

6 CONCLUSIONS

The proposed design for the Cyprus News Agency building that was developed in an interdisciplinary integrated context, addresses in the present paper aspects of sustainability that were considered from the initial design stages. The proposed methodology of design development aimed at first place at the achievement of thermal comfort in the interior spaces, through respective formulation of the building morphology and the functional disposition in the interior, as well as the development of technological systems to form a multi-layering building skin that would allow for environmental protection of the interior spaces and visual correlations between the interior and the exterior.

In particular the bioclimatic performance of the innovative solution of the double mesh layer presented in the paper was obtained by using the Ecotect software, a concept-to-detail sustainable design analysis tool. According to the findings of this interactive analysis, the use of the proposed sun protection system did not reduce the levels of the passive solar exposure of the façade during winter, whereas the magnitude of the solar exposure was found to be constant during summer. The natural lighting levels within the newsroom were also found to be relatively high during summer. The heat gain control and the thermal comfort analysis showed that the internal temperature remained reasonably stable throughout the day, and it was only found slightly increased during midday. It was also found that the temperature levels within the room were quasi constant and no major temperature gradients in the interior space were observed. Finally it was shown that proper choice of the building materials as well as the integrated bioclimatic design of the building resulted to the reduction of the cooling and heating loads which needed to be achieved by mechanical means (HVAC units) for the establishment of thermal comfort conditions in the building.

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Improving the seismic behavior of architectural glazing

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ABSTRACT: Architectural glazing has been a widely practiced façade system since the introduction of modern architecture. Seismic design codes provide procedures for the design of architectural glazing systems, which is mainly based on the idea of providing sufficient clearance between the glass panel edges and the supporting frame. Application of a friction damping connection system, that connects the whole façade system to the main structure of the building, is introduced as an alternative to the existing seismic design considerations, which can result in no window panel clearance and maximum glazing. Given that the story drifts while transferred to the façade system will cause shear in the glass panels, an analytical procedure is developed to determine the shear load bearing capacity of glass window panels based on the theory of plate buckling. The calculated forces will be used to define load transmitting capacity of the connection devices.

1 INTRODUCTION

Architectural glazing has been one of the most practiced envelope systems since its introduction in the middle of the twentieth century. In the recent years the widespread use of double-skin façades, due to energy efficient behavior, has directed more attention to the architectural glazing and technical advances and issues in this architectural trend. One of the technical issues of these systems is their behavior during earthquakes. The fragility of the glass combined with the fact that the building structure is not designed to prevent damage to all the nonstructural elements makes the architectural glazing a vulnerable case during earthquakes. Damage to the envelope system of a building in case o an earthquake will call for considerable amount of activities like dismantling the damaged envelope, production of new elements to replace the damaged ones and installation of the new elements. Preventing damage to the envelope system will result in eliminating a great part of these activities which will highly improve the behavior of the building in terms of both costs and sustainable characteristics in case of an earthquake. The 1985 Mexico earthquake [1] and the 1994 Northridge, California, earthquake [2] are two of the most investigated earthquakes in terms of damage to the glass and nonstructural elements. The damage to the light envelope system during an earthquake is not due to the acceleration caused by earthquake, but it is caused by the deflections and displacements that happen within the structure of the building and are transferred to the envelope. For the case of architectural glazing, building codes include provisions for the protection in case of earthquakes. These provisions are based on providing sufficient clearance between the glass panel edge and the framing system. But considering these provisions finally results in difficulties with offering a smooth glazed surface for the exterior of the façade. In this article following a description of the design provisions for architectural glazing a different philosophy in protecting the glass façades is suggested, which is to control the forces that are on the façade during an earthquake using advanced connecting devices.

2 SEISMIC DESIGN OF ARCHITECTURAL GLAZING

As it was mentioned earlier the basic cause of the damage to the nonstructural elements of the building are the deflections and displacements within the structural elements. In order to protect the nonstructural elements of buildings seismic design codes provide limitations on the story drift (relative displacement between the top and bottom of the story divided by the story height) during the structural design phase [3] yet these limitations are hardly enough for the glass façades and other considerations must be made. The ASCE 7-02 code [4] in section 9.6.2.10 instructs the designers of glazed curtain-walls, store-fronts and glazed partitions to provide enough clearance between the glass panel edges and the frames of such systems to avoid damage to the glass.

2.1 *In-plane deformations in curtain-walls*

Figure (1-a) schematizes a glass panel and its supporting frame having c as clearance between the panel edge and the frame. It can be observed in figures (1-b) and (1-c) that the panel can withstand a relative displacement of D_r according to the clearance length and the dimensions of the panel without having exerted any force on the glass panel, the displacements of the glass are only due to rigid body motion.

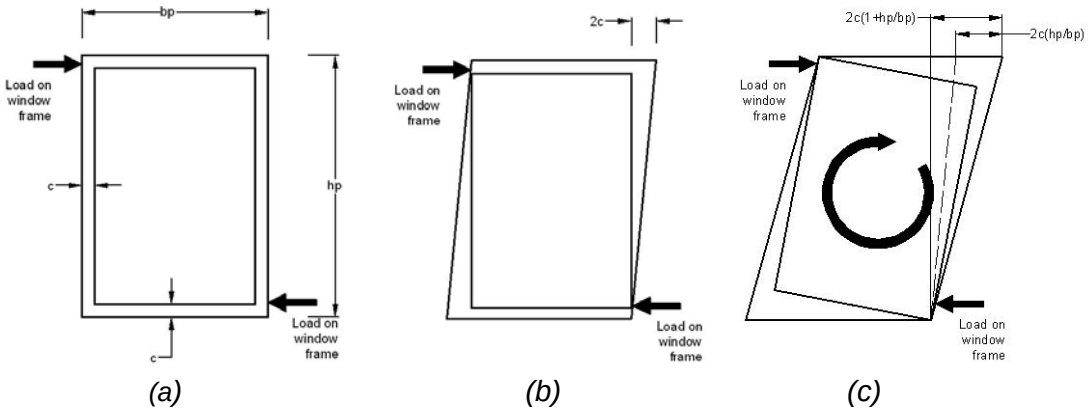

Figure 1. In-plane deformation within a curtain wall system.

Equation (1) shows the relation between allowable panel deformation (D_r) with the panel size (h_p and b_p) and clearance(c).

$$D_r = 2c\left(1+\frac{h_p}{b_p}\right) \tag{1}$$

The above concept is more generalized in ASCE 7-02[4] and is mentioned or referred to in numerous building design codes.

2.2 *Design requirements in ASCE 7-02*

It is required by ASCE 7-02, section 9.6.2.10 that the glazed curtain walls, store fronts and glazed partitions accommodate a relative displacement of D_{clear} throughout the height of the glass panel. Equation (2) expresses the minimum amount of D_{clear}

$$D_{clear} \geq 1.25\, I D_p \tag{2}$$

Or *13 mm*, whichever is greater

Where: I is the occupancy importance factor and D_P is the relative component seismic drift which is applied over the height of glass. D_p shall be derived using the story drift outputs from the numerical modeling of the building; otherwise the maximum allowable values shall be considered.

Equation (3) is also introduced by ASCE 7-02 which is in accordance with the assumptions of the *section 2.1* of this article, only with the difference that it considers different clearances between the glass panel and the frame in vertical and horizontal directions. In this case c_1 is the horizontal clearance between the glass panel and the frame and c_2 the vertical clearance.

$$D_{clear} = 2c_1\left(1+\frac{h_p c_2}{b_p c_1}\right) \tag{3}$$

Where: h_p is the height of the rectangular glass; b_p is the width of the rectangular glass, c_1 is the horizontal clearance between the glass panel and the frame; and c_2 is the vertical clearance between the glass panel and the frame.

It is also stated that the below two cases shall be exempted from the requirements expressed by equation (2):

1. Fully tempered monolithic glass in Seismic Use Groups I and II located no more than 3 m above a walking surface.
2. Annealed or heat-strengthened laminated glass in single thickness with interlayer no less than 0.76 mm that is captured mechanically in a wall system glazing pocket, and whose perimeter is secured to the frame by a wet glazed, gunable curing elastomeric sealant perimeter bead of 13 mm minimum glass contact width, or other approved anchorage system.

3 ADVANCED CONNECTORS

The use of advanced connectors in cladding systems was proposed by many scholars and designers after post-earthquake surveys and laboratory tests had shown that fixed elements of a cladding system are vulnerable to damage during an earthquake due to deformation accruing in the structure of buildings. The idea of using advanced connectors was to provide isolation between the envelope system and the structure and to dissipate seismic energy. Since light weight cladding systems do not affect the dynamic behavior of the building giving very little contribution to it, it is obvious that the energy dissipating approach on a building scale can only be carried out in heavy cladding systems. Barry J. Gondo and James I. craig [5] provide a detailed study of different dissipating connection systems. But since energy dissipating mechanisms can also be used as a means of controlling the forces regarding displacements they still have the potential for being used in the light cladding systems in order to provide a desirable level of isolation. Due to their simplicity, both in terms of analytical study and practical use, friction damping connectors are proposed in this research as connecting devices between the glazed envelope and the structure of the building.

3.1 *Friction damping connectors*

Friction damping connectors are mechanisms that use friction – usually between two sliding surfaces – as the basis of energy dissipation [6]. The load bearing capacity (friction behavior) of the device will be controlled by the friction coefficient between the two sliding surfaces and the force perpendicular to the surfaces attaching them together.

One advantage of this system is that it can be tuned in order to transmit a limited amount of force between the two connected systems and if the force exceeds a certain limit the device will no longer transmit the exceeding force and will only experience displacement in the direction of the exerted force until it reaches its maximum displacement capacity. How to find the limit force for a certain glass panel is described later in the paper.

The other advantage of the friction damping devices is that they are rather simple devices, easy to manufacture and very easy to use in the construction of curtain walls. They can be applied in place of most of the existing brackets with very little or no modification. Figures (2-a) and (2-b) schematically show the friction connection bracket. More intricate friction connectors are discussed by T.T. Soong and G.F. Dargush [6] which can be used for different and more complex details of the curtain wall and the supporting structure, but they all follow the same mechanical behavior, that is, to let go when the force exceeds a predefined limit and keep the pressure on the curtain wall at a constant rate.

It is considered that the glass panels have a framing attached to them using structural silicon bonding (primary framing) which is again connected to a set of vertical mullions (secondary framing). The vertical mullions are fully fastened to the structure of the building. The placing of the connection is between the primary and the secondary framing systems.

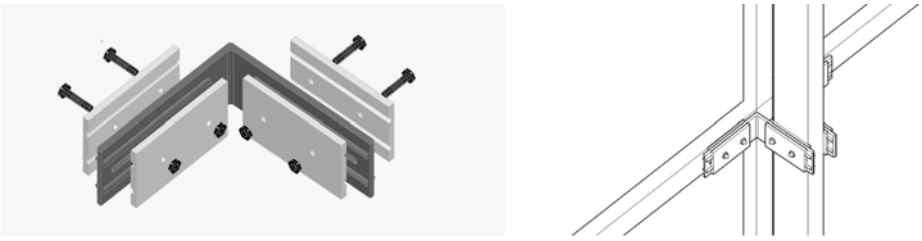

Figure 1. Friction connector bracket.

As shown in the figures, the connection device is almost the same as a connection bracket, with the only difference that the bracket in use for a friction damping connector is provided with a long slotted hole in the middle and accompanied by two more plates on each wing of the bracket. These allow the bracket to slide in two directions between the enclosing plates. The sliding of the bracket between the enclosing plates will be controlled by the pressure of the two plates on the bracket wings. It is essential for the materials used in friction connectors to present the two characteristics below:

1- To have similar friction coefficients in both cases of static and dynamic frictions between the sliding surfaces.
2- To have considerable resistance against environmental attacks, since corrosion and other changes which may happen to the surface of the plates can dramatically change the behavior of the connection device.

3.2 *Designing the friction connector*

Many mechanical properties contribute to the behavior of the friction damping connectors like friction coefficient between the surfaces, the attaching force and etc. This paper does not deal with the details resulting in the behavior of the connection device and only discusses the limit force (F_L) which is transferred through the connection and is the cause of damage to glass panels. In order to find the optimum limit force for the connection device, the mechanical behavior of glass panels during earthquake must be analyzed.

4 BEHAVIOR OF WINDOW GLASS PANELS DURING EARTHQUAKE

The behavior of glass panels remains in elastic range both during the in-plane and out-of-plane deformations. The main causes of damage to glass panels during earthquake are the in plane deformations which occur in the curtain wall system. This is due to the significant stiffness of the glass panels in that direction. In the structural silicon glazing, drift deformations in the curtain wall system do not cause compression forces on opposite corners of the glass panels as it is described by Vallabhan [7] for dry glazed systems. Instead, due to the continuity of the glass panels these deformations act as shear forces on their edges.

4.1 *Shear force capacity of glass panels*

Considering the large dimensions of glass panels compared with thickness, the most probable failure mode of a glass panel subjected to shear force along its edges is the shear buckling. The effects of localized stresses and local buckling may also have contributions to the failure mode of the glass panel, especially near the connection devices.

Using the theory of Navier for simply supported plates, can be determined the critical shear stress for the glass panels. Equation (4) supplies the expression for critical shear stress (τ_{cr}) for plates [8].

$$\tau_{cr} = k\frac{\pi^2 D}{b^2 t} \quad , \quad D = \frac{Et^3}{12\left(1-\nu^2\right)} \tag{4}$$

Where: b is the smaller dimension of the panel, t is the thickness of the panel, E and ν are respectively the modulus of elasticity and Poisson ratio for the glass and finally k is a constant depending on the ratio between the sides of the panel. For the case of square panel, k equals *9.4*, table (1) shows the value of k for different ratios of panel sides ranging between *1* to *4*.

Table (1). Values of factor k in the equation (4).

a/b	1.0	1.2	1.4	1.5	1.6	1.8	2	2.5	3	4
k	9.34	8.0	7.3	7.1	7.0	6.8	6.6	6.1	5.9	5.7

5 TUNING THE FRICTION CONNECTORS

5.1 *Limit force values*

Having known the maximum shear resistance of the glass panels it is now possible to assign the force limits for the friction connectors as:

$$F_L = \frac{\tau_{cr}.l.t}{n.SF} \tag{5}$$

Where l is the horizontal length of the glass panel, t is the thickness of the glass panel, n is the number of friction connectors corresponding to the glass panel on the horizontal edges of the panel and SF represents the safety factor.

Table (2) shows the values of limit forces of friction connectors for different glass panel sizes and thicknesses. In this table it is assumed that the friction dampers are situated at a distance of *0.5m* from one another. Due to the fragility of the glass and its brittle failure the safety factor of 2.5 has been considered for the results.

Table (2). Values of limit force for different window panel sizes

Height	Width	thickness	k	τ_{cr}	F_L
m	m	cm		kg/cm^2	kg
1	1	0.4	9.4	96.93	775.45
1.5	1	0.4	7.1	73.21	585.71
2	1	0.4	6.6	68.06	544.46
2	1.5	0.6	7.5	77.34	928.06
2	2	0.6	9.4	54.52	654.28
3	2	0.8	7.1	73.21	1171.42

5.2 *The cumulative force behavior*

It is important to mention that aside from the friction connections which apply load on the glass panels, the glass panels also apply loads on each other. This fact is mostly true in case of glass panels that are vertically adjacent to each other and are subjected to different lateral drift.

The worst possible case for this type of loading can happen in panels in the middle of the curtain wall system and with the extreme assumption that all the friction connectors above the panel are exerting their limit force in one direction, while all the other friction connectors below are exerting force in the other direction. Although the worst case scenario is not very likely to happen, especially with a large number of panels in a curtain wall, in the absence of numerical si-

mulations in order to protect the glass panels from failure in case of such a cumulative behavior, the safety factor should be multiplied by half the number of panels in vertical direction.

With the help of numerical simulations for varying numbers of vertical panels and sizes it is possible to come up with better safety factors than the over conservative one introduced above. Research destined to generating these safety factors is in progress.

6 CONCLUSIONS

The inter story drifts of the building during an earthquake causes in-plane and out-of-plane deformations in the envelope of the building. In the case of glass façades the in-plane deformations will cause damage to the glass if considerations are not made in advance. In contrast with the common practice of offering clearance between the glass panel edges and the frame, the idea of isolating the façade from the main structure has been investigate. With the help of friction damping connectors it is possible to control the level of isolation, and protect the façade from deformations occurring in the main structure, while the façade is still relying on the structure and not having its own supporting system.

The safety criterion has been considered in order to derive the limit force values of the friction connector. Shear buckling of the glass panels was investigated as the probable failure mode caused by the in-plane deformations. It is clear that when the safety of the façade system has been assured, the serviceability of the system after earthquake needs to be further investigated. Air tightness and water tightness of the façade are the main features they compromised during an earthquake, which might be caused by breaking of the gaskets and failure in the structural silicon. Depending on the details of the façade system, maintaining the functionality of the façade will evidently ask for further reduction in the limit force values of the friction connectors.

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Innovative Technologies for Sustainable Houses with Steel

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ABSTRACT: The advantages of a house with steel are architectural, structural, constructional and beauty or aesthetic. By using steel in construction, the house can be built in impossible hillside areas, can have flexible and expansive spaces, produce strong lines and well-solved detailing of its time. More advantages can be written as it can easily fit in a traditional built environment, with a clarity in construction, common to all styles of architecture. By this way, a house with steel comes to definition with the tectonics of a sustainable material, overcomes all needs of all centuries. Also in a house with steel, all kind of building materials can easily be used to have the spaces as designed.
In the paper, to build the houses with steel in a sustainable manner, the innovative technologies will be defined from the point of structural system, cladding, substructures and their combination with other building materials.

1 INTRODUCTION

The concept of a house defines a sacred environment where a person or a family can have their own life in privacy. The selected building material creates lots of alternatives for the design of the house, according to the needs and wishes. The construction of the house puts an additional value to whole in time and in money and also in sustainability manner. Maybe there can not be lots of different building and construction systems for houses comparing with the variety of people, but it is sure that a house in construction with steel will have lots of alternative solutions, comparing with houses constructed with other building materials. The best to reach a clear view is to observe the principles about building a house with steel for sustainability through the built examples.

2 BUILT EXAMPLES

In every age, there are different houses built with steel. One of them is Farnsworth House by Mies van der Rohe, in 1945-1950, in Plano, Ilinois (Spaeth,1985). It has a clear plan, in the meaning of using the steel structural framing in its best solution for the time and still can be accepted as a master in building a house with steel.
In the following, some built examples around the world are given to make a clear view about how it may be different to build houses with steel in architectural design and construction.

2.1 *Daimler Chrysler Residential, in Berlin, by Richard Rogers and Partnership*

Photograph 1. Daimler Chrysler Residential, Berlin (taken by Y.K. Aktuglu, in 2004)

The buildings complex, built in 1993-1999, is designed for a mixed use scheme, including office space, housing and retail. The part for housing is at the upper levels of B8, which is one of the three blocks. Richard Rogers and Partnership preferred opening up the south-east side of the blocks, to have a building form which allows light to penetrate a building form which will let light penetrate into courtyards and spaces inside. The apartments are around a terraced and green courtyard to make all residents enjoy views out over the park in front of the complex. Penthouses which are double-height are glazed towards the courtyard side and the system for glazing is supported by a steel structure which is water-filled and acts as a radiator during the winter season. Sun-shading devices and opening windows are electronically operated, and they make the solar gain minimum and natural ventilation maximum during the summer season (Imhof, Krempel, 2004).

2.2 *12 canal-side house units of Sainsbury's Superstore, Camden Town, London, by Nicholas Grimshaw and Partners*

Photograph 2. Canal-side house units of Sainsbury's Superstore, Camden Town, London (taken by Y.K. Aktuglu, in 1992-1997-2003)

In Sainsbury's Superstore complex, besides the intelligent architectural solution and structural solution of the store, the three-story steel faced block of 12 canal-side house units is constructed from a mixture of steel and aluminium. There is a solar louver system in the double height living rooms which are approached by a private covered pathway placed beneath the main metal façade. There are access to the canal house units, from canal side and also from the garage side(Blanc, McEvoy, Plank, 1993).

2.3 *Weissenhofsiedlung, House 14-15, by Le Corbusier and Pierre Jeanneret, in Stuttgart*

Photograph 3. House 14-15, Weissenhofsiedlung, Sttutgart (taken by Y.K. Aktuglu, in 2007)

Le Corbusier formulated five parts of a new architecture, which are columns, roof terrace, free floor plan, wide windows, free façade design, in this two-family version of the house, as a manifesto and showed this in a great clarity. Their design became a transformable house, with large sliding doors, which enable flexible forms of living inside of the house. This is an approach to solve the minimization of building effort in 1927. Characteristics of the twin house are the windows which are continous, double steel columns which start from the ground level, continues to the fist floor, and the two staircases, standing out in a manner that they are independent cubes on the western side of the house. The architectural solution of the house looks like a railway carriage, defined with the convertible living and sleeping area, and the narrow corridor which connects the rooms (Joedicke, 1990). Double steel columns are also allowed the door-walls going through them to divide the large space into two smaller.

2.4 *Some other built examples of steel houses in Europe*

Photograph 4. A House in Oxford, UK (taken by Y.K. Aktuglu, in 1997)

This has a different architectural view with its roof form, windows, entrance stairs in construction with steel, with its metal cladding.

Photograph 5. A framed wall partition of an experiment steel house, prepared in an old storage hall in UK (taken by Y.K. Aktuglu, in 2003)

Photograph 6. The experiment steel house, built with ready wall partitions, prepared in the same space, in an old storage hall in UK (taken by Y.K. Aktuglu, in 2003)

In this experiment steel house, built with ready wall partitions, prepared in an old storage hall in UK, the time for building and construction will be saved, and also the amount of building material will be used in a more logical way. Steel in layers, is converted into cold-form structural elements to shape the frame of the ready wall partitions by electronic machines in the site area.

Photograph 7. Steel House of an architect, in Oxford, UK (taken by Y.K. Aktuglu, in 2003)

In this built example, even though there are traditional houses with brick walls, the house has a steel framing, and also brick walls as perimeter walls. So details related with steel framing as steel beams can be easily seen from outside, at the roof level. But the office of the architect in the same garden is not build with steel. For it has a small space, wooden framing is chosen in framing.

Photograph 8. Internationales Begegnungszentrum "Ludwig-Leichardt-Haus", Cottbus, Germany (taken by Y.K. Aktuglu, in 2004)

International Begegnungszentrum "Ludwig-Leichardt-Haus" of BTU Cottbus, Germany, is built in 1999, with the planning of architectural department's professors and students. The international guest house has two parts. First part for apartments is made of wooden framing, the second part for horizontal circulation, corridors, and vertical circulation, stairs and the roof cover and building envelope of this circulation part are built in steel framing, glass and wood, are the building materials for cladding façade and floor. This creates a transparent space for the common areas inside the building. Steel is used as columns and beams for circulation spaces in front of the apartments, covered with glass.

2.5 *Some other built examples of steel houses in Turkey*

Photograph 9. This is an apartment building in high rise, built by architect Melih Birsel, in 1976, in Istanbul, Turkey (taken by Y.K. Aktuglu, in 2007)

This high rise apartment building is towards Bosporus, near Bebek, just under the 2nd Suspension Bosporus Bridge- Fatih Sultan Mehmet Bridge. For the back side was high heels, and for the traffic in front of the house was very busy, to make the construction time shorter, structural steel is chosen for the building material in 1976. The structural system is under the plasters. Then because of the advantages of structure with steel, all windows are open windows along the floor height to have the view of Bosporus unobstructed.

Photograph 10. The inner space of Camlı Köşk, in Dolmabahçe Sarayı, in İstanbul, Turkey (taken by Y.K. Aktuglu, and B. Orbay, in 2006)

Photograph 11. The outer view of Camlı Köşk, in Dolmabahçe Sarayı, in İstanbul, Turkey (taken by Y.K. Aktuglu, and B. Orbay, in 2006)

It is a part of a separate building, like a pavilion, in Dolmabahce Sarayı, 1850-1852, in Istanbul, called Camlı Kosk. It is heated by an oven down the space and the vapor of heating system arrives to the inner space, through the walls under tall windows. The steel structure is outside the space to let the inner volume be free from structural elements. The triangular steel trusses pass the space at the top of the glass cover, and glass panes to cover the roof are hanged to these steel trusses from down side. Also the glass walls are prefabricated with their own secondary structural elements in steel, in circular forms, inside the modular glass-wall partitions, also creating an aesthetical outlook(Aktuglu, 2006).

2.6 *Some built examples*

Photograph 12. Casa Calvet, by Gaudi, Barcelona, Spain (taken by Y.K. Aktuglu, in 2010)

Casa Calvet is buit by Gaudi in 1898- 1900 (Cirlot, 2008). Here Gaudi used steel beams in a tailor-made style. The steel beams are constructed with narrow steel pieces in both sides towards opposite sides, to form the outcome as cross-bracings at once in the beam shape. With the specially designed steel beams, the effect of a steel house changed into an artistic manner as a kind of statue in a museum. In this kind of masonary-looked houses, steel columns are hidden behind the plasters. Then steel columns are invisible.

Photograph 13. Victor Horta House and his Studio, Brussels, Belgium (taken by Y.K. Aktuglu, in 2008)

Victor Horta built this building in 1898, in Brussels (Aubry, Bastin, Evrard, 2007). In his house, to support the floors, I-beams were used in construction in narrow spacing. Also the structural solution for the staircase in the mid of the house part of this building is a very important evidence, how the iron and steel framing can be effective in architectural view through structural solution in appearance. Because iron and steel cables are carrying the loads of stairs up to the structural steel elements in the roof level. Outside of the building, the balcony over the entrance is hanged by steel rods to the upper closed spaces over the balcony. Again the steel columns are hidden behind the plasters.

Photograph 14. Casa Mila, by Gaudi, Barcelona, Spain (taken by Y.K. Aktuglu, in 2010)

Here in Gaudi's Casa Mila, the construction of balconies is made of steel waffles filled with glass. The steel columns are hidden behind the plasters. The huge specially designed entrance door, the stairs hanged on to the columns from one side, and the roof cover of the stairs in the courtyard are constructed with steel. Inside the building, in one of the apartments, while the sliding door moves and disappears inside the wall, then the steel framing of the wall becomes visible. All decorations with steel are very well detailed in the meaning of structural solutions. For the father of Gaudi was a master in ironing, then Gaudi uses iron and steel in an advanced level in his solutions.

Photograph 15. The model of section, showing the iron-beams, of Casa Mila, by Gaudi, Barcelona, Spain (taken by Y.K. Aktuglu, in 2010)

Gaudi built Casa Mila, called also Casa Pedrera in Barcelona, Spain (Moix, 2009). The construction took place from 1906 till 1912 (Cirlot, 2008). In Casa Mila, the floors are constructed with iron beams in narrow spans.

3 GENERAL PRINCIPLES FOR HOUSES IN CONSTRUCTION WITH STEEL

As it will be seen clearly, nearly in every 12 built examples, there are different solutions to space a house with steel. Also there are lots of alternatives to make the products be more sustainable along the centuries. By investigating in details these built examples, we can have lots of building principles while dealing with steel. While steel can be used in construction in high-rise, also it can serve as an ecological device, eg. water filled circular structural elements to heat the interior, or also as cladding elements, or to let the sliding walls trough the double structural elements as columns, or as a framing system of the entrance stairs, or the framing system of prefabricated walls, or as hidden beams of columns of a house, or visible and with light and transparent effect, or to let the openings be wide to have the whole landscape at once, or by using the framing system outside of the space, constructed with prefabricated elements, or with tailor-made beams and invisible columns, or with thin hanging bars to carry all loads to the top, or with I-beams inside the slabs, with invisible columns inside the walls behind the plasters.

4 CONCLUSION

We can easily draw a line in sentence that the use of steel in structure and construction of a house will bring the designer freedom to do what it will be drawn. And then the feature of the building material, structural steel in housing e.g. its togetherness with other building materials, its lightness, its strong micro-structural pattern, its pre-fabricated possibilities, etc. will also produce sustainability in construction, by having a long service life under well maintenance conditions.
For steel has a very strong micro-structure, the dimension of the sections of structural elements are very small, compared with other materials. This will create an advantage also, by using less material in structure, we will get more space in use. We can design more functional structural elements, built by steel.
Through the 12 built examples, with their innovative technologies due to their times, it can be recommended that steel is a very beneficial building material in construction of houses.

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Technical visits to all built examples in the years, written down under the photographs.

Sustainable building assessment tools and the quality of the built environment

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ABSTRACT: Rating systems represent key tools to evaluate and compare sustainable buildings. Various sustainable building assessment methods have been developed in the last years and are used in different European countries. The main differences between methods come from the way they define sustainability of construction. The aim of this research is to evaluate the adaptability and flexibility of the tools by comparing them, in order to propose a framework for a sustainable building assessment in Romania. Environmental assessment methods must reflect national, regional and local differences in order to be accepted and used in all construction phases. A framework for sustainable building assessment has to take into account all the four pillars of sustainable development (ecological, economical, social and cultural) and has to be based on a systemic and integrative approach that brings together specialists from different domains.

1 INTRODUCTION

Sustainable development has become in the last decade the conceptual framework for almost all areas of social and economic life. How can we define sustainable development in construction? One possible definition is "creating the highest quality construction possible while the lowest impact on the environment" (Egmond et al. 2009). Sustainable building assessment and quality of the built environment are two different ways to define the same issue. For this reason, in parallel with different types of environmental certification, a proposal for a building quality evaluation grid developed by the architects will be presented. The major problem is to understand the need to develop and use such systems, what are the possible criterias of the evaluation, when and how to use an environmental assessment system with maximum effect and long-term benefits.

2 SUSTAINABLE DEVELOPMENT AND THE BUILT ENVIRONMENT

2.1 *What is sustainable development*

Sustainable development was intended at first to be a solution to the environmental crisis caused by intense industrial exploitation of resources and to the continue environmental degradation. The first widely accepted definition of sustainable development is "a development that meets the needs of the present without compromising the opportunities for future generations to meet their own needs" (Brundtland, 1987). Bruntland defined the three basic pillars of sustainable development: the environmental, social and economic. In this way, the concept has expanded the quality of life in its complexity, encompassing economic and social aspects in addition to environmental factors. There are two types of representations of this idea: one in which sustainable development is at the intersection of the three areas, and another that states the idea

of social inclusion and economic factors in the environment. This second type of representation is based on the systems theory (see Figure 1).

In recent years a fourth pillar - the cultural one has been defined, considered the key to a truly sustainable development. Why is sustainable development primarily a cultural problem, before being a political, social, environmental or economical one? Because it refers to a global paradigm shift, involving both humanity as a whole and each of us. In this respect the cultural dimension is understood in its widest sense. The cultural pillar thus includes the educational and institutional dimensions. In support of this idea, it is important to note that UNESCO declared the decade 2005-2014 the "Decade of Education for Sustainable Development."

The following chapters will present how the four pillars were integrated in the built environment.

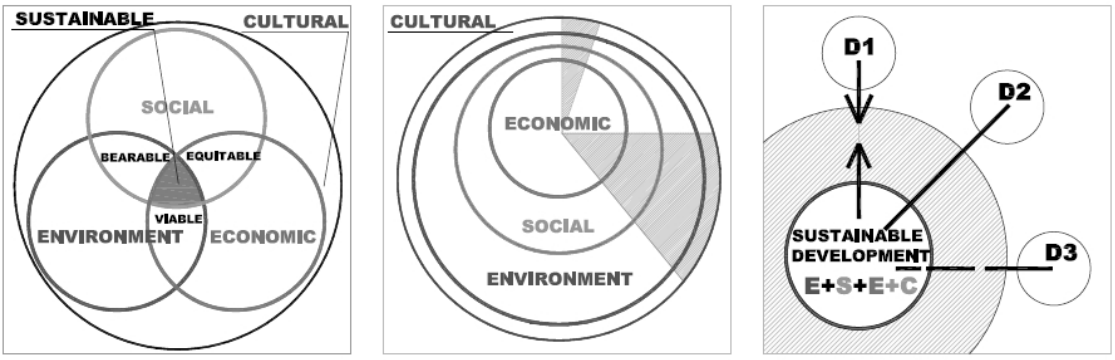

Figure 1. The two types of representation of the pillars of sustainable development and the gray areas, who are not completely defined and provide the maximum opportunities for research: D1,D2,D3 – different domains

2.2 *Systemic approach in sustainability sciences*

In terms of scientific research, any research topic of sustainable development requires an integrative way of thinking and an interdisciplinary approach. At the present moment, the gray areas, those who are not completely defined, are the ones that articulate the concept of sustainability globally defined and specific response in each domain (see Figure 1). These areas are actually the ones that provide maximum opportunities, by creating a dialogue between the various related fields in order to offer viable solutions.

2.3 *The built environment and the integration of the four pillars of sustainable development*

It is not difficult to understand the steps of integrating the sustainability concept in construction. As long as the discourse on sustainable development has been focused on environmental and energy component, the construction industry has found the answer in the energy consumption: the low-energy house, passive house, and then the zero-energy building. In the last decade the focus has shifted on integrating the four pillars of sustainable development (not only the ecological component, but also economic, social and cultural ones), which in the construction industry led to the birth of the green building and sustainable building models. (Dall'O & Galante 2010).

2.4 *Systemic approach to sustainable buildings*

According to data from 2006, responsible for energy consumption in EU are: transportation - 31%, industry - 28%, buildings for dwellings - 26% and buildings with other destinations - 15%. EU's biggest polluter is the construction industry (41% in total, estimated at 50% when taking into account the movement of people and urban problems). In other words, "the construction industry and related processes is half the opportunity to solve our current environmental issues" (UIA Declaration for COP15, 2009). Despite this fact, we can say that the construction industry answered relatively late to this challenge compared with other industries.

Gray areas (section 2.2.) appear not only in terms of top-down approach of the problem (systems of regulations and certification), but especially in terms of bottom-up approach, especially in the integrated design process (in the developed countries is only at the beginning).

In the building sector, this area of research contains rating systems, sustainable building assessment tools, life-cycle assessment and other integrative approaches. Any type of research about sustainable building will have to integrate the four pillars (social, economic, environmental and cultural), otherwise it will provide only a partial solution, without noticeable effects concerning a long term strategy.

3 SUSTAINABLE BUILDING RATING SYSTEMS AND THE QUALITY OF THE BUILT ENVIRONMENT

Defining the parameters of built environment quality and the rating systems on the basis of the four pillars of sustainable development means answering to some questions. What is measured and why such an assessment is necessary (who benefits from it)? What are the objectives and characteristics of these systems? What are the methods, indicators and criteria used in evaluating and which is the weight of different parameters?

Analysis and comparison of some sustainable building rating systems can bring new perspective, by identifying the strengths and weaknesses of each system as a whole. Such a comparison could provide a response to unsolved problems: how these methods could be used more efficiently and how can they affect the decision making process.

3.1 *The main sustainable building rating systems used in Europe*

Despite many common points, the existing certification systems are quite different. Major differences are due to the way they define sustainable development.

In Europe the following sustainable building rating systems are used:

-BREEAM – the UK system, the oldest one; although there are already thousands of certified buildings, the influential area is not too vast (UK, Netherlands, Northern European countries);

-LEED – the system used in the US and imported into several European countries; it has high penetrating power due to the ease with which it can be used; an important strength is the constant improvement of the system according to the response from the political, legislative and market-area; the promoter is World Green Building Council, which extended the global system (World GBC members in Europe are Germany, UK and for several years some other states have joined: Italy, Netherlands, Poland, Spain, Romania);

-systems developed in the Northern European countries (in which both the technical databases and legal framework are extremely well controlled, which makes the systems very effective locally, but more difficult to implement in less advanced countries);

-systems adapted from SB Tool (Canadian origin), which is a tool with great flexibility and versatility; it leaves the possibility of adapting the general frame to local conditions; it was imported in the Mediterranean countries: Portugal, Italy;

-HQE - the French system;

-DGNB – the German system, the newest one, but the most complete and easy to use, highly adaptable, based on clearly defined parameters and well grouped; it is already penetrating the market towards Central and Eastern European countries (Hungary, Russia).

In order to understand the common points and differences between the systems, we will present a comparison between the rating tools with the highest penetration rate in Europe (BREEAM, LEED and DGNB).

3.2 *Stages in preparing a rating system*

The main steps to follow in order to prepare a rating system are:

-defining what the context and to clarify what is evaluated;

-defining the main themes (here the major differences between systems occur: while some of them have as a starting point the pillars of sustainable development, others put great emphasis on environmental impact and energy savings, other issues being subordinate);

-selection the main criteria and assessment levels within each theme; the criteria should cover comprehensive information; also information should be accessible and easy to use; there can be descriptive or measurable parameters, defined as a set indicators; the most clear systems define the indicators within each criterion and quality levels, which will be converted into numerical values with the award of points;
-creation of the system; defining the weight of indicators;
-assessment process (methodology) - should allow self-evaluation and study examples in order to check the feasibility of the system, the competence of those involved in the evaluation process and to identify weaknesses in the procedure;
-presentation of the evaluation results so that they can be used for decisions making, monitoring progress and generally improve the quality of the built environment.

3.3 *Presentation of the systems used for the comparison: BREEAM, LEED, DGNB*

BREEAM (BRE Environmental Assessment Method) is the oldest building rating system, used mainly in UK and some European countries. It has been developed since 1990 by the Building Research Establishment Ltd. And it has different variations depending on functional typology (for administrative and office buildings, commercial, hospitals, homes, schools and infrastructure). The system is subject to continuous update. In some versions there is a guide for pre-estimation, which allows a self-evaluation of the project. The parameters are divided into seven chapters and each chapter has a set of specific indicators. These chapters are the same, only their weighting differs, depending on functional typology: energy, transportation, pollution, materials, water, land use and ecology, health and management. From the viewpoint of the pillars of sustainable development: the environmental pillar - includes all components, the economic pillar is treated completely separately (LCA and LCC are not included in the assessment), the social pillar - is found in chapters referring to transportation, health and management. The system seems tributary to the original version, taking into account especially the energy saving and ecology. Subsequent versions have improved the system without introducing parameters related to the definition of sustainable development and without modifying the chapters, therefore the system is closer to a "green building" rating system, than the "sustainable building" rating system, which focuses on integrating the four pillars of sustainable development.

LEED is the system originally developed by the US Green Building Council as a national standard for sustainable buildings. As a functional typology, LEED covers all types. Parameters are divided into chapters. The first variant dates from 1999, with a much improved version in 2004. Parameters are divided into the following basic categories: sustainable sites, water, energy and atmosphere, materials and resources, indoor environmental quality, innovation and process. In LEED 2009 there are additional points for innovation in design and for regional priority. In terms of the four pillars of sustainable development: the environmental pillar - includes all components, the economic pillar is present in some points, but without specific reference to LCC. The system has undergone many changes from 2004 to 2009, taking into account all pillars of sustainable development. However, a weakness is that, the chapters are the same as in early versions. Two of the most important strengths are: the system can be used easily and the interface can be understood in terms of overall results.

DGNB system is the newest one. The pilot phase was developed in 2008-2009 for administrative buildings and offices and will soon cover the entire functional typology. This system covers all components of sustainable development. The assessment is divided into six major topics: ecology, economy, socio-cultural and functional quality, technical quality, process quality and location (the latter is assessed separately). The concept is based on the idea of integrated design and on the four pillars of sustainability. Initial 63 criteria were studied, of which in the pilot phase remained 49. The DGNB certificate evaluates the building as a whole. In terms of the four pillars of sustainable development is the only system which contains all the pillars in a clear manner. The system has the advantage of being very flexible and easily adaptable to other types of functions. Finally generated diagram gives a clear idea on the strengths and weaknesses of the assessed building. The system requires the use of all basic standards and building databases (quantitative parameters), but also has quality parameters. The system has its weaknesses: it is not easy to use (due to abundance of technical data necessary to evaluate certain criteria) and does not assess innovation.

3.4 *Comparative analysis of the three sustainable rating systems: BREEAM, LEED, DGNB*

A brief comparative analysis of the three systems described above will be presented (the most important in Europe in terms of penetration rate). This analysis does not aim a comparative evaluation of technical and environmental aspects (energy, indoor environment, materials), nor the weights of some key indicators (this can be found in another research papers). The main idea is to understand the strengths and the weaknesses of different systems regarding flexibility and adaptability, the way they incorporate the four pillars of sustainability and the process management (see Table 1).

Table 1. Comparative analysis of three rating systems used in Europe: BREEAM, LEED, DGNB.

CHARACTERISTICS	BREEAM	LEED	DGNB
On the market from:	1990	1999-2000	2008-2009
Main goal	▪ Designed for professionals	▪ Used in the design stages, administrative and educational purposes	▪ Creating a tool easy to understand and easy to use, transparent
Market penetration	▪ More that 115.000 certified buildings and 700.000 registered for certification	▪ High-penetration rate (106 countries around the world due to the promoter USGBC)	▪ New tool, but rapidly expanding ▪ It extends into eastern Europe, China
Main characteristics	▪ Covers all functional types; ▪ Works with certified auditors; ▪ The main priorities remain energy saving and environmental issues; ▪ It works with certified auditors;	▪ Dynamic, updated continuously in relation to the market feed-back; ▪ Covers all functional types; ▪ Some variants allow the self-evaluation in the early stages of the project	▪ Currently there is only the variant for office buildings, but also works on other types; ▪ It works with certified auditors; ▪ The only system in which all four pillars of SD are clearly defined
How does it work	▪ Credits are divided in categories; ▪ The credits are multiplied by different weighing factors, that takes into account their importance	▪ System based on points (5 categories) and bonus points for 3 special categories	▪ The points have different weights (in the current model for office buildings 4 category of 22,5% and one of 10%); ▪ 5 main categories and 1 category separately assessed, related to SD pillars
Strengths	▪ The ecological pillar and its components; ▪ Some variants allow self-evaluation of the project; ▪ LCA and LCC are separately (economical pillar nor included in assessment)	▪ The ecological pillar and its components; ▪ The system can be used easily and the interface can be understood in terms of overall results	▪ Contains all the pillars and covers all the topics of sustainability; ▪ Allows the freedom to choose different variants from the project phase; ▪ Assesses the building as a whole; ▪ Very flexible;
Weaknesses	▪ Social and cultural pillars are poorly represented in the assessment;	▪ LCA economical pillar is present at some point, but there is no connection to	▪ It is not easy to use, due to the abundance of technical data necessary to evaluate cer-

	▪ It is closer to a green building assessment (first generation), instead of sustainable building assessment	LCC; ▪ The chapters are the same as in early versions	tain criteria; ▪ Does not assess innovation
Process management	-Planning/project phase + Construction phase + Final assessment	-/+ Planning/project - Construction phase + Final assessment	+Planning/project +Construction phase +Final assessment
Note: "+" = good process management in the phase of planning/ construction/ final assessment "-" = weak process management in the phase of planning/ construction/ final assessment			

3.5 *Conclusions of the comparative analysis*

While all systems have made great strides in terms of key principles of the assessment tools, known as the Bellagio principles (Hardi & Zdan, 1997), only the German system uses clearly defined criteria based on the four pillars of sustainable development. A weakness of many environmental certification schemes is that building assessment refers to the final object and consequently they cannot affect the decision making process. For this reason, all systems should have an interface flexible enough to allow the assessment of potential alternative decisions in the early stages of the project. In addition there should be developed a system capable to monitor progress throughout the whole building process, even during its life (degree of acceptance, the impact on beneficiaries, results dissemination).

4 STUDIES ABOUT PARAMETERS OF QUALITY IN ARCHITECTURE

In the last years the ACE (Architects Council of Europe) has begun the development of a system in order to clarify the assessment for quality in architecture in relation to sustainable development. The working group Quality of the ACE proposed a diagram of the parameters that define the architectural quality of a building. As it is a work in progress, it has some weaknesses, but is relevant the intention to make a classification construction quality on five levels.

In terms of architecture, different types of parameters are more difficult to quantify, but there is an alternative proposal based on the four pillars of sustainable development (Gaivoronschi & Andreescu, 2010). The types of parameters analyzed are (see Figure 2):

-parameters described by objective criteria of analysis, assessment based on based on calculation and measurements: safety and health, ecology and economy;

-parameters described by objective criteria of analysis, assessment based mainly on estimation: functionality, comfort, maintenance, quality of the process (in all phases, from project to assess post-building), urban and social values;

-parameters described by subjective criteria: cultural value (project's vision, atmosphere, image and identity, space and proportion)

The two big risks from the point of view of the architect are: excessive parameterization versus maintaining architecture in an area of the ineffable, an art that can not be measured. The keen aspiration to measure, classify, evaluate and hierarchies this domain too, will lead to improved buildings from an ethical point of view – improved objective parameters. On the other hand, new architectures, architectures with qualities that can't be physically measured will prove to be more fragile when the feed-back of these classifications will influence the market.

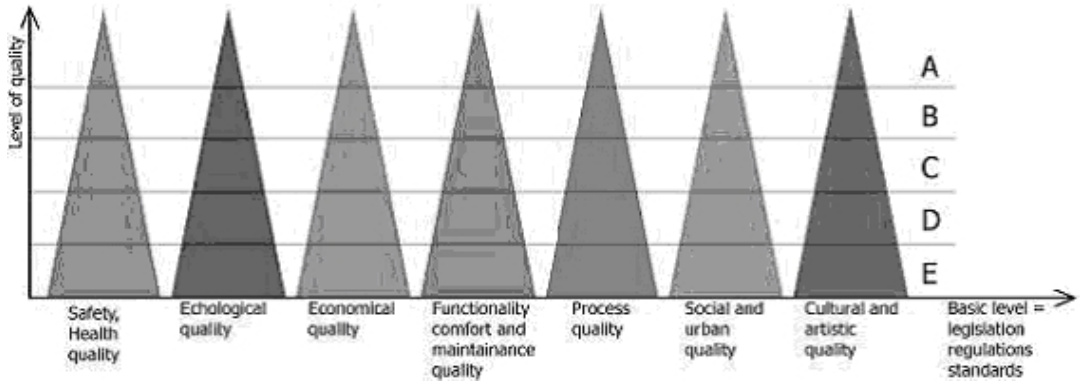

Figure 2. The diagram of quality in architecture proposed by architect Vlad Gaivoronschi.

5 MODELS FOR A BUILDING RATING SYSTEM BASED ON THE FOUR PILLARS OF SUSTAINABLE DEVELOPMENT

There are some new rating system models in an experimental phase. One of the most flexible, simple and efficient method that can be used also in the project phase was presented by a Slovenian team (Zarvl et al. 2009). The method followed the stages of creating a system presented in section 3.2.

The graphic output uses the "radar diagram". This type of graphic representation is the most common way in which people present benchmark information. A set of eight key indicators are used in order to evaluate the performance of residential buildings. The indicators chosen are related to the three pillars of sustainability, similar to the German system DGNB (see Figure 3).

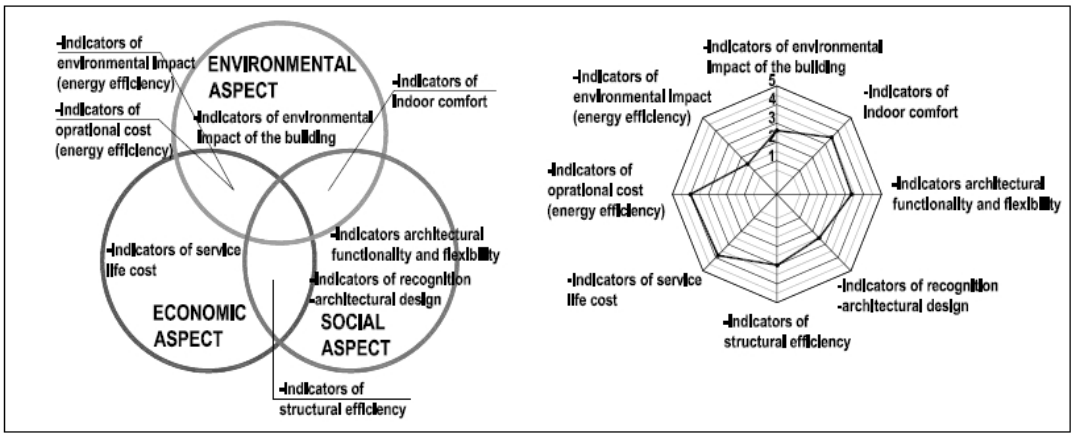

Figure 3. The system proposed by the Slovenian team , based on the pillars of sustainable development (Zarvl et al. 2009)

This model is easy to use in the first phases (the planning and project phases) and contains a minimum of eight key performance indicators that are considered the most relevant for a residential building (usually a number of eight to twelve key indicators organized in five levels are recommended in order to cover the relevant topics in a way that is easy to understand and control). The radar diagram is a good choice that allows the comparison between two different buildings that have the same functionality. It can also be used in order to explain the current status and the degree of improvement in different areas for interventions on existing buildings.

6 CONCLUSIONS

This paper has focused on analyzing the sustainable building assessments and certification systems currently used in Europe in parallel with the architectural quality grid - first integrative approaches to the sustainability issues in the built environment.

Creating a sustainable building assessment tool at national or regional level is necessary and it is particularly useful when it can be integrated in the early stages of the construction process (planning, feasibility study, project). As Romania doesn't have such a rating system, the next step in this research is the creation of an environmental rating system. This will have as a starting point the DGNB criteria, but it will provide more clear and easy to use data, similar to the model presented in chapter 5. The key performance indicators may be different then those presented by the Slovenian team, but they have to be specific, easy to measure and should aim to improve performance in an area that is critical in the studied context. The graphical result will have to be easy to interpret, to make possible the evaluation of the alternatives, strengths and weaknesses in order to make a decision. The radar diagram is considered the best graphic output in this respect, with a number of eight to twelve indicators and five levels of performance.

Certification systems are used mainly to assess the final object. But such an instrument proves to be really useful when it provides a consistent support for alternative solutions in the early stages of design, so that the best variant can be chosen depending on the economic, social, cultural and environmental conditions. As stated at the beginning, any solution built on environmental sustainability must be a systemic and contextual approach. When we will accomplish this step, both the design and decision-making will change totally.

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Analysis of the impacts of economic and social indicators to sustainability assessment

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ABSTRACT: Literature review shows that there is no standard method to assess buildings' sustainability neither to identify which items/indicators should be assess. Literature also reveals that early phases of a building project are essential to assure the buildings' sustainability. As so, a research project has been established aiming at improving early design stages of a building project by providing concepts and methods for increasing the whole life-cycle sustainability performance. Therefore, in a first phase it is essential to analyse which is the impact of taking into account sustainable indicators during the initial phases of a building, and which should be the chosen ones. Hence, the paper proposes a methodology to analyse the impact of considering social and economic indicators in a sustainable building construction and its assessment.

1 INTRODUCTION

The concept of sustainability is widespread since 1987 with the publication of the Bruntland Report "*Our Common Future*". Since that, several definitions and implications to the concept have been made (Forsberg and von Malmborg, 2004, Weytjens, 2009). Nowadays, it is accepted that sustainable development is supported by three pillars: environment, society and economics. Since construction plays an important role in the world's economy and society has a strong environmental impact, it seems obvious to link it with the sustainable development concept (Burgan and Sansom, 2006, Ding, 2008). Thus, all dimensions should be considered by all construction stakeholders during its entire life cycle and also should go hand in hand as part of the construction framework evolution (Ilomaki et al., 2008, Mateus et al., 2008).

Accordingly to the United Nations, more than 50% of the world's population live in urban areas (UN, 2010) and 80% to 90% of time is passed inside buildings (Direcção-Geral da Saúde - Ministério da Saúde Português, 2010). Therefore, it is critical to embed the building sector in the sustainability concept.

In the nineties, industrial sectors, including the building sector, started to recognise that their activity has a great impact on the environment. Since then, a shift in how buildings are design, built and operated was preformed, in order to mitigate the environmental impacts (Crawley and Aho, 1999). For this to happen, there were two main driving forces, public policy, which increasingly became more conscious and tighter in what regards environmental issues, and the growing market demand for environmentally friendly products. Public policies have been settled down to meet the objectives outlined by the *Rio de Janeiro Conference,* in 1992. However, according to (Ugwu et al., 2005) this conversion into real practice remains a difficult task. Science and research in sustainability represent an important contribution to facilitate this step. With this in mind, a lot of methodologies and tools have been developed since 1990, year in which the first sustainability assessment tool was published (Haapio and Viitaniemi, 2008). Nowadays, it is possible to count more than 70 tools for evaluating and classifying buildings according to sustainability indicators. Nevertheless, most of them are mainly focused on

environmental protection and there is a lack of participation of all the stakeholders involved in the building life cycle (Ugwu et al., 2005, Saparauskas, 2007, Braganca et al., 2010).

Taking into account the high number of existing tools and methodologies, which have inherent problems and variables, the International Organisation for standardisation (ISO) is attempting to achieve harmonisation in sustainability building assessment and in environmental construction products declarations. A summary of the ISO standards in this regard, developed until now has been made e. g. by Fernández-Sánchez (2010). Also the European Committee for Standardisation (CEN) and CEN/TC "Sustainability of construction work" have been developing voluntary horizontal standardised methods for the assessment of the sustainability aspects of new and existing construction works and standards for the environmental product declaration (EPD) of construction products (Haapio and Viitaniemi, 2008, FOLVIK and WAERP, 2009).

Many authors support that early design phases of a building are the most crucial for the sustainability performance of the building (Weytjens, 2009, Thompson and Bank, 2010). In building design various aspects are analysed, compared and compromised. Selecting final solutions among alternative systems and products requires good understanding of the owner's and end users' needs. Moreover, performance requirements and sustainability aspects need to be considered. All these issues influence the building's life-cycle sustainability performance.

Consequently, and considering the constant evolution on the building sector towards a sustainable built environment there is a need to establish and develop a design support tool to integrate, deal with and to ensure the sustainability of buildings. As so, this paper shows the first steps to achieve the mentioned goal. It is aimed to analyse the influence of the social and economic indicators on the execution of a building project and construction.

2 OBJECTIVES AND SCOPE

As it was previously referred there is a need to develop and implement a systemic methodology, which supports the design process and is capable of gathering, in a simple and easy understandable way, all the information needed to build up a sustainable new building. At the moment there is no norm or standard to indentify indicators and measure a building's sustainability, following a technical-scientific model, existing however some proposals. It is now defended by many authors that the best way to improve a building's sustainability is to consider all the sustainable dimensions right at the early design phases of the building project. In order to be sustainable, a building must obey the following aspects: respect for the environment, social integration and social economy, maintaining cost, time, quality and performance within an acceptable range (Braganca, 2010).

With this in mind, this paper represents a part of what is being developed to achieve an early stage design support tool. A first and important task of the research is to analyse the design process of buildings in order to identity how the process is organized, to know which are and how the sustainability performance requirements are defined and how these requirements influence the buildings' sustainability assessment, being this latter aspect the aim of the paper.

3 METHODOLOGY

3.1 *Background*

The basis of the presented research is to, in a first stage, identify and establish a set of economic and social indicators, through literature review and by inquiring the buildings' stakeholders. In a second phase, is to survey and interview designers, suppliers, users and clients and by following up on developers processes.

The literature review showed several studies concerning the sustainability indicators' identification. Fernández-Sánchez (2010) proposed a methodology, based on the identification of sustainability indicators by considering sustainability as opportunities for the project and on the establishment of indicators for measuring and controlling these opportunities. For that, they used risk management standard methods (PRAM and PMBoK) and the framework of ISO 21929-1. The identification phase was performed through literature review, survey to

stakeholders, comparison between answers, analysis of check-lists and diagramming techniques. The authors reach a set of 30 indicators and verified that the best technique to understand accurately the differences between all stakeholders, allowing a better identification of indicators, is the stakeholders' survey.

Ugwu *et al*, had published several papers over the key performance indicators (KPIs) identification aim (Ugwu et al., 2006a, Ugwu et al., 2006b, Ugwu and Haupt, 2007). In (Ugwu et al., 2006a) they propose an analytical decision model and a structured methodology for sustainability appraisal in infrastructure projects – SUSAIP. Specifically for the KPIs identification they propose a framework based on a primary literature and governmental guidelines review and case-study data collection, a stakeholders questionnaire to identify the core sustainable indices and a survey to senior stakeholders to test, select and map the indicators to national sustainability goals. This proposed methodology was used by them in the other mentioned papers. From the different case-studies preformed it was possible to identify the existence of a vast set of indicators, including not just environmental, economic and social indicators, but also health and safety, resource utilization, and project administration.

Alwear and Clements-Croome in (Alwaer and Clements-Croome, 2010) presented a conceptual model for the selection of KPIs for intelligent buildings. They propose a three-step model that, like in previous studies. The first step is to identify the main KPIs based on literature review and on a pre-survey to selected stakeholders; the second is to refine and test the selected KPIs by testing the level of importance of the selected indicators and the third step is the development of a sustainability assessment model – SuBETool).

Huovila and Rozado in (Huovila and Rozado, 2010) show an approach towards value metrics from the point of view of end users of facilities. They start from a life cycle performance measurement against related costs and carbon footprint. Those indicators are then bridged with owner's sustainable businesses, happiness of changing users of the facility and citizens' quality of life. First, they used CREDIT (Construction and Real Estate - Development of Indicators for Transparency) project (Porkka et al., 2010), which has developed an indicator framework focusing on issues that are relevant for the users in the operation phase of buildings, trying to link that with metrics, which can be used in real estate business by owners, and also with the user experience. On the other hand, they applied also the Perfection (Performance Indicators for Health, Comfort and Safety of the Indoor Environment) project (Huovila et al., 2010, Desmyter and Huovila, 2010) which aims at developing a framework for indoor performance indicators and mapping them to sustainability.

In what regards cost indicators, Stoy *et al.* in (Stoy et al., 2008) intended to develop a methodology to considerably reduce the prediction error during the cost estimation in early design and propose positive drivers for the success of construction projects. To achieve these goals the author started with a literature review to identify the potential cost drivers and their relation with the building construction costs. The collected drivers were than exposed to a group of specialist in order to selected and determine the main ones. After that, an empirical study was performed on 75 residential properties. A regression model was used to exam the correlation between the construction costs and several cost drivers. The study allowed the identification of the following cost drivers: Compactness of the building, number of elevators, absolute size of the project, construction duration, proportion of opening in external wall and region.

3.2 *Indicators identification*

In order to achieve the goal, the followed methodology is divided into 3 phases, as the reviewed literature proposes:

- Critical selection factors and indicators;
- Survey to stakeholders;
- Results analysis.

The first phase consists in choosing the most appropriate criteria to formulate the set of indicators. As so, as primary approach a literature review was preformed, like it is stated in background section and a second step consists in surveying the main stakeholders as: architect, engineers, suppliers and clients (Alwaer and Clements-Croome, 2010), in order to determine which would be the most relevant social and economic indicators to interfere in the sustainability of a building and its assessment.

By the literature review it is proposed to put under analysis the set of indicators presented in Table 1. To select these indicators, besides using the publications mentioned in the previous

section, there were also taken into account the indicators from (World Steel Association, 2010, BRE Global Ltd, 2009, iiSBE Portugal, 2010).

Table 1. Proposed Social and Economic Indicators.

Social Indicators	Economic Indicators
Culture	Costs
Cultural heritage	Direct Costs
Built heritage	Indirect Costs
Respect customs and beauty of the place	Life Cycle costs (investment, initial cost, maintenance costs, demolition costs
Accessibility	Local economy
Public access (transports and amenities)	Bureaucracy
Biodiversity access	Types of contracts
Safety and Health	Synergies with actors
Safety and health for workers	Product warranties
Impact on global community	Installations and set
Security of infrastructures	Project management
Safety and durability	
Usability	
Thermal quality	
Acoustic quality	
Indoor air quality	
Lighting conditions	
Ventilation conditions	
Materials toxicity	
Aesthetics quality of building and indoor spaces	
Functionality	

The list shown in Table 1 should be presented to the stakeholders, for them to identify the main indicators based on their influence on the whole life cycle of a building. Nevertheless, they should be invited to attach new attributes to the proposed indicators and new ones, according to their experience and knowledge.

3.3 *Survey*

After selecting the main indicators a second and deeper survey is needed. This survey aims at finding the impacts of considering social and economic issues during the early phases of a building's life cycle. Therefore, there is a need to select few running projects of several actors in the building project, as following up a building design in a design office and following up the construction of materials and technologies needed for the building construction. This is an important phase of the research project, as it allows the understanding about the knowledge of the actors on these issues, their concerns, doubts and fears when applying them. The gained know-how enables to reduce the barriers of up taking sustainability principles. This is possible since it allows improving the methods of considering these issues, giving also an excellent basis for the work that needs to be done in order to achieve the support design tool and its acceptance by the stakeholders. In order to have a better view over the actual reality, the survey should be performed to different types of building solutions, as steel-framed and reinforced concrete, and in different locals, as different regions in a country or even in different countries analysis.

In this way, the parameters analyse during the survey for each set of indictors is shown in Table 2. This task might need a long period of time to be executed, as so, it is essential to design a cohesive and coherent data management system and that reliable data is collected. However, this back-office work is not under analysis in this paper.

Table 2. Proposed parameters and stakeholders under survey.

Stakeholders	Parameters
Architect	Expectations
Engineer	Difficulties
Construction Materials Supplier	Advantages
Project Manager/Coordinator	Personal opinion
Client	How the issues are deal with
	Main constrains
	Importance of each item

3.4 *Results analysis*

The analysis of the gathered data is a decisive and extremely important process of this methodology. As proven in background sections, there is not only one method of analysing the collected data. So, it is proposed to be used statistic methods as well as sensitive and multi-criteria analysis methods, (Alwaer and Clements-Croome, 2010, Balcomb and Curtner, 2000). These methods must be applied to help on an empirical assessment, allowing reducing errors and subjectivity on the results. It is important to rank all the aspects given as answer to the parameters and determine their final impact in the building sustainability.

The results should allow identifying the weaknesses and strengths of all stakeholders when considering social and economic issues.

4 CONCLUSION AND FURTHER RESEARCH

As stated in the introduction there is no standard methodology to assess and guarantee the sustainability of a building. With this in mind a research project is being carried out to develop a support design tool aiming at improving the buildings' sustainability in early design phases. This paper presents the first step of the research, the development of a method for identifying the impacts of social and economic indicators on a sustainable building construction and assessment. It is of high importance to understand how these issues are dealt with, during the early phases of a building, and how they interfere in the final assessment.

The proposed methodology constitutes a first approach towards the development of the aimed tool and allows a true knowledge on how design process is conducted and which are the barriers of up taking sustainability principles.

It is important to state that the methodology needs further research. It is mandatory to develop and deepen the results analysis by applying the methodology to case-studies.

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Examination of Turkish House in the Context of Sustainability

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ABSTRACT: The Turkish House can be defined as the type of houses which Turks have lived in throughout history. The basic system of construction is the timber frame with infilling material or the lathe and plaster. In this paper the traditional Turkish houses will be examined in the frame of sustainability of the timber frame construction system. The sustainability criteria will be summarized below and will be discussed with several cases.

1 INTRODUCTION

The traditional architectural style can be considered as modern and permanent in terms of, reflecting the community's life style, reasonable interpretation of the material and the structure, the building and the environment relationship's integrity. When traditional architecture is examined, it is seen that, sustainable building design approach is achieved at the very beginning adapting to climate conditions. The aim of the sustainable design approach is, to maintain to adapt to the characteristics of the topography of the land and to the climatic conditions, minimizing the energy use by the building material and structural elements. Traditional Turkish House, as one of the representatives of the traditional architecture, has a sustainable building design approach which can be read both from the plan, the section, the volume and the building components details.

2 GENERAL DESCRIPTION OF TRADITIONAL TURKISH HOUSE

2.1 *Vernacular Settlement*

Since the beginning of tribal acts of the human beings, housing has been one of the main needs of the mankind. Within this need, many settlements were formed and most of them grew, becoming the cities of today. These mature brought different variations of settlements depending on the cultural, economical, physical features of the environments and communities, which they were built in. A fast examination on these settlements may form an idea of complete difference at every comparable element. But a closer look could point out to some similarities of the formation of the settlements. These can be the materials, construction techniques, and formation of the house plans and body according to the climatic conditions and sunlight or the topographic features of the environment. The Traditional Turkish House we know today has begun to be formed during the settlement of the nomadic Turks from the Middle East to Anatolia. This type of housing has spread through the Southern Anatolia to the Balkans forming a large area of social and cultural typology. The principles of construction for the houses mostly are the same but the cultural details completely vary.

Accepting the Islamic religious life and settling in Anatolia as a homeland, and changes in the cultural and social characteristics joining with the aerial properties of Anatolia, like climate, topography, materials etc., started the progress of a new settlement style and house typology, Turkish house (Tanac, 2007).

The vernacular settlements have developed with a similar process just like the Turkish house. The main fact about the settlements is to acquire a source of any kind in order for the community to survive and defray their needs. Just like the settlements, the decision for the area needed for a house is decided by the needs of the family and an area is bordered for construction of the house. At this point the relations with the street, or in other words "the community" is shaped and formed (Tanac, 2007). A high garden wall with an organic formation of the streets and roads according to the topographic criteria is the mostly seen part of a vernacular settlement. And finally the houses are built in these areas. The ground level is formed by the organic development of the streets where the upper levels are built with wooden frame structures forming a 3rd dimensional accent (Küçükerman, 1995). *It is interesting that the houses that form a street have a volumetric architecture instead of architecture of facades.* This is the most important feature of the Turkish House. *When the houses are studied in relation with street, garden and the neighboring buildings, it is noted that in each example a different space or spaces are facing the street, garden or neighboring building, these spaces being the rooms, room and hayat, or hayat* (Yürekli, 2007).

2.2 *The plan typology of the Turkish House*

A ground floor closed to the street with a stone or adobe wall and a upper floor which sits on either load bearing stone walls or wooden studs characterizes the house type generally seen within the geographical boundaries where the Turkish house is to be found. The upper floors have a timber frame construction. The middle floor, if there is one, has a low ceiling and is either a mezzanine floor or a whole floor. The top floor has, through time, become ever livelier with several projections and with multitude of windows which are of a standard size. The roof always slopes on all four sides. This is one of the main discriminating characteristics of the Traditional Turkish House (Günay, 2007).

The most important parts of the Turkish House is the "sofa-hayat" and the "room". Sofa-Hayat; (Hall) is the main space within the Traditional Turkish House. It is the circulation and distribution space. One can reach to the sofa which is the most crucial detail of Traditional Turkish architecture from the garden-courtyard. "Sofa" in the Turkish House has an intrinsic regulatory role in the integration with surrounding cells (Ünlü, 1997).Turkish plan typology was firstly classified by S.H.Eldem due to the spatial organization of Sofa spaces, as Outer-Inner-Central Sofa typed houses (Eldem, 1955-1972) (Eldem, 1984). Eldem defines the "Turkish House" according to the plan type of the piano nobile-the first floor of the main building of the dwelling unit. The sofa; as a semi-closed or a closed space shared by the members of the family is the basis of the typology (Eruzun, 1989, s. 70). The evaluation process of Traditional Turkish House indicates that the outer sofa type house is a very common typology especially in the small towns of the countryside (Eldem, 1955-1972) (Goodwin, 1971). Many of the daily activities occurs in Sofa space due to its semi-private character. A raised wooden platform for sitting on one, two or three sides oriented towards a vista/panorama is the architectural elements of this space. A semi-open projection with a lattice-window, a projection to the street and/or to the courtyard, staircases, projected and raised platforms for resting, a rectangular planned space open at one side, either in the form of an extension of the Sofa or as a single semi-open space acting as a Sofa are the other important features of the Sofa (Asatekin, 2005, s. 403). Room; Oda, literally "room" but a multipurpose room often with an elevated platform that was used as a seating area by day and a place to lay sleeping mattresses by night (Finkel,2010). The main private unit, and designed according to ergonomic requirements (Asatekin, 2005, s. 403).The most important approach to typology according to the room has been established by Kuban (Kuban D., 1995, s. 227-230) (Kuban, 1975). He relates the typical plan of the "Anatolian Turkish House" directly to Turkish-Islamic family structure and the status of the family unit within the social structure. The main feature of the plan is the room with a semi-open space in front. Repetition of this unit is the basis of the typology (Kuban, 1975, s. 199). There may be

differentiations of room use including: summer/winter rooms. Summer rooms are mostly placed on the upper floors with larger openings to street or courtyard, and the winter rooms are placed mostly at ground floors with smaller openings and thick walls (Asatekin, 2005, s. 407). Surfaces of the rooms are carefully designed both horizontal and vertical surfaces are designed to express the hierarchy of the space.

3 EXAMINATION OF TRADITIONAL TURKISH HOUSE IN THE CONTEXT OF SUSTAINABILITY

The only effective factor which human being cannot change and have to adapt his constructions and settlements to is climate. The vernacular settlements of Traditional Turkish Houses are generally formed as concentric settlements in desert conditions and climates, or separate and dependently formations according to the wind and the sun in moist areas. They obtain the sustainable building design criteria. The sustainability context will be examined in three titles;

- Adaptation of Turkish House to climate, environment and nature
- The shelter of the building and selection of materials
- Preventing the Energy Loss

3.1 *Adaptation to Climate, Environment and Nature*

The main idea of Turkish House is a house type which adapts well to the environmental features, to climatic conditions and the nature. The most important criteria are considering the direction of the sun or the primary wind direction parallel to the view aspects. To obtain this criterion, the plan and the façade typology of the house is organized according to the climate conditions, and the topography of the land.

"Sofa" – the open family areas of the Turkish house which forms the facade of the vernacular settlement is shaped due to the climate conditions as outer, inner, and central type. Location of the sofa indicates the main criteria of the settlement. It is mostly located at the most important place of the house. In desert climates "sofa" is always placed in the middle of the house or in some examples it does not exist. "sofa" is mostly placed according to the visual criteria but being on the foot of a hill the "sofa's direction can be dedicated considering the climate effects like the sun direction and local permanent winds. In some cases, floors are established according to seasons as well. The first floor which has more openings is used during summer time, and the mezzanine floors which have better sheltering are used during winter time. The mezzanine floors when designed according to winter conditions are equipped with furnaces, and are placed over the barns, to obtain heat isolation of the rooms. The height of the ceiling of this floor is lowered to obtain heat isolation.

The Turkish House is placed on every kind of land in a matured way. Effect of the topographic factors on the vernacular settlements is the areas' being in a slope or plain land. Houses built in a slope area, like the foot of a hill or similar, are more independent than the houses built in plains. The criteria of a house at the foot of a hill can be the view aspects, direction of the sun or the primary wind directions where a house on plains can only consider a choice between facing the street or the garden and can only take constructive precautions for the sun or the winds of the area. Because of this the streets of a settlement at the foot of a hill, is more deserted than the streets of a settlement in plains. But the streets of a settlement in plains are mostly the center of the social life. The streets of a hillside settlement are formed according to the topographic slopes of the area, and mostly follow the slope as parallel as possible. The connections between two or more parallel streets are made through stairs or short street connections at points where the slope drops to a comfortable value for such connections. In every land type, the house is located on land on south-north direction, to obtain more efficient daylight into the living spaces of the house.

This formation brings forth very good examples of an organic vernacular facade. Although it is expected for the plain settlements to have a more organized and functional facades, but they

don't. The settlements at plains are as much organic as the hillside settlements (Arû, K. A. 1998, pp.76).

The walls facing the south facade are mostly designed for the location and a climate criterion's in order to get a better use of the sun. The south façade of the buildings has more openings than north façade, it has rhythmic fenestration orders, two windows are placed one below the other. The lower windows have wooden shutters. The upper window is for getting light into the room when the shutters of the lower window are closed during the cold weathers. Several projections, from rooms or sofa spaces are made to obtain more sun and breeze into the spaces on the south facades. The eaves of the vernacular settlements' facades are also formed according to sun. The length of the eaves changes the character of the settlements directly. A closer research on the eaves points out a group of values matching the sun light directions of the seasonal turns. The lengths of the eaves are directionally related with the areas' seasonal turns' sun direction angles.

The walls facing to North are mostly solid and as thick as possible to prevent the cold air, and keep the wind away from the house. The furnace is placed on the thick and solid stonewall to prevent the fire diffuse. The furnaces are placed in the rooms located near the south directions, or in the rooms, which are in the middle of the two rooms that don't have furnace equipment.

The spatial organization of the elements of the room is not only functional but also arranged to prevent energy loss. The closet-cupboard is the most important element within the room. Every room has its individual closet. The purpose of the wooden closet in the houses is to obtain the noise control between two individual rooms located side by side, and the "sofa" placed between the rooms (Kuban, D.(1995), pp.109, Küçükerman, Ö. (1996), pp.45). The wooden floors are covered with carpets to obtain the heat isolation of the room. The ceiling and the ornaments of the ceiling have much more symbolic meanings than the building physics. The doors; are placed angular not to be opened directly into the rooms, just not to cause grow cold in the room (Kuban, D.(1995), pp.121, Küçükerman, Ö. (1996), pp.38).

3.2 *The shelter of the building and selection of materials*

The structural elements and materials used in Traditional Turkish House changes according to the climatic conditions, natural sources of the settlements. That is the reason why the structures adapt to the land efficiently, and are easily designed according to sustainable design approaches. The Anatolian region can be classified within 4 regions as; Aegean –Marmara Region, Black Sea Region, Middle Anatolia Region, Eastern Anatolia Region, and according to the conditions of the region's the material types can be differed.

A ground floor closed to the street with a stone or adobe wall and an upper floor which sits on either load bearing stone walls or wooden studs characterizes the house type generally seen within these geographical boundaries. The utilization rate of timber, stone, adobe and brick materials change according to regional differences. In cases when going to the settlements located in eastern Anatolia, it is really hard to find timber as the structural system element, it is used as the sub-structural element supporting the masonry stone load bearing wall, but when going to west, timber becomes the main structural system element. The upper floor sits on the masonry ground floor and has a timber frame construction. The middle floor if there is one, has a low ceiling and is either a mezzanine floor or a whole floor.

Climatic conditions, flora of the region, technical limitations and or traditions are counted as factors influencing the choice of construction materials and techniques. The timber skeleton system with various infill materials is used to identify the "Turkish House" (Günay, Türk Evi Geleneği ve Safranbolu Evleri, 1998, p. 22). (Günay, 2007) The houses can be classified in two main construction techniques.

- Traditional dwelling units constructed with a load bearing wall system: construction materials can be timber, mud brick, brick and Stone. This system is called as Hatıl construction system. The main construction material is stone with mud mortar.
- Traditional dwelling units constructed with timber frame and infill system; this group varies according to the use of different infilling materials: without any infill material, the outer surfaces of walls are covered by lath plaster work or wood which is called as

Bagdadi construction system; with mud brick infill; with timber infill, with Stone infill which is called as Hımıs construction system.

Hatıl construction system is a system where a masonry wall is supported by horizontal timbers. The material of the masonry wall is mainly stone with mud mortar, but mud brick, brick or timber can be used as the material of the masonry wall depending on the geographical conditions (Langenbach, 1999). Horizontal timbers are embedded into bearing wall masonry. The uses of horizontal timber beams which are embedded within the masonry load bearing walls give the building the ability of resist the horizontal lateral forces that occur during earthquakes. These beams are called as "Hatıl" in Turkish Traditional houses.

Hımıs construction system is simply described as a timber frame with masonry infill such as bricks, adobes or stones. It is possible to classify traditional hımış construction depending on the structural system such as; system contained bracing elements and no bracing elements. In this system studs are themselves tied by only other horizontal timbers. In this system studs are themselves tied by only other horizontal timbers. In this buildings, vertical timber elements do not subjected to tension direction to grain whereas timber have high specific strength for this grain direction. Structural timber, with all of its natural defects, shows an unquestionable brittle character under certain when subjected to shear or tension perpendicular to grain direction. Thus, it is not expected to resist lateral forces without damage during an earthquake due to low lateral stiffness of the frame system (Dogangün, Tuluk, Livaoğlu, & Acar, 2006, s. 986).

Bagdadi construction where the voids between timber framing members is filled lighter materials or with trunk shells are transformed into a filling material by sand and lime mortar. The interior surfaces of walls are covered by lath and plaster work or wood, whereas the outer surfaces are either plastered or non-plastered or wooden plastered (Dogangün, Tuluk, Livaoğlu, & Acar, 2006, s. 987).

The timber frame construction is compatible with the forest cover Anatolia and the Trace region and is also preferable because these regions are within the seismic zones. Furthermore, this method enabled quick construction and therefore suited the needs of an ever-expanding society, continuously on to move. For the same reason the details of wood construction are very simple. This construction method facilitated the reconstruction within a short time when whole quarters were destroyed instantaneously by fire.

Roof is purely structural. To construct a roof rafters are placed on the top plate of the frame but in some cases a secondary beam-a purlin can be used as well on the top plate. Rafters are connected to the top purlin on top of the roof. This top purlin is supported by posts in approximately 200 cm intervals. Like the floor rafters are covered with firstly a timber boarding, then tiles are placed on this timber layer.. The roof construction usually cannot be seen inside the rooms since the ceiling of the room is covered with timber boarding, this coating layer is supported by ceiling joists similar with the floor joists. The ceilings of the important rooms are usually ornamented. The moldings are used in the connections of wall and ceiling surfaces.

3.3 *Preventing the Energy Loss*

The space organization and the materials that are used according to this space organization are very well designed to prevent the energy loss of the building in Traditional Turkish houses.

The sofa and direction of the sofa chances according to the weather conditions to prevent the energy loss. Location of the sofa indicates the main criteria of the settlement. In desert climates sofa is always placed in the middle of the house or in some cases it does not exist. The sofa space can be a semi-open place or an open place according to the weather conditions of the settlement. The sofa can be as inner sofa-outer sofa-central sofa.

The design of the facades of the buildings reflect the climatic conditions. The timber frame construction; facilitated opening more windows building projections and wide eaves are located on south direction. These items provide control over climatic conditions and enable the building to breathe in humid climates, help to prevent condensation and moisture in the rooms. On the contrary to south façade, the north façade is solid and have very small openings to prevent the building from cold air.

The walls facing the south facade are mostly designed for the location and a climate criterion's in order to get a better use of the sun. The south façade of the buildings has more open-

ings than north façade, it has rhythmic fenestration orders. For preventing energy loss from the spaces that get the sun light, the doors do not open to the rooms directly. The floors have carpet coverings to obtain heat isolation. The fireplace is placed on the thick and solid wall to prevent the fire diffuse.

The eaves are very important elements in preventing the energy loss. It matches the sun light directions of the seasonal turns. The length of the eaves change according to the facades of the houses. Eaves locating on south direction are wider than eaves locating on north direction to control the sun light. The length of the eaves is directionally related with the areas seasonal turns sun direction angles.

4 CONCLUSION

These historical traditional settlements are preserved to nowadays since 18th –19th centuries. and can be an example of sustaining the eco-efficiency of the buildings. In dry and desert areas the settlement forms a concentric formation in order to protect from the sun. But in moist areas the settlement forms itself according to winds like offshore breezes. In cold areas the North walls are thick and solid, but the south walls are light and organized for the best use of the sun. The only factor, which always is tried to be controlled, is the sun. Long eaves and location of the "sofa"s are the main acts, which affect the facade of the settlement. The elements of the rooms are used both as noise, heat and the light control elements, and as elements of the houses.

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Role of Codes for Sustainability Assessment of Constructions

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ABSTRACT: Regional cites have been growing rapidly over the past decade as a result of global urbanization. The build environment displays us a major challenge. A performance of Sustainable Building Management is the key to solve a serious problem when responsible authorities are encouraged managing efficiently social, spatial and environmental consequences due to fundamental misconception that sustainability and the environment are one and the same issue. Possibly, improving the use of misapplied Codes of the Sustainability Assessment of Constructions (CSAC) may lead to a reduction of environmental chaos. In this paper is presented the aim towards the identification of challenges to suggest the best suitable solutions for management methods and tools attempting to enhance the proposal and implementation of CSAC. Derived conclusions from this study are given towards promotion of Sustainable buildings – for designing, construction and maintenance in order to protect public interest, sustainable and healthy environment for all in Region.

1 INTRUDUCTION

Alongside the environmental destruction in developing countries there are many new ecological towns being developed in the world as a beneficial example. They could challenge all interested parties in developing appropriate sustainable environment. Within urban planning the build environment displays a major role and their failure will probably determine life quality for the majority of end-users. In addition, the building programmers' requires enduring appliances of common used model of sustainability, which has to do with idea of long term well-being construction and takes place when community, environment and economy are in balance, or "triple bottom line", abbreviated as TBL as known as "the three pillars" or "people, planet, profit".

The inquire of identification and recognition the environmental destruction, inappropriate planning and designing and an unsustainable buildings, requires an assessment of abovementioned demanding targets, in particular the sustainability assessment of constructions and comparable alternatives of buildings assessment management methods, which should be leaded seriously, with an attempt to act in sensitive and human manner towards a better build environment.

During the emphasis to analyze recent efforts for measuring sustainability of buildings, across the areas of lack of sustainable developing process and it consequences, we faced the complexes diversity of sustainability issues, such as: differences of wealth and opportunity between the city's well-heeled and poor habitants, well-being, security and sanitary conditions, and other differences of human needs, Maslow's Hierarchy of needs. To live healthy and truly could become more than easy, it takes effort and commitment not only to oneself but also the environment for everyone and the next generation to have their physiological needs met too.

The physiological needs, basic needs, which includes Air, Water, Food, Shelter, Sleep, in today's conditions emphasized as proper human function that people need, "clean' air, 'clean' water, 'clean and real' food, 'clean' dwelling, 'restful and safe' sleep, are basically sustainability build environmental concerns. But look at the earth today, at studied case – expansible cities,

trash as a major problem, water getting contaminated, chaotic build environment, unintended consequences of our daily activities! Inattentive issues which impacts directly on our current live! Are we capable to ensure next generations better environmental conditions and manage efficiently corporate giants involved in big environmental mishaps? How we could manage and improve methods of control of global, social and cultural discrepancy towards a better environmental developer in general and/or sustainability of construction in particular?

2 OBJECTIVES

The overall objective of our paper work was towards the identification of challenges to suggest the best suitable solutions for management methods and tools attempting to enhance Sustainable Environmental Management. Specific objectives were to introduce findings and useful data to suggest draft proposal for Code of Sustainability assessment of Construction (CSAC) guidance, as a new national and/or regional standard form, that links Codes for Sustainable buildings – for designing, constructing and maintenance of buildings to a higher standard of sustainability. That will protect public interest and secure a sustainable and healthy environment for all in Region.

The goal of implementing the CSAC include: identifying and benchmarking best practices of construction; communicating common goals, experiences, and methods; and providing a directional tool to measure progress toward the concept of a "sustainable habitat". Ideal assessment code identifies the most important attributes of a sustainable habitat, is calculable and comparable, measure more than eco-efficiency, assesses processes and motivations and is comprehensible to multiple stakeholders. The cross-institutional assessment, the CSAC presented in this paper varies in terms of stage of development and closeness to the "ideal tool", is relevant and its variables are shown through its structure and content. The following critical parameters to achieving sustainability in higher level are matters to decrease whitewashes, pursuing incremental and systemic change simultaneously, to increase habitant conscience by sustainable development education, and engaging in cross-functional and cross-institutional efforts.

3 GENERAL INFORMATION

3.1 *Background: Requirement of Sustainable development*

The example taken for expansible city type is Pristina, capital city of the newly independent state of Kosovo, Kosovo's wealthiest municipality, grown from a small trading town, with 18,800 inhabitants in 1910, to a recorded 20,000 inhabitants in 1948, 108,000 by 1981 and approximately more than 550,000 inhabitants recently. This growth, developments and the proceedings of economic and political changes within two late decades, and conflict, have impacted upon the achievement of the city's Strategic Plans and developers. Rapid growth effected beyond the harmonic balance of community, environment and economy. Actually, habitants, area and cost aren't harmonically apprehended. For a long time the sustainability environment is seen by many as a restraint on development and only recently has it been recognized as a justified restraint on inappropriate development.

Moreover, there is a lack of capacity in terms of qualified and experienced environmental managers, necessary when rising expectation and speed of population, or when answering surfaced questions: can we maintain and improve live quality whiles radically improving the effectiveness in how we use all our resources, reducing pollution and waste, uncontrollable build environment, and manage sustainability environment? Which appropriate forms, contest, methods and authorities to use when building human and health environment?

3.2 *Observable evidence of codes and standard appliances*

All stakeholders in regional construction industry today need to adopt the principles of sustainability in their activities. There is consequently a rising demand for tools to support decision-makers in finding sustainable solutions. Within region are not yet obligatory policy to imple-

ment accepted regulations, policies, standards or guidelines on how successfully implement a sustainable project management process that delivers sustainability constructions. Despite all those laws, application and management confronts with difficulties, especially in environmental assessment.

Sustainable environment, thus sustainable construction has become an essential factor in planning new developments. Sustainability comprises social, economic and environmental issues and these overlaps with many specialist disciplines in the course of building phases. Defining sustainable performance is complex, and careful assessment is needed to make sure that the objectives are realistic, manageable and deliverable. For designers, clients and project managers this means we have to create healthy buildings and places to support communities, enhance biodiversity and contribute to reversing unsustainable trends in pollution and resource consumption. Towards a better environmental construction the significant and appropriate CSAC – design stage and CSAC – post construction stage will benefit to all end-product and end-users.

The code of sustainability assessment of buildings plays a vital role in enabling clients to procure buildings which are more 'environmentally responsible'. This achievement could be reached by working closely with both architects and clients to establish what sustainable construction involves and how it can be incorporated into the building design. Our extensive experience gives us a unique insight into the challenges and a proven ability to create workable solutions for each individual project.

At the initial stage of design, clients have to be fully aware of regulatory requirements for sustainable development and follow it to producers, in order to accompany a planning application. In this case, CSAC design stage helps to develop an environmental policy statement that clearly lays out the objectives and advise the project teams on design options for meeting sustainability targets – for example, low energy heating, natural ventilation systems, etc. The environmental impact of the design options assessed using proven methods of Sustainable Construction to assess contractors and suppliers too, by using sustainability criteria. During construction, the CSAC construction stage ensures the site is registered under the 'considerate constructors' scheme and monitor the delivery of sustainability goals – for example, to encourage the supply of materials from sustainable sources, the adoption of a sustainable waste strategy, etc.

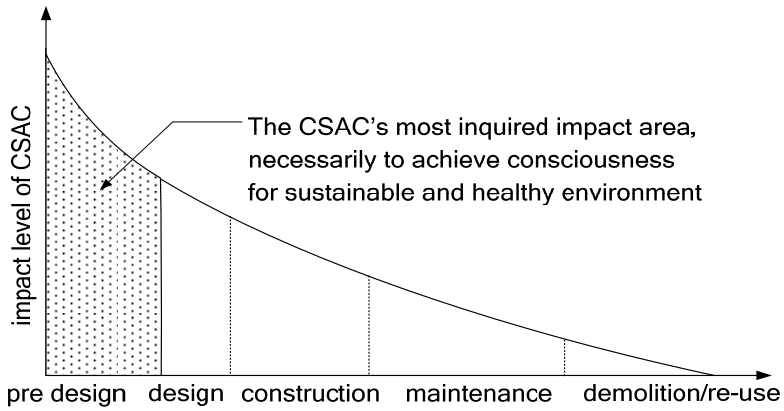

Figure 1. The impact of CSAC during building life cycle.

Thus, all relevant planning, design, construction, management and operational issues can be discussed, with the aim of working towards the delivery of a building solution that efficiently integrates the building fabric, services and environmental initiatives, and responds to the client brief and needs of building occupiers, managers and stakeholders. As the figure 1 describes, most environmental impacts (and therefore the greater number of opportunities to minimize environmental impacts) are determined in the early design stages of a project based on life cycle assessment, which estimates the environmental burdens and impacts associated with materials manufacture and the construction, use, maintenance and end-of-life (demolition) of building.

3.3 *The need of environmental administration: framework for sustainable development*

The background information, a state-of-art information identified at Pristina City, such as the lack of public administration's responsibility to enforce legislation, low level of social consciousness for sustainable and healthy environment, insufficiency of continue analysis for Sustainable Building Management and protection of public interest, were considered as a significant and an important part of causes that affect Urban Chaos.

Due to the absence of applicable and/or obligatory Code for Sustainable Assessment of Construction (CSAC) in local and/or regional level, as the benchmark for measuring the sustainability of new building structures, our research particularly attempted to overview generally the measures and activities to be taken for environmental assessment of buildings, assessment of sustainability of constructions and solutions for management methods to be implemented successfully. The CSAC becomes efficient if derivates form the frame work of sustainable development, complex approach that considers the social, economic and environmental impacts of development and requires the full participation of planners, architects, developers, building owners, contractors, manufacturers, as well as governmental and non-governmental agencies.

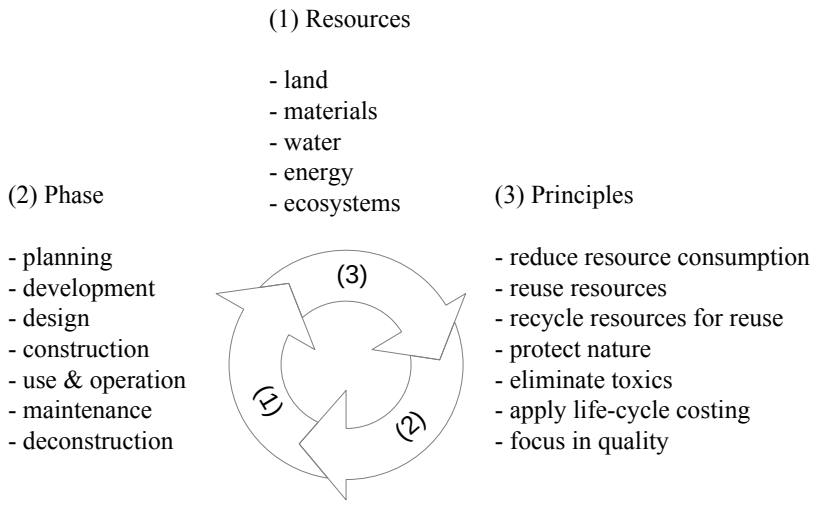

Figure 2. Framework of Sustainable Development.

The following proposed CSAC will help all building design, management and processionals to understand sustainable design and provide the technical skills needed to implement the most up-to-date concepts. Based on hugely successful series of workshops for professionals in construction, the Code covers the history of ideas, materials, measurement – cost and benchmarking performance, environmental services, and the building design and delivery process through the post-occupancy evaluation. It covers individual buildings and the urban scale.

3.4 *Why fore CSAC*

The Codes of the Sustainability Assessment of Constructions, as standard for key elements of design and construction which affect the sustainability of new buildings, will change sustainable construction practice, will become the single and common regional standard for sustainable Buildings, used by designers, builders as a guide to development, home-buyers to assist in their choice of home, thus will also provide us with improved overall well-being and quality of life. It will form the basis for future developments of the Building Regulations in relation to carbon emissions from, and energy use in Buildings, therefore offering greater regulatory certainty to developers. In this era of environmental awareness amongst consumers and increasing demand for a more sustainable product, it will offer a tool for developers to distinguish themselves. As well, the CSAC will enable changes in sustainable building practice for new constructions. It has to be prepared by the Government in close working consultation with the building and de-

sign institutions and through consultation with expert comity consisting of Government, Construction Industry and NGO representatives.

4 GENERAL APPROACHIES TO DEVELOP THE CODE OF SUSTAINABLITY ASSESMENT OF CONSTRUCTION (CSAC)

Seeing that negative environmental impact of development, build environment, could be minimized by sustainability assessment, thus should be emerged as a policy tool whose fundamental purpose is direct planning (of pre design, design, construction, monitoring, etc.) and decision-making towards sustainability. Its fundamental principles relay in well-established practices such as project environmental and more recent experience with strategic environmental assessment applied to codes and standards.

The distinguishing feature of sustainability assessment when compared with other, more established forms of impact assessment and planning, is that the complex and ambiguous concept of sustainability adhere at its human conscience, stoutness in a sustainable manner which requires paying attention to the predictable and comprehensive outcomes of decisions, actions, and events through the life cycle of a building, from the conception of site allocation, design, construction, use, and maintenance of new buildings as well as the renovation process for existing buildings and the reshaping of communities, especially within developing-expansible cities.

The CSAC measures the sustainability of a construction against design categories, rating the 'whole construction' as a complete package. In addition with existing building regulations in region, CSAC will be as a major departure from current practice towards sustainable development interrelationship with the design categories included at CSAC, such as: energy/CO2, water, materials, surface water run-off, waste, pollution, health and well-being, management and ecology.

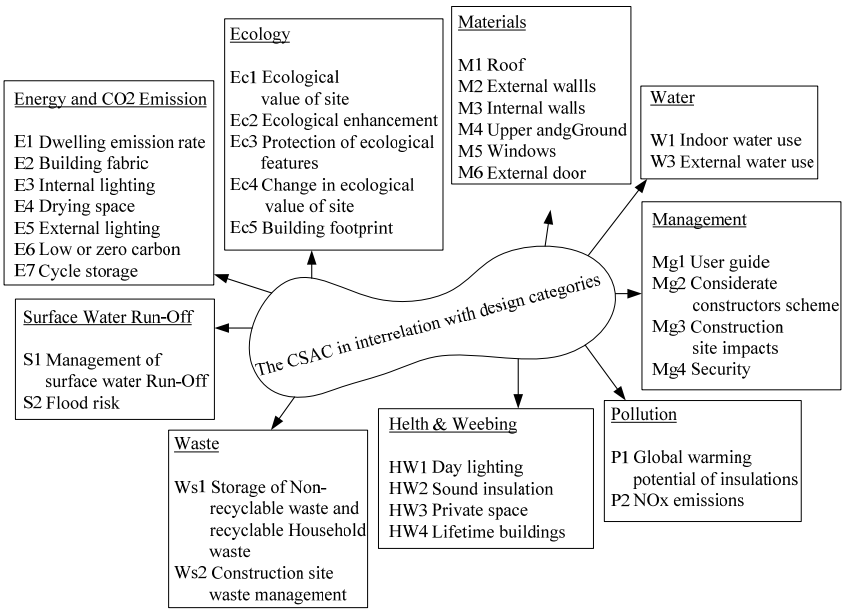

Figure 3. The CSAC' interrelation with design categories.

The implementation of CSAC will contribute as a key role in achieving this target. Following tables' represents draft Checklist proposals for improving building performance within region. Checklists for improving performance are grouped in three stages of construction development: Pre-Design, Design and Post construction, as show on following Tables.

Table 1. Pre – design stage* Checklist

No.	Description of general content – CODE Checklist (Pre – design stage)	N	Y
C1	A completed construction calculation worksheet	□	□
C2	A copy of the Design Building Regulations Compliance Checklist	□	□
C3	Specification of internal and external lightening	□	□
C4	Specification for primary and secondary system	□	□
C5	Full specification of construction materials & source including heat and sound insulation	□	□
C6	Is there internal ore external drying areas	□	□
C7	Details of any low or zero carbon technologies	□	□
C8	Is there any areas dedicated to cycle storage	□	□
C9	Please provide Details of indoor and external water use	□	□
C10	Please provide Details of surface water runoff and flood risk assessment	□	□
C11	Please provide Details of storage for non recyclable and recyclable household waste	□	□
C12	Please provide Details for waste management plan or development construction cost	□	□
C13	Please provide Details of any facilities to compost household waste	□	□
C14	Have you adopted the policy for life time constructions	□	□
C15	Have you adopted policy for sustainable construction design	□	□
C16	Have you a strategy to monitor and operate site management procedures	□	□
C17	Have you appointed or taken any advice from international environmental organizations	□	□
C18	Provide details if you have appointed an environmentalist to make recommendations to the site and provide a site survey	□	□

Table 2. Design stage* Checklist

No.	Description of general content – CODE Checklist (Design stage)	N	Y
C1	A completed construction calculation worksheet	□	□
C2	A copy of the Design Building Regulations Compliance Checklist	□	□
C3	Specification of internal and external lightening	□	□
C4	Specification for primary and secondary system	□	□
C5	Full specification of construction materials & source including heat & sound insulation	□	□
C6	Is there internal or external drying areas	□	□
C7	Details of any low or zero carbon technologies	□	□
C8	Is there any areas dedicated to cycle storage	□	□
C9	Details of indoor and external water use	□	□
C10	Details of surface water runoff and flood risk assessment	□	□
C11	Details of storage for non recyclable and recyclable household waste	□	□
C12	Details for waste management plan or development construction cost	□	□
C13	Details of any facilities to compost household waste	□	□
C14	Is there construction user guide	□	□
C15	Is there any adopted policy for sustainable construction design	□	□
C16	Is there a strategy to monitor and operate site management procedures	□	□
C17	Is there any advice from international environmental organizations	□	□
C18	Is there a appointed environmentalist to make recommendations to the site and provide a site survey	□	□

* Each stage requires from Project manager to maintain the vision and direction of the project, despite the inevitable pressures they will face to save time and costs

During the documentation of construction stages, the project manager shall ensure the principles and priorities are maintained and reported. With these checklists, the opportunities and the role of CSAC and its sustainable performance will influence at other stages too: Procurement and Tendering. The project manager must influence the performance of a sustainable construction at each stage of the building project. In the earlier stages, the project manager must help to set targets and allocate the time and resources (e.g. consultants) to achieve them. Finally, at completion and occupation, the project manager must ensure that the building is handed over thoroughly, so that the building will be operated in the way its designers intended. Post-construction evaluation (Tab. 3) must be performed when assess the success of the building design and operation against the original targets set during the early stages of the project, construction and pos–construction and/or operational tests.

Table 3. Post – construction stage* Checklist

No.	Description of general content – CODE Checklist (Post – construction stage)		N	Y
C1	A completed 'As Built' (AB) construction worksheet and evidence that the build form is as described in the 'AB' worksheet. Copies of purchase orders, photographs or specification clauses with letter of conformity.	□	□	□
C2	A copy of the 'AB' - building regulations compliance checklist. Copies of agreements with Building Control (supervisors) if full compliance is not achieved.	□	□	□
C3	Evidence of final installed Internal and External lighting specification in the form of photographs or purchase orders. Det. of control systems for space& security lighting.	□	□	□
C4	Evidence of final installed Prim. & Second. heating systems. Copy of the manuf. literature.	□	□	□
C5	Copies of daylight calculations fur dwellings and confirmation that the input parameters are correct. Copies of 'AB' draw & specific. Shown calculation of the building footprint ratio.	□	□	□
C6	Written confirmation that the dwellings have been constructed In accordance with the design stage drawings/specifications or 'AB' drawings or specifications. The type of product details used within the elements, the location of product/materials used and copies of purchase orders or receipts or certificate/letters of conformity fur all applicable materials, including those recycled or re-used.	□	□	□
C7	For all instilled insulation: copy of manufacturers or installers literature for any foamed insulation material or materials installed used blowing agents. Confirmation of where sound testing has been carried out with results and evidence that the tests are compliant with details of accreditation.	□	□	□
C8	Copies of purchase orders/receipts of internal and external drying areas.	□	□	□
C9	Confirmation that any Low or Zero carbon technologies has been funded under the low carbon building programme or that the design has been carried out by an independent energy specialist.	□	□	□
C0	Confirmation that the design stage solution for cycle storage was implemented or copy of purchase orders/receipts containing information on the capacity of the storage.	□	□	□
C11	Confirmation that the design stage solution for the building was implemented or full details (drawings/specifications) provided of 'AB'.	□	□	□
C12	Copy of manufactures details of indoor and External Water use equipment as well as letter confirming details of the installed fittings and equipment including details of action taken to avoid microbial contamination.	□	□	□
C13	Confirmation that the solutions designed for Surface water runoff and flood risk assessment have been Implemented and details that the basis of the flood risk assessment has not changed due to the length of time from design stage to post construction.	□	□	□
C14	Detail of storage for non recyclable and recyclable household waste, with the design stage draw/spec written justification where it has not been possible to locate bins within 30m of an external door, a letter or other confirmation from the local authority or private scheme operator to maintain and empty waste bins.	□	□	□
C15	Details of Site Waste Management Plan and completed final copy of CHECKLIST if different from Design stage and copies of record confirming the monitoring of site waste throughout the whole construction period or documentary legal evidence confirming the agreed development construction cost.	□	□	□
C16	Confirmation that the design stage composting solution was implemented or will be by the time 60% of the development is complete or details of the 'AB' spec.	□	□	□
C17	Copies of the Building User Guide (BUG) for each dwelling covering all the issues required and confirmation that the BUG has been supplied to all dwellings.	□	□	□
C18	A completed 'AB' lifetime buildings checklist indicating compliance with features from completed design stage.	□	□	□
C19	For monitoring and operating site management procedures documentary evidence demonstrating that all specif. requirements have been adhered to with evidence where applicable.	□	□	□
C20	Confirmation from the environmentalist that all of their recommendations have been incorporated in the design and that the site meets the standards required.	□	□	□
C21	All the relevant design stage evidence for the ecology report must be provide and confirmation that any land of ecological value outside the construction zone was adequately protected during construction works.	□	□	□
C22	Evidence of Protection of Ecological future during site clearance and construction where the whole site has not been built out.	□	□	□

5 CONCLUSION

Based on the analysis and comparison of the observable evidences for environmental administration within region and appliance of standards for Sustainable Development in general, in regard to increase better understanding for all stakeholders and authorities, our research presents suitable recommendations for principles, methods and checklists (comprehensive measures) for sustainability of new constructions during entire life cycle, thus explicitly the role of appliance of Codes for Sustainability Assessment of Construction (CSAC), emphasizing as follows:

- this research and its publication in addition, will promote overall benefits for environment, builders and end-user when implementing CSAC, for instance during the construction and post construction stage, the increment of the sustainable build environment performance will mutually increase the social, spatial and environmental benefits;
- the CSAC's promotion will ensure users that the construction industry will start building in more sustainable way, with real improvements in key areas, such as: energy, carbon dioxide emissions, water use, better management of surface water run-off, usage of less pollution materials thus encourage household recycling etc;
- the implementation CSAC, using its methods and suggested tools, will improve environment today and sustainable environment of the region in the future, such as: increasing public attention and its conscience through education and media concern over environmental issues, notably climate change, giving rise to a continues education among consumers for more sustainable products and services, etc;
- the CSAC will increase the builder's performance towards sustainability performance of their Buildings , quality and efficient completion in that regards, lower running cost, improved comfort and satisfaction of tenants too;
- the CSAC will provide valuable information to costumers / end-users, sufficient knowledge for sustainability performance of different buildings, assisting them in their choice for a new dwelling CSAC which should meet the sustainability criteria for a more pleasant and healthy place to live.

Therefore, the role of CSAC for all involved parties, construction industry, including designers, builders, product manufacturers, and assessors is signifying. In the short-term, CSAC compliance is voluntary, a lot of builders are encouraged to follow CSAC principles ahead (besides already existing Codes and standards) and perform willing towards self evaluation since the Authorities are under the consideration making assessment, Code of Sustainability Assessment of Buildings mandatory in near future.

Our recommendation for responsible Authorities is to understand importance of quick impact of CSAC and how it works, what benefits it brings, thus to initiate immediate creation and action for mandatory implementation of CSAC, in order to prepare the preventive measures to additional regulation and/or evaluate possibilities to improve existing regulations for better future and protection of environmental values.

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How Durability is considered in Sustainability Codes?

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ABSTRACT: Sustainability is an important concept today. Material resources are getting depleted as well as our planet is effected in a bad way because of the poor results of productions. Building industry is one of the most important industries in the world which can play a major role in the natural balance of sustainability. Construction and Demolition process consumes a big amount of our resources such as energy, material and water. It would be useful to think about sustainability of the system as a whole. One of the main elements of sustainability is the material used in the construction industry, its quality and more specifically its Durability.
This paper presents part of a research which is currently on at Politecnico di Milano studying the effects and notification of durability (focusing on service life) in sustainability with regards to Life Cycle Assessment (LCA) in the area of Life Cycle Management (LCM). This is being done to distinguish between these two aspects, LCA and Service life.
This overview is useful to improve links between two important aspects of the material quality, and covers the idea of sustainability from Agenda 21, green building associations, ISO standards and includes eco invents which is more practical from the point of the sustainability aspects.

1 INTRODUCTION

1.1 *Importance of the concept*

As Sustainability is an important concept today. Material resources are getting depleted as well as our planet is effected in a bad way because of the poor results of productions. Building industry is one of the most important industries which can be the critical factor in the natural balance of sustainability. Construction and Demolition process consumes a big amount of resources such as energy, resources and water. It would be useful to consider the sustainability as a major concept of the construction process. One of the main elements of sustainability is material. Materials are used in the construction industry because of their quality and especially their Durability.

This work describes a part of a current research at Politecnico di Milano about the effects and notification of durability (with main characteristic of service life) in sustainability with regards to Life Cycle Assessment (LCA) in the area of Life Cycle Management (LCM). This is done to distinguish these two aspects, LCA and Service life.
This overview is useful to improve links between two important aspects of the material quality, and covers the idea of sustainability from Agenda 21, green building associations and ISO standards, also considers eco invents which is more practical from the point of the sustainability aspects.

2 METHODOLOGY

2.1 *Relation between different implementations*

Resource consumption pose an impact challenge for the construction sector. Energy saving measures, extensive retrofit programs and transports are great challenges linked to energy usage. Reduction of mineral resources usage and conservation of life support function should be better considered because

this way we can all result in a better environment. So we should use renewable or recycled materials and prediction of service life.

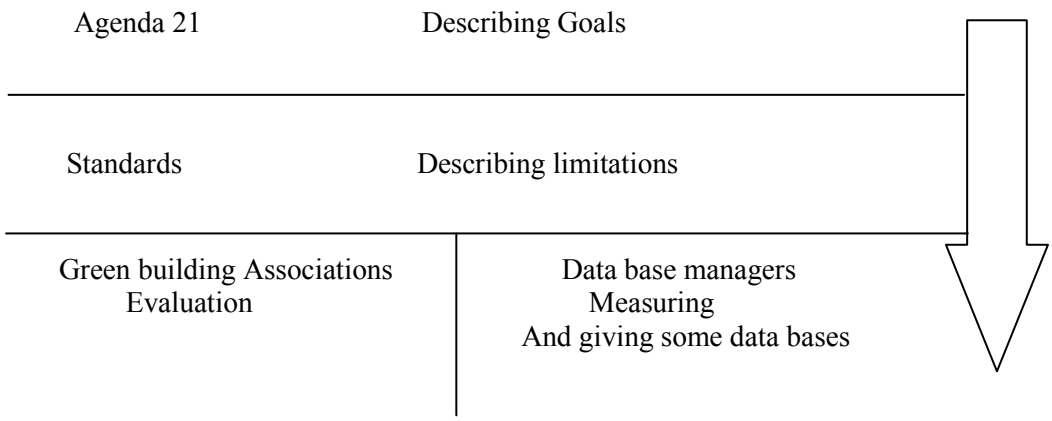

Figure 1. Sustainability in order to implementation.

Water management in building should be developed. In several countries land management is effected by construction related issues such as choices of site and land use, longevity and use of land for production of building material.

ISO 15686 part 1, 2, 5, 6 describe Building and constructed service life planning. ISO 15392 is about Sustainability in building construction – General principles. Breeam and Leed and other advisers started to grade buildings and now they consider recyclability and reusability. Even if they consider the effects of production quality they do not evaluate the production and the system directly.

The diagrams below show the system better.

In figure 2 the problem occurs on the dashed line. Because these codes are grading materials in different levels but only with recyclability of their whole system. It causes in fact that producers who are the main controllers lose their attention on the quality in the whole system.

These four different impacts highlight the different properties in production processes to evaluate the environmental effects: Air, Land, Resources, Water. These impacts are at the end of the environmental process of the LCA. Without considering their quality effect we cannot improve the sustainability as it should be. Sima pro is so numerical, detailed and not designed for building.

Used products should be recycled. To reach this goal, designers and building material manufacturers should co-operate closely in developing new building concepts (lightweight components and new jointing and assembly techniques). Moreover, a better co-operation with related industries.

2.2 *Some evidences how to treat durability in sustainability references*

The movement of sustainability starts with Agenda 21 in 1999. Agenda 21 describes the very general idea of sustainability and there Durability can be observed clearly.

Support function of the environment requires use of renewable or recycled materials and production of service life. Water management in building should be developed. In several countries management of the land is effected by construction related issues which are choices of site and land use, the longevity and use of land for production of building material. To assist in the selection of building materials environmental labels should be introduced for the purpose of identifying such factors as expected service life, embedded energy, composition and recyclability. The energy-reduction targets offer ample opportunities with innovative products in the fields of heating, cooling, ventilation, lighting and thermal insulation.

What can be expected is an increased responsibility on the part of manufacturers for their products from cradles to grave, namely to develop the followings: New material recycled or made from new resources, plug-in systems, easy to disassemble and re-use, standardization and modularity of

components, improved tools for prediction of service life of component and systems, new logistics for closed-loop recycling on line production information system (internet).

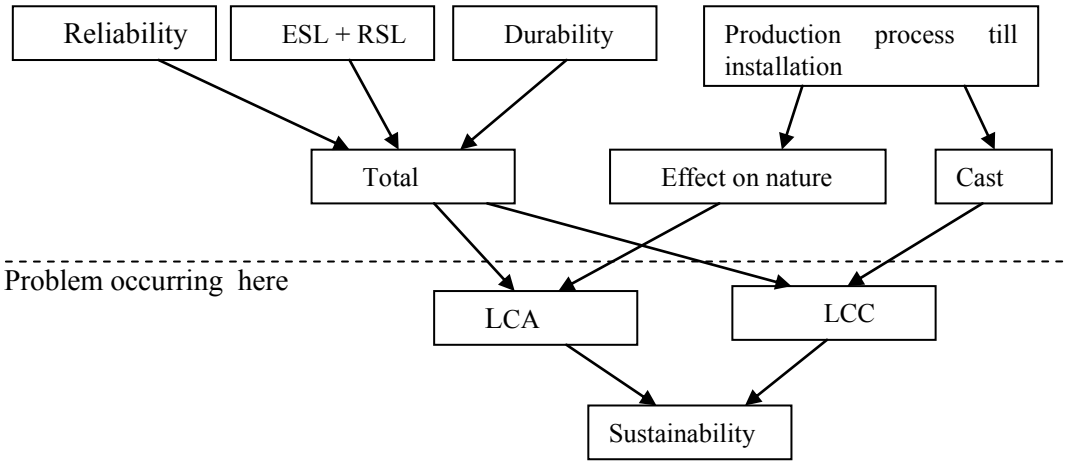

Figure 2. Product process Sustainability

In the developing world the creation of jobs is important and where appropriate construction should use more labor intensive construction methods and improve indigenous materials. In developed countries an additional challenge is the prediction of service life. The building structure is one of the most important parts in society. In the developed society building stock and infrastructure constitutes more than 50% of each country's capital. To pursue sustainable development, make maintenance more efficient and reduce cost there is a need to predict service life of the building components and materials service life defined as "the period of time after installation during which all conditions of a building part meet or exceed performance requirements".

It is expected that the importance of renewal engineering will exceed new construction at least in the developed market economies. Operation for construction lie in the development refurbishment processes which cause minimal disruption to the occupants' immediate environment and also in development modular systems for refurbishment. Demolition constructions should develop new deconstruction and stripping techniques to facilitate optimal recycling and re-using of building materials.

"For components that can be easily reused the first priority is durability and long service life."

Then it will go deeper in details with ISO 15686 from parts 1-9. In ISO 15686 part 5 & 6 is talking clearly about LCA & LCC which describes sustainability. 15686 part 2 is talking about SLP in building and constructed assets.

2.3 *social aspect*

Aspect of construction works, parts of works, processes or services related to their life cycle that can cause a change to society or quality of life.

On Figure 3 the left part is taken from ISO 15686-1. In that division the sustainability and durability is based on ISO standard. The merge point is service life planning.

"Very durable materials may cause problems in disposal since they are, by definition, resistant to the effects of normal weathering which cause degradation. However, they may be suitable for recycle."

2.4 *Life cycle assessment (LCA) (ISO 15686-1)*

Life cycle assessment (LCA) should not be confused with life cycle costing (LCC). It is a broader concept which entails identifying the "cradle to grave" resources consumed and/or effects on the environment throughout the service life of a product, such as a building (see ISO 14040). It is commonly used in considering sustainability of development but there are overlaps with life cycle

costing. Each requires an assessment of what will happen over a prolonged period, and each may "count" replacements as relevant "costs" in provision of the building. There is therefore a complementary preference for components or materials with lower whole-life "costs" and reduced replacement or maintenance requirements. Both may also take into account the residual value when a material or component is reused or recycled. However, the optimum economic option may not have the least environmental cost.

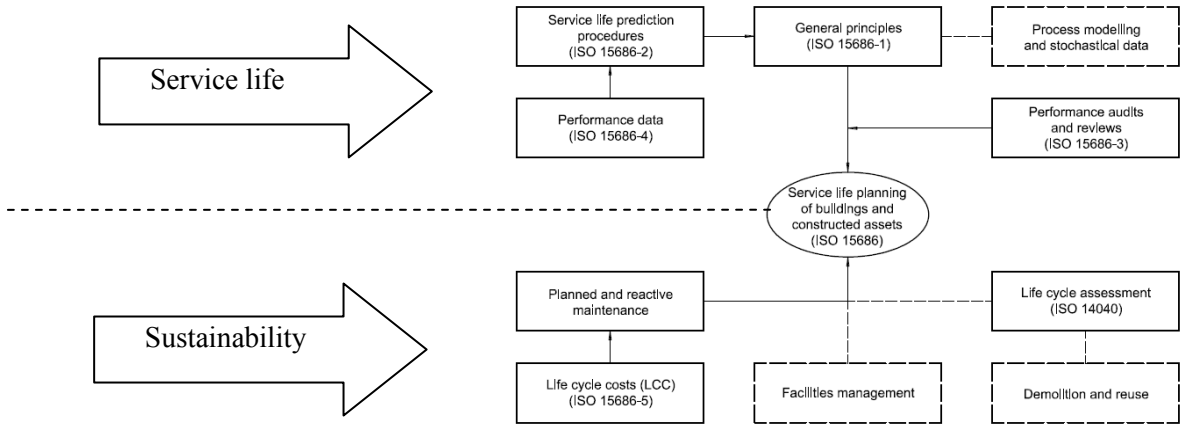

Figure 3. ISO 15686-1. 2000. Financial and environmental costs over time

2.5 *Life cycle costing (LCC) (ISO 15686-1)*

Life cycle costing (also known as whole-life or through-life costing) is a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors both in terms of initial capital costs and future operational costs. Being able to compare the future costs of alternatives allows selection of the most economic overall design and helps planning and control of the cost of ownership. This subject will be covered in more detail in ISO 15686-5. Some essential features include the following.

a) Only designs and/or components which meet the design life, functional and performance requirements should be considered as alternatives.

b) Alternatives which meet the performance requirements but which have lower life cycle costs should be preferred.

c) LCC should be undertaken on the entire estimated service life of the whole building and its components and assemblies, or on a less-foreseeable service life.

d) All relevant economic factors, including opportunity costs (i.e. cost of choosing this investment rather than another), should be included within the analysis.

e) Initial costs include costs directly related to the whole building and its components and assemblies, including design, construction and installation, fees and charges.

f) Future costs include all operating (e.g. energy and cleaning), maintenance, inspection, replacement and demolition or removal costs.

g) Maintenance costs include costs of replacement, repair, refurbishment, disassembly and re-assembly. Planned cyclical maintenance and day-to-day maintenance as well as improvements and alterations should be included. An allowance should be made for unplanned remedial maintenance, based wherever possible on recorded historic costs and experience. Depending on the use of the building, costs associated with unavailability or provision of a replacement during maintenance work may also be required.

h) Timing of future costs should be taken into account in LCC [e.g. by discounting future costs to present day (PV) values].

i) Evaluation of alternative specifications may entail value engineering (VE) techniques.

Future use of the building

A building is generally a very durable capital asset, and the initial client may only have a limited foreseeable use of it. Service life planning can allow future sale or reuse by subsequent owners, thereby increasing the residual value of the building. Extending the service life of the building and reducing component maintenance and replacements also contribute to achieving sustainable development and preservation of scarce resources.

To achieve the specified environmental quality a three-step procedure should be followed. Requirements regarding environmental impact may be expressed in terms of use of materials, use of energy, use of water, emission of substances, including hazardous and toxic emissions, and use of land and impact on biodiversity. (ISO 15686-1.)

2.6 *Considering service life in LCA (ISO 15686-5)*

LCA should concern the entire life cycle of the assessed product. Therefore, the use phase should be included. For construction products and constructed assets, the use phase is usually long. Further differences between considered design options can also concern the service life duration. For that reason, the displayed LCA results can be significantly dependent on scenarios and assumptions concerning the duration and the processes involved in the use phase. To establish realistic scenarios that reflect the current preconditions these scenarios should incorporate information that can be obtained from the SLP process, namely the estimated service life (ESL) and use, exposure and maintenance assumptions.

Environmental impacts commonly arise from activities that take place during the life cycle of the constructed asset, such as raw material extraction, product manufacturing, asset construction, use and maintenance and end of life.

2.7 *LEED and BREEAM*

Green Building associations like Leed in US and BREAAM try to give a clearer idea about construction sustainability in higher levels like ISO and Agenda. But there are still not enough details for design sustainable and efficient buildings.

Leed has the following processes to evaluate material sustainability: extend the life cycle of existing building stock, conserve resources, retain cultural resources, reduce waste and reduce environmental impacts of new buildings as they relate to manufacturing and transport materials.

Requirements

Reuse large portions of existing structures during renovation or redevelopment projects:

-Credit 1.1 (1 point) Maintain at least 75% of existing building structure and shell (exterior skin and framing excluding window assemblies).

-Credit 1.2 (1 point) Maintain an additional 25% (100% total) of existing building structure and shell (exterior skin and framing excluding window assemblies)

-Credit 1.3 (1 point) Maintain 100% of existing building structure and shell and 50% non-shell (walls, floor coverings, and ceiling systems)

Technologies & Strategies

Consider reuse of existing buildings, including structure, shell, and non-shell elements. Remove elements that pose contamination risk to building occupants and upgrade outdated components such as windows, mechanical systems, and plumbing fixtures. Quantify the extent of building reuse.

2.8 *BREEAM*

Suitable durability and protection measures or design features have been specified to prevent damage to the vulnerable parts of these building areas from such traffic. This must include, but is not necessarily limited to:

a. Protection from the effects of high pedestrian traffic in main entrances, public areas and thoroughfares (corridors, lifts, stairs, doors etc).
b. Protection against any internal vehicular/trolley movement within 1 m of the internal building fabric in storage, delivery, corridor and kitchen areas.
c. Protection against or prevention from any potential vehicular collision where vehicular parking and maneuvering occurs within 1 m of the external building façade for all car parking areas and within.
Then eco-invent can be observed. The challenge is that sima pro considers many details of production and it is hard to use it in construction systems. When you finally compare it with higher level of building efficiency tools, then it is clear that they do not focus well enough on durability in use of material and components directly because LCA (Life Cycle Assessment) effects the material's life cycle.

Eco-invent includes different methods. All of them consider one point of product affect on the eco system. That is a range of methodological problems and questions while linking the LCIA methods with the elementary flows of a database. This leads to different results in the past even if the same LCIA method was applied on the same inventory results.

But still there are some missing points, namely these codes take SL as a constant number but LCA varies by time and quality. The solution describes there is index between the effect and usage of product on nature, for example the effects of production, distraction, transportation and installation of each building product in compare with time and amount of usage of product. [*Frischknecht, R.; Jungbluth, N. 2007*]

3 CONCLUSION

At first green building tools do not evaluate their subjects precisely, however they should pay more attention what kind of building materials are used because there is a tight connection between LCA and durability. Fuzzy method can give a very good solution because durability and LCA are both numerical aspects.

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Standards for Sustainability Assessment of Construction Works

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ABSTRACT: Several methods for sustainability assessment of the construction works were developed in different countries according different methodologies. This diversity of assessment methods is interesting by the point of view of the progress and improvement of methodologies. Few years ago the European Commission mandated the CEN, European Standardization Organisation to develop a standard method to assess the sustainability of construction works. This presentation shows the progress and the work program of the CEN/TC 350 that is in charged of development of the standards to assess the sustainability of construction works.

1. INTRODUCTION

There are different methods available for assess the sustainability of construction works. This diversity demonstrates the interest in this subject and is a mean of progress and improvement. By the other side this diversity doesn't allow an inter-comparability of the buildings assessed by different methods. This limitation inspired the European Commission to mandate the CEN to develop a European set of standards that could be used in the same way in all European Countries.

2. THE MANDATE

To allow comparison of buildings across Europe and encourage exchange of best practices, the Commission has mandated the European Standardisation Organisation (CEN) to develop methods to assess the integrated environmental performance of buildings (beyond energy efficiency).

The Technical Committee CEN/TC 350 was created in 2005 in response to the mandate from DG ENTR of the European Commission (M/350 Standardisation Mandate to CEN dated 29 March 2004) [1]. The Mandate directed CEN to "provide a method for the voluntary delivery of environmental information that supports the construction of sustainable works including new and existing buildings."

The standards being developed by CEN/TC 350 are to provide a harmonised, horizontal (i.e. applicable to all products/building types) approach to the measurement of embodied and operational environmental impacts of construction products and whole buildings across the entire lifecycle. The standards are to be voluntary.

The scope of the standards being developed in CEN/TC 350 has been extended to include all the sustainability aspects as economic performance and social performance of buildings.

3. *INTERRELATIONSHIP*

The interrelationship between the CEN/TC 350 standards and other European initiatives is complex, as illustrated by the diagram below:

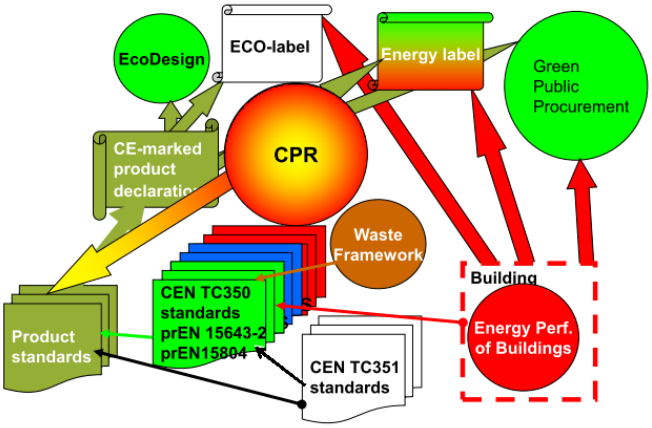

Figure 1. Interrelationship between CEN/TC 350 and other European initiatives [2].

This interrelationship involves both taking information as inputs used by the standards, and providing information in a consolidated format as outputs for application in other areas.

Wherever practicable the CEN/TC 350 standards will draw upon the outputs of other European (e.g. the Standards that support the Energy Performance in Buildings Directive [3]) and International Standards (e.g. the ISO 15686 series of standards relating to Service Life planning [4]) for their input data/processes and methodologies.

In turn it is expected that the CEN/TC 350 standards will contribute with information to support initiatives such as the Basic Works Requirement (BWR) proposed in the draft Construction Product Regulations (CPR) [5]. In this particular context, for example, it has been envisaged the CEN/TC 350 standards can provide a route to demonstrating that the requirements of BWR7 of the CPR are met.

The CEN/TC 350 standards will provide the rules by which construction products make Product Declarations (Environmental, and Social and Economic where relevant), and the means to aggregate this information into an assessment for a building as a whole.

This will require development of a consistent and uniform approach to the implementation of the CEN/TC 350 standards across each construction product category, and this will have to be developed in conjunction with the CEN Technical Committees for each of the product groups.

4. *SUSTAINABILITY*

Despite the EC Mandate have been issued with the focus on the environmental performance of the construction works, the CEN/TC 350 decided to cover the three main aspects of the sustainability as the social and the economic behind the environmental.

The concept of sustainability emerged in the 60s. Several studies have drawn attention to this matter and have been building up consensus on sustainability.

Sustainability is now a science that combines environmental, economic and social aspects. Those three aspects, combined and optimized, will result in indicators that will be the criteria for selection the most interesting solution for a building, a bridge, or a road.

The assessment will be based on quantified indicators of the complete building Life Cycle, from cradle to grave.

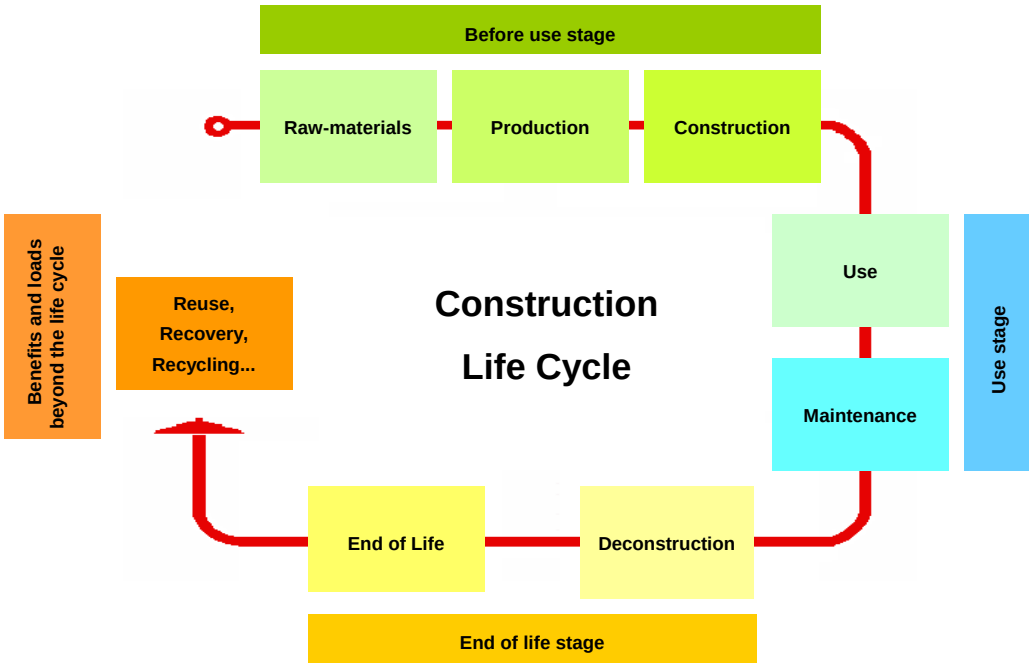

Figure 2. Construction Life Cycle.

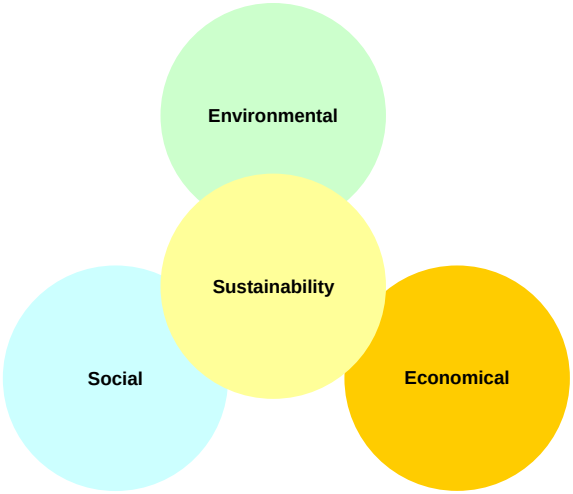

Figure 3. Aspects of Sustainability Assessment.

4.1. *Environmental*

Environmental aspects are perhaps the most comprehensive and relate to the environment preservation to the future generations.

These are aspects to which we do not pay much attention but they are so important as the price. Some indicators used in environmental assessment are:

a) Output indicators for environmental impacts:
- Climate change;
- Destruction of the stratospheric ozone layer;
- Acidification of land and water resources;
- Eutrophication;
- Formation of ground level ozone.

b) Input indicators for material and energy flows:
- Use of non-renewable materials;
- Use of renewable materials;

- Use of non-renewable primary energy;
- Use of renewable primary energy;
- Use of freshwater resources;

c) Output indicators for material and energy flows:
- Materials for recycling;
- Materials for energy recovery;
- Non-hazardous waste to disposal;
- Hazardous waste to disposal;
- Radioactive waste to disposal.

4.2. *Social*

The social aspects are related to the wellbeing and comfort. These are the most subjective aspects. They are fundamental to the perception that the user has on the building.
The aspects related to indoor comfort are also important, including thermal and acoustic insulation, or air quality but they are assessed by other standards. Some indicators stated in the prEN15643-3 are:
- Accessibility;
- Health and Comfort;
- Loadings on the neighbourhood.
- Maintenance;
- Safety / Security.

4.3. *Economical*

The price has always been and will remain one of the selection criteria in the acquisition of a property. However, when buying a good, the price reflects only the cost of its production and transport to reach us. The economic aspects will have to consider also the cost analysis with the use, maintenance, repair and replacement parts, and post use as deconstruction, recycling or end of life of each material.

5. *STRUCTURE OF CEN/TC 350*

CEN/TC 350 is based on the work of several groups Task Groups (TG) or Working Groups (WG) of experts in different domains of sustainability. The organization is shown in the figure 4:

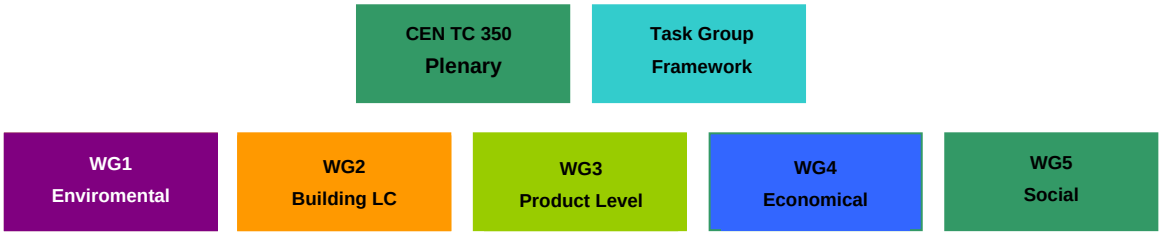

Figure 4. Structure of CEN/TC 350.

The Plenary of CEN/TC 350 is a board where take part all the National Standard Bodies of the CEN and is a decision body. The decisions are taken in order to approve strategic resolutions or documents to be sent to enquiry by the National Standard Bodies.

TG Framework is a group of experts in charge to harmonize the work to be done by the WG's and to develop the framework standards. Those are guideline standards or umbrella standards.

WG1 – "Environmental Performance of Buildings" is a Group of experts that is assigned to develop standards to assess the environmental performance of buildings.

WG2 – "Building Life Cycle Description" was a Group that was intended to develop guidelines for the description of the building Life Cycle but it didn't start the work.

WG3 – "Products Level" is a Group of experts that is intended to develop the standards for PCR (Product Category Rules) and EPD (Environmental Product Declaration).

WG4 – "Economic Performance of Buildings" is a Group of experts that is intended to develop the standards to assess the economic performance of buildings.

WG5 – "Social Performance of Buildings" is a Group of experts that is intended to develop the standards to assess the social performance of buildings.

6. *WORK PROGRAM OF CEN/TC 350*

The Work Program of CEN/TC 350 is shown at figure 5 and the time schedule of the work program is shown at figure 6. The technical report CEN/TR 15941 – "EPDs - Methodology for selection and use of generic data" and the EN 15641-1 – "General framework" are the first standards approved by the CEN.

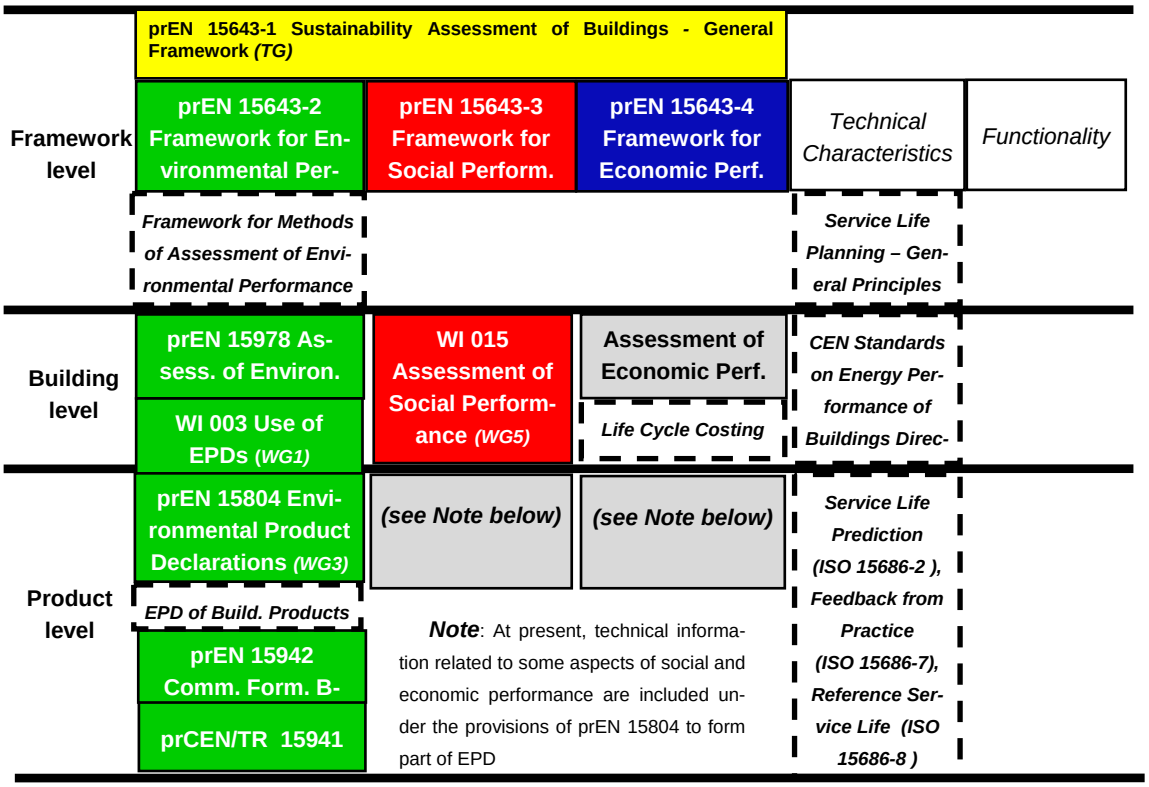

Figure 5. CEN/TC 350 Work program [6].

The current status of the CEN/TC 350 standards is shown in the table 1.

7. *CONCEPT OF SUSTAINABILITY ASSESSMENT*

In concept, the integrated building performance incorporates environmental, social and economic performance as well the technical and functional performance, and these are intrinsically related to each other, as illustrated in Figure 5. Although the assessment of technical and functional performance does not form part of this suite of standards, their interrelationship with environmental, social and economic performance is prerequisite for an assessment of sustainability performance of buildings, and therefore is taken into account.

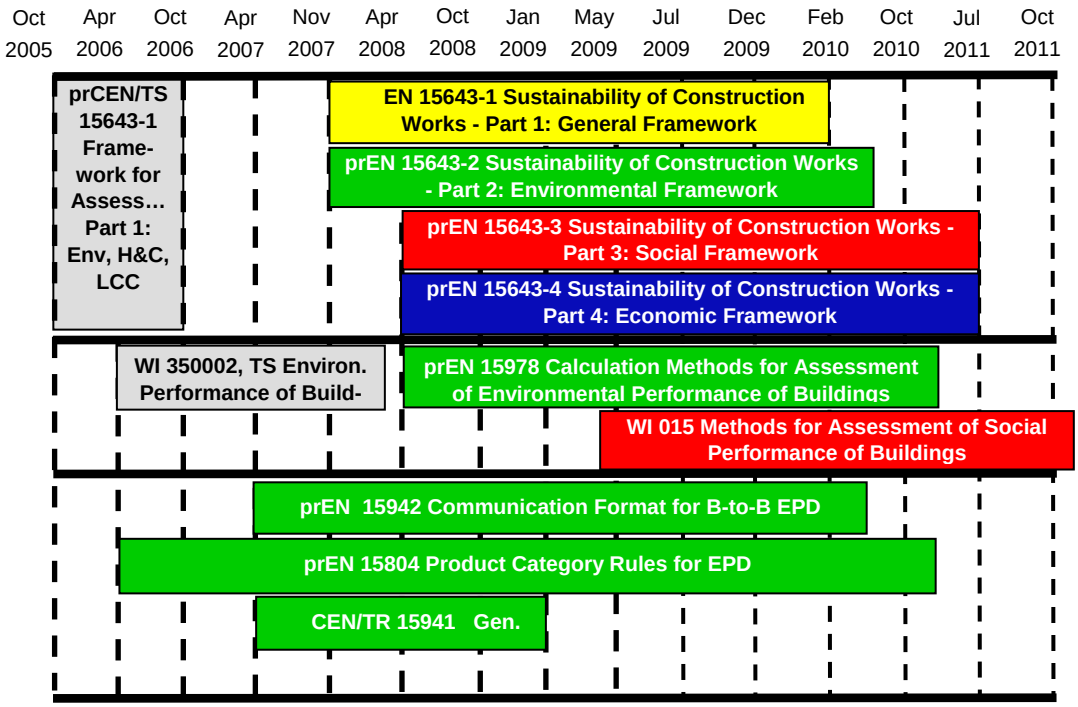

Figure 6. Time Schedule of CEN/TC 350 work program [7].

Table 1. Current status of the CEN/TC 350 standards.

Reference	Title	Status	Expected date of availability
EN 15643-1	Sustainability of construction works – Integrated assessment of building performance. Part 1: General Framework	Standard published	
FprEN 15643-2	Sustainability of construction works – Integrated assessment of building performance. Part 2: Framework for the assessment of environmental performance	Standard under approval for final vote	2011-03
prEN 15643-3	Sustainability of construction works – Integrated assessment of building performance. Part 3: Framework for the assessment of social performance	Standard under approval for CEN enquiry	2012-01
prEN 15643-4	Sustainability of construction works – Integrated assessment of building performance- Part 4: Framework for the assessment of economic performance	Standard under approval for CEN enquiry	2012-01
Work Item WI00350015	Sustainability of construction works - Assessment of social performance of buildings - Methods	Standard under development	2013-04
prEN 15978	Sustainability of construction works – Assessment of environmental performance of buildings – Calculation methods	Standard under approval for CEN enquiry	2011-05
Work Item WI3500003	Sustainability of construction works – Use of information from environmental product declarations (EPD)	Work on this standard has just started	
Work Item WI3500007	Sustainability of Construction Works - Building Life Cycle (TR)	Work abandoned	
prEN 15804	Sustainability of construction works - Environmental product declarations - Product category rules	Standard under development	2012-06
FprEN 15942	Sustainability of construction works - Environmental product declarations - Communication format - Business to Business	Standard under approval for final vote	2011-04
CEN/TR 15941	Sustainability of construction works — Environmental product declarations — Methodology for selection and use of generic data	Standard published	

The concept of sustainability assessment is shown at figure 7. The sustainability assessment of buildings uses different types of information. The results of a sustainability assessment of the building provide information on the different type of indicators, the related building scenarios and on the life cycle stages included in the assessment.

The suite of CEN/TC 350 standards will allow the sustainability assessment, i.e. the assessment of environmental, social and economic performance of a building, to be made concurrently and on an equal footing, on the basis of the same technical characteristics and functionality of the object of assessment.

In the future, the assessment methodologies within this suite of standards may be part of an overall assessment of integrated building performance. The assessment methodologies may also be extended to an assessment of the neighborhoods and wider built environment.

In carrying out assessments, scenarios and a functional equivalent are determined at the building level. Assessment at the building level means that the descriptive model of the building with the major technical and functional requirements has been defined in the client's brief or in the regulations as illustrated in Figure 7. Assessments can be undertaken for the whole building, for parts of the building which can be used separately or for elements of the building.

Although the evaluation of technical and functional performance is beyond the scope of this suite of standards, the technical and functional characteristics are considered within this framework by reference to the functional equivalent. The functional equivalent takes into account the technical and functional requirements and forms the basis for comparisons of the results of the assessment.

Any particular demands for or related to the environmental, social and economic performance defined in the client’s brief or in the regulations may be declared and communicated. Figure 7, shows how the functional equivalent and the technical and functional characteristics that deviate from those required, either by the client's brief or through regulations, are to be declared and communicated with the results of the assessment.

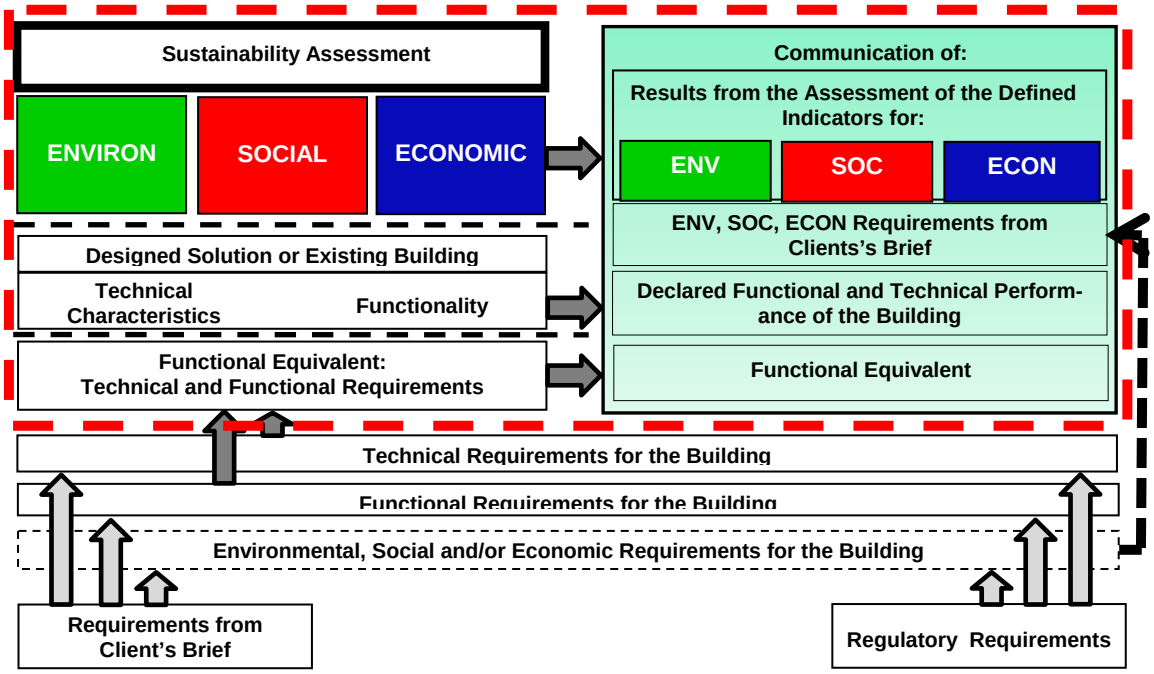

Figure 7. Concept of sustainability assessment [6].

8. CONCLUSIONS

The standardization is a voluntary process to develop standards that is based on consensus between the NSB. This is the situation of CEN/TC 350 work started some years ago. Several years of work, a lot of meetings over the Europe with discussions and progress have been done. Now the first standards were approved and soon the complete set of framework standards, but at least on 2013 all the complete set of standards prepared by CEN/TC 350 will be available to architects, engineers, consultants, verifiers, to work in the European Sustainability Assessment of Buildings. This will be the first generation of sustainability standards but CEN/TC 350 will be ready to improve them after a practical use during the implementation.

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Improving the Design of a Residential Building Using the Portuguese Rating System SBTool^{PT}

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ABSTRACT: Construction affects all dimensions of sustainability (environment, society and economy) and therefore a sustainable building design has to cope with tens of criteria, most of them interrelated and partly contradictory. There are a great number of indicators and assessment tools that have been developed recently in order to evaluate the sustainability of buildings and urban settlements. Most of these tools are based on national standards, building codes and local methods of construction. Sustainable design of construction is only possible through a real methodological work. Sustainability assessment tools play an important role at this level, since they convert the sustainability issues into tangible goals while are used to collect and communicate the results of a sustainability assessment. This paper will present the role of the Portuguese Sustainability Rating System SBTool^{PT} in promoting the sustainability of residential buildings.

1 INTRODUCTION

In Portugal, most of the impacts of the built environment in the sustainable development are related to the residential sector (Mateus, 2009). At the environmental level this sector is directly and indirectly related to the consumption of a great amount of natural resources (energy, water, mineral, wood, etc.) and to the production of a significant quantity of residues. For example, although Portugal has a mild climate, residential sector accounts for about 17% of the total national energy consumption (DGGE, 2005). Additionally, it uses a considerable amount of water resources, about 132 l/inhabitant/day of potable water, being a significant part of this capitation used in toilets (INAG, 2005). At the socioeconomic level and compared to other sectors, buildings is the most important sector, not only because about 10% of the global economy is related with its construction and operation, but also because it significantly influences the quality of life and heath of its inhabitants: in the developed countries, people are inside buildings in about 80% to 90% of the period of their life (Roodman and Lessen, 1995). Nevertheless, some studies in Portugal showed that most buildings are not sustainable in terms of operating and maintenance costs and do not provide a comfortable and healthy indoor environment for their occupants (Mateus, 2009). For example, the reality shows that 23% of the Portuguese residential buildings need to be repaired and their owners do not have the necessary income for the necessary investment (INE, 2001).

Due to the increasing awareness about the consequence of the contemporary model of development in the climate change and to the growing international movement toward high-performance/sustainable buildings, more and more the current paradigm of building is changing. This is changing both the nature of the built environment as well the actual way of designing and constructing a facility. This new approach is different from the actual practice by the selection of project teams members based on their eco-efficient and sustainable building expertise; increased collaboration among the project team members and other stakeholders; more focus on global building performance that on building systems; the heavy emphasis placed on environ-

mental protection during the whole life-cycle of a building; careful consideration of worker health and occupant health and comfort through all phases; scrutiny of all decision for their resource and life-cycle implications; the added requirement of building commissioning; and the emphasis placed on reducing construction and demolition waste (Kibert, 2005).

Although there are several definitions for a sustainable building, generally speaking, it uses resources like energy, water, land, materials in a much more efficient way than conventional buildings. These buildings are also designed and used in order to produce healthier and more productive living, work and living environments, from the use of natural light and improved indoor environmental quality (Syphers et al, 2003). Therefore, sustainable building aims the proper balance between the three dimensions of the sustainable development: Environment, Society and Economy.

Archiving sustainability at the building sector is only possible through a real methodological work. In order to be feasible this work should be carried out during the preliminary phases of design. At this level sustainability assessment tools are playing an important role, since they gather and report information for decision-making during the different phases of construction, design and use of a building. The sustainability scores or profiles based on indicators result from a process in which the relevant phenomena are identified, analyzed and valued.

Building sustainability assessments based on a life-cycle approach can produce important long-term benefits for both building owners and occupants (Hilkmat, 2009), namely: helping to minimize environmental impacts; solving existing building problems; creating healthier, more comfortable and more productive indoor spaces, and reducing building operation and maintenance costs. Life-cycle analysis considers all the inputs and outputs of acquiring, owning, and disposing of a building system. This approach is particularly useful when project alternatives, which fulfil the same performance requirements, but differ with respect to initial costs and operating costs, have to be compared in order to select the one that maximizes net savings (Hilkmat, 2009).

This paper aims to highlight the contribution of the sustainability assessment tools for the sustainable building design. Moreover it will present the role of the Portuguese Sustainability Assessment Tool ($SBTool^{PT}$) in promoting the design of a sustainable affordable residential building by presenting a case study.

2 BRIEF PRESENTATION OF THE $SBTool^{PT}$ METHODOLOGY

2.1 *Framework*

The Sustainable Building Tool - SBTool is a building sustainability assessment method that result from the collaborative work of several countries, since 1996 and it was promoted by the International Initiative for a Sustainable Built Environment (iiSBE). This international involvement supported its distinction among the others methodologies, since SBTool was designed to allow users to reflect different priorities and to adapt it to the regional's environmental, socio-cultural, economy and technological contexts.

The Portuguese version of SBTool - $SBTool^{PT}$ - was developed by the Portuguese chapter of iiSBE, with the support of University of Minho and the private company EcoChoice. In this methodology all the three dimensions of the sustainable development are considered and the final rate of a building depends on the comparison of its performance with two benchmarks: conventional practice and best practice. This methodology has a specific module for each type of building and in this paper the module to assess residential buildings ($SBTool^{PT}$ – H) was used.

The physical boundary of this methodology includes the building, its foundations and the external works in the building site. Issues as the urban impact in the surroundings, the construction of communication, energy and transport networks are excluded. Regarding the time boundary, it includes the whole life cycle, from cradle to grave.

Table 1 lists the categories (global indicators) and indicators that are used in the methodology to access residential buildings. It has a total of nine sustainability categories (summarizes the building performance at the level of some key-sustainability aspects) and 25 sustainability indicators within the three sustainability dimensions.

The methodology is supported by an evaluation guide and its framework includes (Figure 1):

i) Quantification of performance of the building at the level of each indicator presented in a evaluation guide;
ii) Normalization and aggregation of parameters;
iii) Sustainable score calculation and global assessment.

In order to facilitate the interpretation of the results of this study the main steps of the SBTool^{PT} approach will be presented in the next sections.

Table 1. List of categories and sustainability indicators of the SBTool^{PT} methodology.

Dimension	Categories	Sustainability indicators
Environment	C1 – Climate change and outdoor air quality	P1 – Construction materials' embodied environmental impact
	C2 – Land use and biodiversity	P2 - Urban density P3 – Water permeability of the development P4 - Use of pre-developed land P5 – Use of local flora P6 – Heat-island effect
	C3 – Energy efficiency	P7 – Primary energy P8 – In-situ energy production from renewable
	C4 – Materials and waste management	P9 – Materials and products reused P10 – Use of materials with recycled contend P11 – Use of certified organic materials P12 – Use of cement substitutes in concrete P13 – Waste management during operation
	C5 – Water efficiency	P14 – Fresh water consumption P15 – Reuse of grey and rainwater
Society	C6 – Occupant's health and comfort	P16 – Natural ventilation efficiency P17 – Toxicity of finishing P18 – Thermal comfort P19 – Lighting comfort P20 – Acoustic comfort
	C7 – Accessibilities	P21 – Accessibility to public transportations P22 – Accessibility to urban amenities
	C8 – Awareness and education for sustainability	P23 – Education of occupants
Economy	C9 – Life-cycle costs	P24 – Capital cost P25 – Operation cost

2.2 *Assessment procedure*

i) Quantification

The evaluation guide presents the methodologies that should be used by the assessor in order to quantify the performance of the building at level of each sustainability indicator.

At the level of the environmental parameters, SBTool^{PT} uses the same environmental categories that are declared in the Environmental Product Declarations. At the moment, there are limitations with this approach due to the small number of available EPD. Therefore the methodology integrates a Life-cycle Assessment (LCA) database that covers many of the building technologies conventionally used in buildings (Bragança et al, 2008b). Nevertheless, since the LCA database did not cover all building technologies used in the assessed building, in this study was necessary to use one external LCA tool (SimaPro).

At the level of the societal performance, the evaluation guide presents the analytical methods that should be used to quantify the parameters.

The economical performance is based in the market value of the dwellings and in their operation costs (costs related to water and energy consumption).

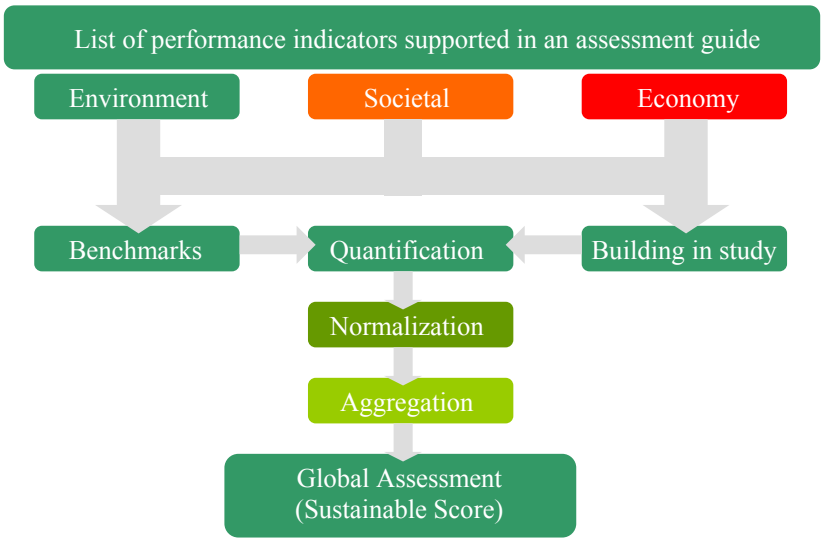

Figure 1. Framework of the SBTool^{PT} methodology.

ii) Normalization and aggregation of parameters

The objective of the normalization is to avoid the scale effects in the aggregation of parameters inside each indicator and to solve the problem that some parameters are of the type "higher is better" and others "lower is better".

The used normalization process allows comparing the performance of the building under assessment with two benchmarks: best practice and conventional. This process in addition to turning dimensionless the value of the parameters considered in the assessment, converts the values between best and conventional practices into a scale bounded between 0 (worst value) and 1 (best value). In order to facilitate the interpretation of results, the normalized values of each parameter are converted in a graded scale, as presented in Figure 2.

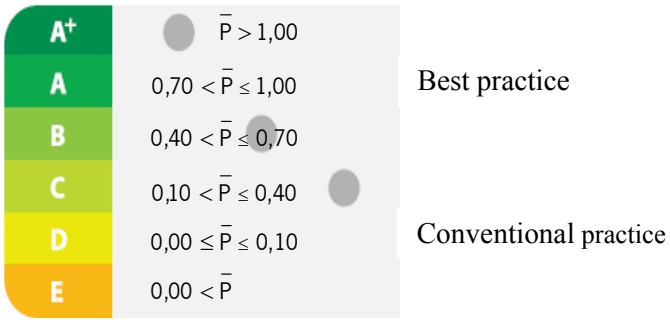

Figure 2. Conversion of the quantitative normalized parameters into a qualitative graded scale.

As an example, Figure 3 presents the differences between the qualitative level A+ and the qualitative level D when normalizing the parameter P14 - Fresh water consumption. In this case, the water consumption of an A+ building is more than 50% lower than a conventional one.

The aggregation consists on a weighted average of the indicators into categories and the categories into dimensions in order to obtain three single indicators. These three values are obtained using the equation (1) and the final result gives the performance of the building at the level of each sustainability dimension.

$$I_j = \sum_{i=1}^{n} w_i . \overline{P_i} \qquad (1)$$

The indicator I_j is the result of the weighting average of all the normalized parameters $\overline{P_i}$. w_i is the weight of the ith parameter. The sum of all weights must be equal to 1. The weights of the environmental indicators are based in a study from the US Environmental Protection Agency's

Science Advisory Board study (TRACI) and the societal weights are base on studies that were carried out in the Portuguese population (Bragança *et al*, 2008a).

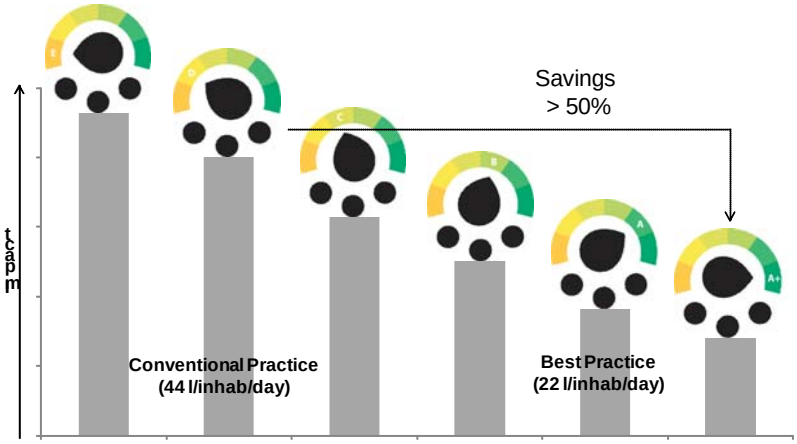

Figure 3. Benefits of an A^+ building (example for the parameter P14 – Water consumption).

iii) Global assessment and labelling

The last step of the methodology is to calculate the sustainable score (SS). The SS is a single index that represents the global sustainability performance of the building, and it is evaluated using the equation (2).

$$SS = w_E x I_E + W_S x I_S + W_C x I_C \quad (2)$$

Where, *SS* is the sustainability score, I_i is the performance at the level of the dimension *i* and w_j is the weight of the dimension j^{th}. Table 2 presents the weight of each sustainable solution in the assessment of the global performance.

Table 2. Weight of each sustainability dimension on the methodology $SBTool^{PT}$ – H.

Dimension	Weight (%)
Environmental	40
Societal	30
Economy	30

At the end, the performance of a building is measured against each category, sustainable dimension and global score (sustainable score) and is ranked on a qualitative scale bounded from A+ to E.

3 PRESENTATION OF THE CASE STUDY

The case-study is a multifamily cooperative housing building block that is the Portuguese pilot - project of the European Program "SHE: Sustainable Housing in Europe" (http://www.she.coop).

The Portuguese pilot project was the second phase of the Ponte da Pedra housing state that was built in the municipality of Matosinhos, Northern Portugal (Figure 1). It is a multifamily social housing project, which promoter is NORBICETA - União de Cooperativas de Habitação, U.C.R.L. This project has two building blocks, a footprint of 3105m^2, a total gross area of 14.852m^2 and 101 dwellings. It was co-sponsored by the project SHE and by the National Housing Institute (INH) and had the support of the FENACHE (national federation of social housing cooperatives), FEUP (Faculty of Engineering of the University of Porto) and UM (University of Minho). This project aimed to demonstrate the real feasibility of sustainable housing in Portugal and it succeed since it proved the practical feasibility of building a residential building with lower environmental impacts, higher comfort and lower life-cycle costs, when compared to a conventional one.

During the design phase, the project team adopted a series of priorities in order to create a sustainable affordable building block. The most important priorities were:

i) To use pre-developed land: this housing state was built in an area that was occupied by decayed industrial buildings (Figures 4 and 5). By contributing to the regeneration of the land and to the improvement of around urban area, this project had a positive local impact. On the other hand, due to the fact of not using new land it will contribute for the maintenance of local biodiversity;
ii) Energy efficiency: the primary energy consumption is about 25% of the local's conventional practice; it uses efficient lighting in public spaces; and solar collectors for hot water (Figure 6);
iii) Water efficiency: building is equipped with a rainwater harvesting system that guarantees at about 100% of the water supply for green areas and toilets (Figure 7); and it is equipped with low water flow devices (Figures 8 and 9);
iv) Improvement of the indoor air quality: all window frames are equipped with ventilation grids (Figure 10);
v) Management of household waste: all kitchens are equipped with containers for each of the four types of household solid waste (Figure 11); the outside containers are located nearby the building's entrance;
vi) Controlled costs: compared to the first phase of the Ponte da Pedra housing state (that have the same type of architecture but uses the conventional building technologies) the construction cost was about 9% higher. The promoter assumed part of this higher capital cost and the dwellings were sold at a price 5% higher than the first phase. According to the promoter, the turn-off of this higher capital cost will about 5 to 6 years. Nevertheless, dwellings were sold at an average price that was 20% below the local's average market practice.


Figure 4. General exterior view of the building blocks.


Figure 5. Aspect of the local before the intervention.


Figure 6. Hot water solar collectors (thermodynamic system).


Figure 7. Rainwater tank (construction phase).


Figure 8. Low flow showers.


Figure 9. Double flush toilets (6/3 l).


Figure 10. Ventilation grids on window frames.


Figure 11. Containers for solid waste separation.

4 RESULTS

4.1 *Performance at the level of each sustainability category and dimension*

Table 3 presents the values obtained in the assessment of the performance at the level of each sustainability category and dimension. Analysing the results it is possible to verify that all priorities adopted by the project team (described above) were recognised by the SBTool^{PT} methodology and therefore almost all categories (except one) have a performance grade above the conventional practice. The analysed building is only worst than the conventional practice in the category C1 "Climate change and outdoor air quality". This situation results from the fact that the building uses solid clay bricks on the exterior cladding (one material with greater embodied environmental impacts than the conventionally used materials). In compensation, building is above the best practice's benchmarks at the level of three categories: C5 "Water efficiency", C8 "Awareness and education for sustainability", C9 "Life-cycle costs". The good performance at the level of the water efficiency is mainly influenced by the implementation of the rainwater harvesting system; the good performance on category C8 is because all dwelling have a complete user manual that guides the inhabitants for the sustainable management of it; and the good economy performance is quite dependable on the lower market price of the dwellings (20% lower than average local's market practice).

Table 3. Results obtained from the SBTool^{PT} – H for each sustainability category and dimension.

Dimension	Category	Performance (normalized value)	Performance (qualitative value)	Weight (%)	Dimension Performance (I_A)
Environmental	C1	-0,20	E	13	B
	C2	0,56	B	20	
	C3	0,72	A	32	
	C4	0,10	D	29	
	C5	1,03	A+	6	
Societal	C6	0,60	B	60	B
	C7	0,74	A	30	
	C8	1,13	A+	10	
Economy	C9	1,20	A+	100	A^+

4.2 *Global assessment*

Table 5 resumes the obtained results at the level of each dimension of the sustainable development and the global performance (Sustainable Score). According to the results this building has an A grade, which means that it is considered the best practice in the Portuguese context. Figure 12 shows the SBTool^{PT}'s sustainability label according to the presented results.

Table 5: Results obtained from the SBTool^{PT} – H for the global assessment.

Dimension	Performance (normalized value)	Performance (qualitative value)	Weight (%)	Sustainable Score (SS)
Environmental	0,41	B	40	A
Societal	0,69	B	30	
Economy	1,20	A^+	30	

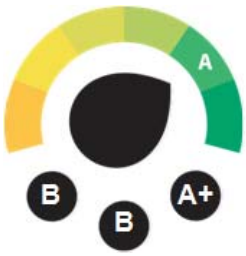

Figure 12. Ponte da Pedra real state's SBTool^{PT} label.

5 CONCLUSIONS

The sustainable design, construction and use of buildings are based on the best trade-off between environmental pressure (relating to environmental impacts), social aspects (relating to users' comfort and other social benefits) and economic aspects (relating to life-cycle costs). Sustainable design strives for greater compatibility between the artificial and the natural environments without compromising the functional requirements of the buildings and the associated costs.

This paper presented the contribution of the SBTool^{PT} in promoting the sustainability of existing, new and renovated residential buildings in urban areas, specifically in the Portuguese context. The definition of an objective list of indicators and related parameters is a fundamental tool for designers which help the implementation of the sustainable construction goals since the preliminary phases of a design.

The presented case-study showed that even with little increase on capital costs (9%) it is possible to design a building with a good level of sustainability, even in cooperative housing (dwellings' price was 20% lower than the local conventional prices). Being this pilot-project nationally and internationally recognized has a good sustainability practice it is possible to conclude that the SBTool^{PT} – H is well adapted to the Portuguese's environmental, societal and economy contexts.

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Development of a sustainability assessment tool for office buildings

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ABSTRACT: The main objective of this work is to develop a sustainability assessment tool to assess the sustainability of office buildings in urban areas, according to the Portuguese environmental, social and economy contexts. This new approach is a contribution for the office buildings module of SBTool^{PT} methodology. Since there is already a module suitable to assess the sustainability of residential buildings, this work is aimed to adapt the work developed so far to the context of office buildings. This paper starts with the analysis and discussion of the urgency to develop tools that could be used to support the design of sustainable office buildings. Afterwards the development of the proposed methodology is presented, discussing the parameters proposed to support the sustainable design and the sustainability assessment.

1. INTRODUCTION

1.1 *The urgency for a new developing model*

Nowadays, the world is facing several environmental, social and economic problems. These problems result essentially by the combination of tree main factors: world population growth; resources consumption and pollution of air, soil and water.

The world population has been increasing in a scary way in the last decades. To better understand the rapid population growth, world population reached one billion people by the year 1804, increased to 2 billion in 1927, three billion in 1960, 4 billion in 1974, 5 billion in 1987 and finally reached 6 billion in 1999. The world population in 2010 has reached 6.850 billion people and is expected to reach the 8 billion in 2028 (UN, 2010). This major increase in world population combined with the lifestyle of today's society, which is beginning to be adopted by developing countries, is causing a great demand for the natural resources of the planet. This fact is being a major cause of the global crisis that the world is experiencing nowadays. If the entire world's population was living in a European lifestyle it would take two and a half planets to supply resources for the entire population (EU, 2009).

Global warming, a major cause of environmental problems, result mainly from the increased greenhouse gases emissions to the atmosphere. Some of the main gases are carbon dioxide, methane, nitrous oxide and fluorocarbons, which are derived mainly from burning fossil fuels. This phenomenon has caused severe consequences for the world's population as, among others: increasing the average level of the sea; climate changes; biodiversity loss; and desertification. For example, 12 of the 13 warmest years ever have occurred since 1995. In 2005, the average global temperature was 0.76 ºC above the average temperature of the pre-industrial era and it is expected that by the end of this century the temperature will increase 1.8 to 4.0 ºC. To understand the importance of preventing such a steady increase in temperature there are considerable scientific evidences showing that there is a risk of irreversible climate change and possibly catastrophic consequences, such as melting ice at the poles and corresponding rise in water level

of the sea, if the temperature rises 2 ºC above the temperature of the pre-industrial era, i.e. about 1.2 ºC above the current temperature (EU, 2009).

Energy is one of the most important factors in the quest for sustainable development. That is because the increase in energy consumption is a major factor leading to global warming. Energy consumption is the main responsible for emissions of greenhouse gases in the European Union (EU). It is also estimated that the construction sector accounts for about 35% of greenhouse gas emissions (EC, 2006). Thus, the efficient use of energy is certainly one of the most important ways to minimize the environmental problems; however, the demand for energy is increasing worldwide. The International Energy Agency predicts that the global energy demand will increase by more than 50% by 2030 if policies remain unchanged and more than 60% of this increase respects to developing countries. This will lead to a 52% increase in emissions of carbon dioxide (CO^2), the main greenhouse gas (Nelson, 2010).

Protecting biodiversity is also seen as an important factor against the greenhouse effect, since the photosynthesis of plants provide an important natural mechanism for storing huge amounts of carbon.

At other field, according to the European Environment Agency, in 2005 Europe produced 1300 million tons of waste, equivalent to 3.5 tons of waste per capita and 518 kg of Municipal Solid Waste (MSW) per capita. According to data from the Portuguese Environmental Agency, in the same year Portugal produced 4.5 million tons of MSW, the equivalent to 450 kg of MSW/capita and 1.24 kg of MSW per capita per day (Lipor, 2009).

Water is also one of the essential elements for life on the planet. It is an invaluable resource for the continuity of human life, not only for drinking, but it is also essential for the production of other food resources. In fact, it takes a lot more water to produce food than for direct consumption. The needs of drinking water per person per day are 2 to 4 litres, but it is needed 2000 to 5000 litres of water daily to produce the food needed for one person (UN-Water, 2010).

1.2 *The relevance of the construction sector*

Worldwide the construction sector is responsible for consuming about 40% of raw materials and 55% of the extracted wood (Gaspar, 2009). The sector represents 40% of final energy consumption in Europe (Directive 31/2001/EU) and about 35% of emissions of greenhouse gases (Nelson, 2010). When it comes to waste, construction activities generate about 22% of all waste generated in Europe (APA, 2010).

According to the Portuguese Energy Balance of 2005, the buildings were responsible for the consumption of 5.8 Mtoe (million tons oil equivalent), representing about 30% of total primary energy consumption in the country and 62% of electricity consumption (Isolani, 2008). However, over 50% of this consumption can be reduced through energy efficiency measures (ADENE, 2009). For this reason, over the last decades emerged a number of Directives and Laws at European and national levels which aim at promoting both the reduction of energy consumption and the increase in share of renewable energies.

The economic and social impact of the sector is also enormous. Construction is directly and indirectly related to almost 10% of GDP at the European level, it directly employs 12 million EU citizens and indirectly 26 million workers are dependent on this sector (EP, 2010).

The building sector (residential & SME) produces also 17% of emissions of greenhouse gases. However, as mentioned above, the building sector accounts for about 40% of energy consumption. Thus, 40% of emissions in the energy sector are also related to the buildings, resulting in a total emission corresponding to this sector of approximately 28% (EU, 2009).

In 2002, the office buildings sector accounted for about 15% of final energy consumption in Europe and 12% of final energy consumption in Portugal (Pires, 2005). However, this sector's growth rate in average energy consumption is 12% (Decree Law 79/2006) and therefore, nowadays the rate of energy consumption that corresponds to this sector is higher than the values predicted for 2002. This sector, along with the residential property sector is among those who have the greatest potential for energy savings in Europe. The potential energy savings due to the offices sector is about 30% (EC, 2007).

1.3 *The role of the sustainability assessment tools*

Achieving sustainability in the building sector is only possible through a real methodological work. In order to be feasible, this work should be carried out during the preliminary phases of design. At this level sustainability assessment tools are playing an important role since they gather and report information for decision-making during the different phases of design, construction and use of a building. The sustainability scores or profiles based on indicators result from a process in which the relevant phenomena are identified, analyzed and valued.

There are currently many tools for assessing the sustainability of buildings. A sustainability assessment of a building should take into account the political, cultural, social and economic aspects of the site where it will be applied. Hence, given the subjectivity inherent in assessing sustainability, none of these methods is widely accepted (Mateus, 2009).

BREEAM was the first environmental assessment method for buildings. It was developed by researchers in the UK's BRE and the private sector in 1988. It is estimated that over 30% of buildings in the UK are assessed by this method. In order to allow assessments outside the United Kingdom there is nowadays the BREEAM International. LEED is an American rating system that was established in 1996 and is managed by the NGO U.S. Green Building Council. The expansion of this system to the outside of the United States is notorious as this system is being used in many countries around the world. HQE is a French association founded in 1996 that brings together professionals in the construction sector with the aim of improving the environmental quality of construction. The label replaces the HPE HQE - Haute Performance Énergétique existed since early 1990. The SBTool is a rating system for sustainable construction developed through the participation of more than 20 countries since 1996. This tool was developed and is updated by the International Initiative for a Sustainable Built Environment (iiSBE). SBTool was aimed to allow the assessment and internationally comparison of the environmental performance of buildings. CASBEE is a Japanese system of environmental assessment of buildings and was developed by the Japan Sustainable Building Consortium in 2002. DGNB System is a German environmental assessment tool that was developed by the German Sustainable Building Council in cooperation with the Federal Ministry of Transport, Building and Urban Affairs and released in 2009 to be used to support the sustainable design and to assess the sustainability of buildings.

Such tools are increasingly emerging as important solutions to decrease the impacts of the construction sector. As it was presented above, sustainability assessment of buildings is based in several goals that are much wider than the energy efficiency aims.

Although there are several definitions for a sustainable building, generally speaking, resources like energy, water, land, materials should be considered in a much more efficient way than in conventional buildings. These buildings are also designed and used in order to create healthier living conditions and more productive working environments, through the use of natural light and improved indoor environmental quality (Syphers et al, 2003). Therefore, sustainable building aims the proper balance between the three dimensions of the sustainable development: Environment, Society and Economy.

1.4 *Aim of this study*

The main objective of this work is to develop a sustainability assessment tool aimed to support the sustainable design and performance assessment of office buildings. This new approach is a contribution for the SBTool^{PT}'s module of office buildings. SBTool^{PT} is a Portuguese assessment system that results from the adaptation of the international SBTool to the national environmental, society and economy contexts. In the development of the SBTool^{PT} it is considered the ongoing standardization works on the Technical Committee 350 (CEN/TC 350), "Sustainability of Construction Works".

The module of the SBTool^{PT} developed so far is suitable to assess the sustainability of residential buildings (SBTool^{PT}-H). Therefore this work is aimed to contribute for the adaption of the work developed so far to the context of office buildings.

This methodology, henceforward called MARS-S, has a structure and assessment method similar to SBTool^{PT}. It was developed through a system based in a number of performance parameters, which allow comparing the performance of a building with two reference practices

(benchmarks) adapted to the Portuguese contexts: best practice and conventional practice. At the end, the global sustainability of a building is provided by using a single value that is obtained by the weighted normalized performance of the building at the level of each parameter. In order to provide a better support in the sustainable assessments, this methodology is also based in an evaluation guide. This guide has a similar structure to the one developed for the residential buildings.

2. DEVELOPMENT OF THE METHODOLOGY

2.1 *Main updates in the assessment structure*

Similar to the tool developed for residential buildings (SBTool^{PT}-H), the evaluation methodology is based on the calculation of the normalized performance level of the building at the level of several indicators that are considered relevant for the sustainability of office buildings. This process in addition to turning dimensionless the value of the parameters considered in the assessment, converts the values between best and conventional practices into a scale bounded between 0 (worst value) and 1 (best value). Normalisation is done using the Diaz-Baltero equation (1).

$$\overline{P_i} = \frac{P_i - P_{i*}}{P_i^* - P_{i*}} \tag{1}$$

The global sustainability of a building is the weighted average of the performance that was obtained at the level of each parameter. This evaluation methodology is actually a comparison between the building and reference national practices and therefore it can be said that this is a relative evaluation of sustainability. Therefore this methodology was named Methodology for the Relative Sustainability Assessment of Service Buildings (MARS-S). MARS-S system has an assessment method sustained in the three dimensions of sustainability: environment, society and economy. Each of these dimensions is subdivided into categories which in turn are subdivided into parameters.

Table 1 lists the categories (global indicators) and parameters that are used in the methodology to access residential buildings. It has a total of nine sustainability categories (summarizing the building performance at the level of some key-sustainability aspects) and 25 sustainability parameters within the three sustainability dimensions.

The methodology is supported by an evaluation guide and its framework includes:

i) Quantification of performance of the building at the level of each parameter presented in a evaluation guide;
ii) Normalization and aggregation of parameters;
iii) Sustainable score calculation and global assessment.

The work carried out to adapt the methodology for residential buildings to office buildings is subdivided in four steps:

i) Initially, the state of the art of existing methodologies to assess office buildings was studied. This task was focused in the international SBTool system and also considered the ongoing work on standardization bodies and other national and international *fora*;
ii) The next phase was the detailed analysis of the SBTool^{PT}-H methodology, examining the assessment methods of the various parameters in order to verify their compatibility and applicability in the case of office buildings. In this stage it was also considered whether new parameters are needed to address specific issues of office buildings that were not covered by the residential module. On the other hand, the structure of the methodology was also analysed and some recommendations for changes were made;
iii) In a third step the needs of making adjustments on the system of weights was addressed. This step is of particularly importance since there are some changes both at the level of the number of parameters and structure of the methodology;
iv) As a final step, it was developed an assessment guide to support the assessor. This

guide is aimed to promoting the assessment in a more quickly and effectively way.

Table 1. List of categories and sustainability indicators of the SBTool^{PT}-H module.

Dimension	Categories	Sustainability indicators
Environment	C1 – Climate change and outdoor air quality	P1 – Construction materials' embodied environmental impact
	C2 – Land use and biodiversity	P2 - Urban density P3 – Water permeability of the development P4 - Use of pre-developed land P5 – Use of local flora P6 – Heat-island effect
	C3 – Energy efficiency	P7 – Primary energy P8 – In-situ energy production from renewable
	C4 – Materials and waste management	P9 – Reused materials and products P10 – Use of materials with recycled contend P11 – Use of certified organic materials P12 – Use of cement substitutes in concrete P13 – Waste management during operation
	C5 – Water efficiency	P14 – Fresh water consumption P15 – Reuse of grey and rainwater
Society	C6 – Occupant's health and comfort	P16 – Natural ventilation efficiency P17 – Toxicity of finishing materials P18 – Thermal comfort P19 – Lighting comfort P20 – Acoustic comfort
	C7 – Accessibilities	P21 – Accessibility to public transportations P22 – Accessibility to urban amenities
	C8 – Awareness and education for sustainability	P23 – Education of occupants
Economy	C9 – Life-cycle costs	P24 – Capital cost P25 – Operation cost

For each indicator there is a specific assessment methodology according to the building life-cycle phase that is under assessment. Moreover it covers the two Portuguese thermal regulations that an office building must fulfil. This approach is different from the residential module since it is not only focused on the design phase. Therefore, the developed approach could be used in the assessment of new buildings or rehabilitation operations and in the stage of preliminary design, design, construction and operation phases. These different stages are the same as those used in the global methodology SBTool (iiSBE, 2010). Table 2 presents the results of the abovementioned steps.

2.2 *Brief presentation of the indicators, assessment procedure and benchmarks*

In this section the changes made at the level of the indicators, assessment procedure and benchmarks will be highlighted. This process compares the residential module of the SBTool^{PT} methodology with the proposed methodology for the relative sustainability assessment of office buildings (MARS-S). This section covers only those proposed indicators (PI) were some changes were made.

PI1 – Life cycle environmental impacts

The MARS-S's indicator "PI1 – Life cycle environmental impacts" resulted from a deep analysis of the calculation method used in the SBTool^{PT}-H's indicator "P1– Construction materials' embodied environmental impact" in order to determine some characteristics that could lead an assessor to make some calculation mistakes.

Thus, keeping the original base, some improvements were made to the calculation method to correct these problems and also to facilitate the implementation of this parameter that was quite

complex. These changes reduced not only the number of variables and tables of this parameter but also its complexity and calculation time, above all enabling greater clarity in the results.

Table 2. List of categories and sustainability indicators of the proposed methodology to assess the sustainability of office buildings (MARS-S)

Dimension	Categories	Sustainability Proposed Indicators
Environment	C1 – Climate change and outdoor air quality	PI1 – Life cycle environmental impacts PI2 – Replacement of cement in concrete PI3 – Heat-island effect
	C2 – Biodiversity and land use	PI4 – Net area index PI5 – Previously contaminated or built areas PI6 – Native plants PI7 – Certified organic products
	C3 – Energy	PI8 – Energy consumption PI9 – Renewable energy
	C4 – Materials and solid waste	PI10 – Reuse of materials PI11 – Materials with recycled content PI12 – Solid waste separation
	C5 – Water	PI13 – Water consumption PI14 – Fresh water consumption reduction PI15 – Waterproofing index
Society	C6 – Users health and comfort	PI16 – Indoor air quality PI17 – Thermal comfort PI18 – Visual comfort PI19 – Acoustic comfort
	C7 – Accessibility	PI20 – Accessibility to public transportation PI21 – Accessibility to amenities
	C8 – Awareness and education for sustainability	PI22 –Sustainable management of the Building
Economy	C9 – Life cycle costs	PI23 – Life cycle costs

PI2 – Replacement of cement in concrete

The indicator "PI2 – Replacement of cement in concrete" is very similar to the indicator "PI12 – Use of cement substitutes in concrete", however, as the use of cement has a major influence on global warming, climate change and outdoor air quality, it is proposed to move this parameter to "Category 1 – Climate change and outdoor air quality", although this parameter is related to materials selection.

In what concerns the benchmarks, it is proposed an update changing the best practice from 30% to 40%. This figure is referred as an optimal dosage for the use of cement substitutes in concrete (Camões, 2005).

PI3 – Heat-island effect

The indicator parameter "PI3 – Heat-island effect" is similar to SBTool^{PT}-H's P6. However, as the heat-island effect is more related to global warming, tropospheric ozone and outdoor air quality than to biodiversity, it was decided to move this parameter to "Category 1 – Climate change and outdoor air quality".

PI5 – Previously contaminated or built areas

The indicator "PI5 – Previously contaminated or built areas" is similar to SBTool^{PT}-H's indicator "PI4 – Use of pre-developed land". In this parameter, the conventional practice benchmark was changed from 0% to 30%. This value was obtained by taking into account recent studies (INE, 2009) that indicates a percentage of 30% for rehabilitation works in Portugal. In the rehabilitation works there are always occupied pre-built or pre-contaminated areas. This change, be-

sides being a value more representative of conventional practice, is more negative for new buildings on Greenfield sites, giving a clear incentive to reduce the occupation of areas with important ecological value.

PI7 – Certified organic products

The indicator "PI7 – Certified organic products" is similar to SBTool^{PT}-H's indicator "P11 – Use of certified organic materials". Taking into account that this indicator is focused on the protection of biodiversity by promoting the reduction of deforestation and illegal logging, it was decided to change this parameter to the Category 2: "Biodiversity and Land Use."

PI8 – Energy consumption

The indicator "PI8 – Energy consumption" is similar to SBTool^{PT}-H's indicator P7 – Primary energy. Nevertheless, to adapt the calculation method of this parameter to evaluate commercial buildings, it was necessary to define a new calculation method that enables assessment of the office buildings that are covered by different energy building regulations. Another change was made to evaluate the performance of the building without accounting the in-situ energy produced through renewable sources. Reasoning for this is that if a building produces a considerable amount of energy from renewable sources, it is possible to get a low value for the global primary energy needs and to get a good score at this parameter, using energy inefficient solutions. Additionally, this building would be doubly benefited by getting a good grade in the parameter that refers to renewable energy (SBTool^{PT}-H's P8).

PI11 – Materials with recycled content

The indicator "PI11 – Materials with recycled content" is similar to SBTool^{PT}-H's indicator "P10 – Use of materials with recycled contend". A new calculation method was developed that assesses the percentage of cost of materials and products with recycled content bigger than the conventional practice. Since this indicator is assessed using a new parameter it was necessary to establish new benchmarks. In Portugal the practice of selecting materials with high recycled content is not a common practice and therefore it was decided to consider as standard practice a value of 0%. With this value, it is possible to reward those designers who prescribe a small percentage of cost of materials with recycled content, which turns out to be an encouragement to this practice. The best practice for this parameter was set at 10%. This value is shown in a study by WRAP (WRAP, 2010) as an increasingly requirement sought by owners.

PI13 – Water consumption

The indicator "PI13 – Water consumption" is similar to SBTool^{PT}-H's indicator "P14– Fresh water consumption". In order to adapt the assessment method of this parameter to office buildings, it was defined a new calculation method, since these buildings can have various types of uses and therefore considerable variation in water consumption. Furthermore, it was taken into account that in office and commercial buildings is usual the use of automatic irrigation systems in gardens.

PI15 – Waterproofing index

The indicator "PI15 – Waterproofing index" is similar to parameter SBTool^{PT}'s P3. Nevertheless, since there is no objective relationship between the waterproofing index and its influence on biodiversity, it was decided to change this parameter to Category 5: "Water." To adapt the assessment method of this parameter for office buildings, a study was made covering different municipalities in all the districts of Portugal. This processes allowed setting new benchmarks for this type of buildings. As a result, the waterproofing index for the standard practice is 70% and the best practice 35%. A reference was added to account waterproofed areas from which runoff water is collected in tanks intended for the use of rainwater. These areas were considered 100% permeable.

PI16 – Indoor air quality

The indicator "PI16 – Indoor air quality" results from the fusion of two SBTool^{PT}'s indicators: "P16 – Natural ventilation efficiency" and "P17 – Toxicity of finishing materials". To adapt this parameter to office buildings some changes were made in the calculation method. For this pur-

pose, was taken into account that office buildings the conventional practice uses mechanical ventilation. The change made in the calculation method is also due to the fact that in office buildings covered by the Portuguese thermal regulation for residential and office buildings (RCCTE and RSECE, respectively), it is necessary to perform air quality audits by measuring the concentration of various pollutants. This is the best method for assessing the quality of air. Thus, the method for evaluating this parameter was separated according to the building design of and the applicable regulation. Thus, for buildings covered by the RSECE and in operation phase, air quality is assessed by measuring the in-situ concentrations of pollutants. For buildings covered by RCCTE or RSECE in the phases of preliminary design, design or construction, the assessment is made taking into account the predicted air quality, as a function of two factors: the ventilation rate of the building and the selection of finishing materials with low Volatile Organic Compounds (VOC).

PI17 – Thermal comfort

The indicator "PI17 – Thermal comfort" is similar to SBTool^{PT}-H's indicator P18. In the adaptation of this parameter to office buildings it was necessary to introduce some adjustments in the calculation method. Most of these adjustments are due to the fact that in this type of buildings the cooling systems are commonly used in summer. Therefore there were no changes in the calculation method for the heating season, but there were changes in the calculating method for the cooling season. To define the new benchmarks, it was used the values from the standard EN15251 for each type of space. Conventional practices were related to the comfort class III and best practices to class I.

PI18 – Visual comfort

The indicator "PI18 – Visual comfort" is equivalent to SBTool^{PT}-H's indicator "P19 – Lighting comfort". Nevertheless, the assessment method of this parameter has changed from daylight factor to illuminance levels. This change had not only in mind the need for adaptation for office buildings, but was also an improvement in order to measure more correctly the comfort of users depending on the lighting. Thus, the performance of a building in this parameter is obtained through the level of the annual weighted average of the daily lighting of the building. This value is obtained after determining the annual daily average levels of illumination in different compartments of the building, adding the portions relating to natural and artificial light, depending on the operating hours of building and average daily number of annual hours of sunlight. Since major changes were made in the calculation method, new benchmarks were adopted using the recommended values for each type of space and use that are recommended in the standard EN12464-1.

PI23 – Life cycle costs

The indicator "PI23 – Life cycle costs" results from the fusion of two SBTool^{PT}-H's indicators: "P24 – Capital costs" and "P25 – Operation costs". The adaptation of the methodology for evaluating these indicators for office buildings was carried out simultaneously, since both indicators were merged into a single indicator that evaluates the economic performance of the building throughout its life-cycle. This change considers that in office buildings the owner of the building is often the same entity that uses the building. Thus, it makes more sense to carry out a joint assessment that considers the real contribution of each phase for the life-cycle costs of a building.

3. CONCLUSIONS

This work successfully achieved its main objectives. The developed sustainability assessment tool is well suited to office buildings and several modifications to the existing module for the residential buildings of the SBTool^{PT} were proposed, improving and correcting some of its weaknesses.

The development of the methodology took into consideration the applicability of various parameters in different phases of building design, as well as its scope in terms of regulations, so it

is an important contribution in the approach of the calculation methods of various parameters in order to make their evaluation more comprehensive and objective.

The proposed methodology also took into account the diversity of uses that offices and commercial buildings may have, adapting the calculation method of some parameters by increasing their flexibility. However the objectivity remained unchanged and, whenever possible, the processes were improved in order to facilitate their applicability.

There were also some changes in some parameters through its change to categories that represent in a more realistic way their real impact on the sustainability of buildings. Important updates were also made in the benchmarks of most parameters.

Finally, this work was done probably at the stage of human history in which man is more open to be sensitized towards sustainability, because previous generations sensitization was based on the awareness to prevent future generations to suffer serious problems and nowadays, the problems have begun to emerge and the effects of the unsustainability of our current society is already felt by the citizens.

The sustainable building rating tool that is being developed intends to contribute positively to the sustainable construction in Portugal through the definition of a list of goals and aims, easily understandable by all intervenient in construction market and compatible with the Portuguese construction technology background. Nevertheless there is still one important step to fulfil before applying the methodology: validation of the list of indicators and parameters through case studies. Although the list of indicators and parameters is partially based in the framework for assessment of integrated building performance (CEN/TC 350), further work includes its validation in Portugal through thematic interviews and surveys to experts in each dimension of the sustainable development.

The uptake of sustainable building design is in its infancy. Even with the actual limitations linked to the different methods available, the widespread of assessment methods is gradually gaining more market in the construction sector. Globally, the urgency to turn the economic growth toward sustainable development will require more efforts in the construction sector, too.

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Selecting Environmental Friendly Alternatives in Infrastructure Projects

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ABSTRACT: From a project management perspective, it is proposed the application of sustainable criteria from the initial phases (conception, design and selection of alternatives) for the infrastructure projects in Spain. It is also applied to a practical case study to allow the comparison between the technique alternative selected by the project and the alternative considered the most sustainable solution following the proposed indicators. There are also studied the opportunities and limitations of the application of sustainable criteria for infrastructure projects in early stages, the future needs of the civil engineering sector and possible future research lines. This means a first approach in sustainable infrastructures in Spain.

1 INTRODUCTION

1.1 *Context*

Sustainable construction as a new paradigm in our sector includes human satisfaction, minimal consumption of resources and energy and minimal negative environmental impact (Augenbroe et al, 1998), looking for a balance between project objectives (cost, time and quality) and a proper balance of environment, society and economy.

Generally, this concept has been applied to building sector but it has also begun to be applied in civil engineering projects such as an expansion of the existing Environmental Impact Assessment. Some of the sustainability indicators systems existing in the scientific literature are shown in Table 1 schematically.

However, in pursuing the new objectives related to sustainable construction in linear infrastructure projects such as highways or railways, it is needed practical and simple models for its implementation from the initial stages and to allow the selection of the most sustainable alternatives. As noted by several authors, there is not a sufficiently robust methodology for managing a sustainable construction in projects (Kemmler and Spreng, 2007; Saparauskas, 2007). Specifically in linear infrastructure projects, except timid approach, there are no proposals for sustainable assessment for selecting the friendliest alternatives with the environment, being inexistent in the case of Spain.

Table 1. Sustainability assessment systems in civil engineering projects

Name	Scope	Project type	Country - Year
-SUSAIP-	Sustainability is managed integrally.	Infraestructures - Bridges	China and South-Africa (Ugwu et al, 2006; Ugwu and Haupt, 2007)
-TSI-	Indicators classified in two categories: environmental and technical indicators.	Infraestructures – Power lines	Canada (Dasgupta and Tam, 2005)
Aplications of LEED system to infraestructures	Based on checklists, adapting LEED criteria from building projects.	Linear infraestructures	United States (Campbell, 2009; Soderlund, 2007)
-CEEQual-	Assessment and awards scheme in civil engineering projects (design & construction stages), evaluating areas of environmental and social concerns qualitatively with checklists, since 2003.	All Civil engineering projects	UK (Campbell-Lendrum and Feris, 2008)
-ICES-	Based on ISMA (environmental sensitivity index) with social and life cycle variables.	All kind of concrete structures	Spain (Aguado et al, 2007)

1.2 *Objetives*

The objectives pursued in this article are mainly the proposal of an indicator set based on the identification and selection of sustainability variables by those involved in linear infrastructure projects (stakeholders); and to assess with those indicators the life cycle of a project from the beginning: the creation and selection of alternatives, where the project has a greater capacity to change and the possibility of greater participation by all agents (PMI, 2008).

In addition, it it is applied on a case study (informative study of highway) to check the status of technical and professional knowledge to emerging concepts related to sustainability and to identify the strengths and limitations of the measurement of sustainable criteria in a practical case study. Finally, it is compared the technical solution selected in the project with the most sustainable solution according to the indicator set proposed.

2 SUSTAINABILITY INDICATORS SYSTEM FOR INFRASTRUCTURE PROJECTS

2.1 *Indicators set*

According to the sustainable development principles and sustainability indicator standards in construction sector (ISO 21929-1:2006), it has been tried to include all stakeholders in linear infrastructure projects life cycle for the identification and selection of indicators by using eight different techniques based on risk and opportunities management: review of existing scientific literature, revision of applicable law, surveys, interviews, brainstorming, comparison with other similar areas, checklists and layout techniques (cause-effect diagrams). Thus, we have tried to agree on the variables considered by the different actors to achieve a relevant system of sustainability indicators for assessing the sustainability of different solutions and selecting the friendliest with the environment in the three dimensions: environment, society and economy.

The following Table 2 shows the finally selected indicators developed from Fernandez-Sanchez and Rodriguez-Lopez (2010), the individual assess of each criterion, the corresponding units and the weight obtained by pairwise comparison using the AHP method (Analytic Hierarchy Process).

Table 2. Set of sustainability indicators – Assessment and units

Dimensions	Macro-indicators	Assessment type	Units	Weight
Environment	Waste management	- % recycled-reused -Balance clearance and bank	%	4,96 %
	Ecological footprint	-Footprint of project activity	Ha	4,78 %
	CO2eq emissions	-Emissions in life cycle	Tm CO2eq	4,72 %
	Material consumption	-Materials by activity	T, m3, m2	4,22 %
	Water resource protection	-Expert rating , protection measures	Qualitative	3,45 %
	Barrier effect of the project	-Expert rating	Qualitative	3,00 %
	Biodiversity protection	-Expert rating, protection measures	Qualitative	2,75 %
	Environmental management	-Environmental sistems applied	Qualitative, quantitative	2,45 %
	Ecological value of soil	-Soil value, experts	Qualitative	2,43 %
	Noise pollution	-Estimated measures	dB	2,26 %
Society	Safety and Health	-% budget and expert	Qualit & quantitative	4,68 %
	Necessity of work – urgency of work	-Surveys and experts	Qualitative	4,58 %
	Project of general interest	-Expert rating	Qualitative	3,60 %
	Disaster risks (quakes, floods)	-Emergency plan	Qualitative	3,45 %
	Public participation and control on the project	-Implemented proposals / suggested	Quantitative	3,15 %
	Accessibility for human biodiversity	-Expert rating	Qualitative	2,75 %
	Respect for local customs	-Cultural and historic heritage	Qualitative	2,60 %
	Use of regional materials	-% Budget in local materials	%	2,13 %
	Visual impact	-Expert rating	Qualitative	2,13 %
	Functional and flexible	-Ability to change, experts	Qualitative	1,93 %
Economy	Energy consumption	-Energy in life cycle	MJ	5,32 %
	Life Cycle Cost	-Cost in life cycle	€	4,52 %
	Renewable energy use	-% of total energy	%	4,19 %
	Cost / benefit	-Ratio cost/benefit	c/b	3,94 %
	Adaptation & vulnerability to climate change	-Expert rating	Qualitative	3,34 %
	DfD - design for disassembly	-Expert rating	Qualitative	3,26 %
	Project governance and strategic management	-Expert rating	Qualitative	2,89 %
	Innovative elements	-R+D+i project implementations	Quantitative	2,49 %
	Cost incurred to users	-User cost using the infrastructure	€	2,30 %
	Increase in economic value of environment	-Estimation of future value, experts	Qualitative	1,73 %

2.2 *Case study*

It has been applied the selected indicator set on a highway in northern Spain (highway Medinaceli-Soria) currently under construction. The alternatives suggested in the informative study analyzed are based primarily on the route and divided into four sections, the latter of which is the access to the city of Soria. Thus, for the first three sections are considered the following solutions:

- Alternative 1: alternative corridor that has a total length of 65,709 meters, as newly built highway corridor following a default.

- Alternative 2: free alternative with a length of 65,554 meters, as well as new high-way construction.
- Alternative 3: alternative A-80, which aims to exploit the current N-111 road as a highway A-80. Thus, the aim is mainly to know the cost savings that could potentially occur. This alternative is very similar to the first (roughly the same path).

Finally, in the fourth and final section it is proposed a link with the south of Soria as the first choice or a link to the existing A-800 road.

It should be noted as a limitation of the case study that the project took into account the evaluation of mandatory environmental impact assessment and certain socio-economic criteria, but in some cases has not been possible to directly analyze some data required by all indicators proposed due to the absence of the necessary information. This is logical since the application of sustainable criteria for projects is relatively new, some of the indicators are emergent (which has recently acquired a social significance) and the application of sustainability criteria is still not implemented in practice. What is sought in this case study is to test the functionality of the proposed indicator set and to make a critical analysis of the adopted solutions. It has also been quantified those indicators on which necessary data were available for its development and subsequent calculation. When there was no information or necessary data, we used the expert appraisal or the authors' valuation in a range of [0, 10].

From qualitative and quantitative assessments obtained for each indicator with respect to the alternatives of the case study project, it has proceeded to the normalization of all criteria to the range [0,1] as it is customary in Spain (Calderon et al, 2009) and the application of a multicriteria decision-making model using Pres Method (Gomez-Senent et al, 1997; Aragones, 1997). It has been obtained the sustainability index for each alternative according to selected criteria (Figure 1).

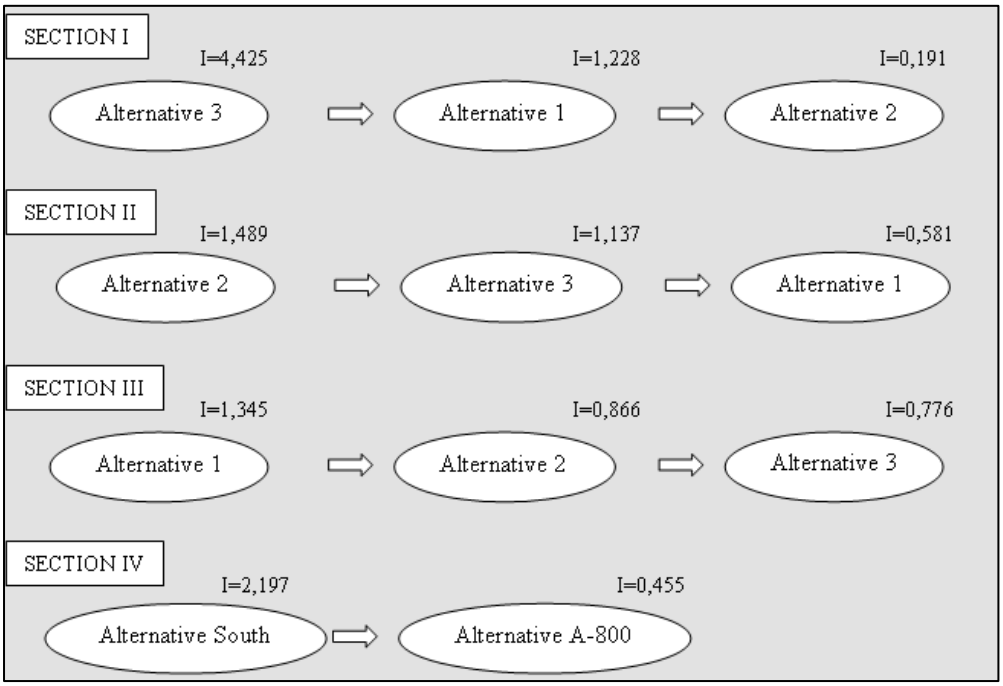

Figure 1. Sustainability index of the alternatives based on a multicriteria assessment

2.3 *Selected alternative vs Sustainable alternative*

The selected alternative by the project, chosen for its techno-economic characteristics, in addition to the results of the mandatory Environmental Impact Assessment (in this case all alternatives were rated almost equally), has been the combination of Alternative 1 in section I, Alternative 3 in section II, Alternative 2 in section III and the South Alternative in the last section. As shown in Figure 1, the most sustainable solution according to the sustainability index obtained

would be Alternatives 3, 2 and 1 in the first three sections and the South Alternative in the last section.

It is shown in next Figure 2 the comparative graphs by the assessment in environment, economy and society dimensions between the final selected solution and the solution considered the most sustainable alternative, according to the indicator set proposed.

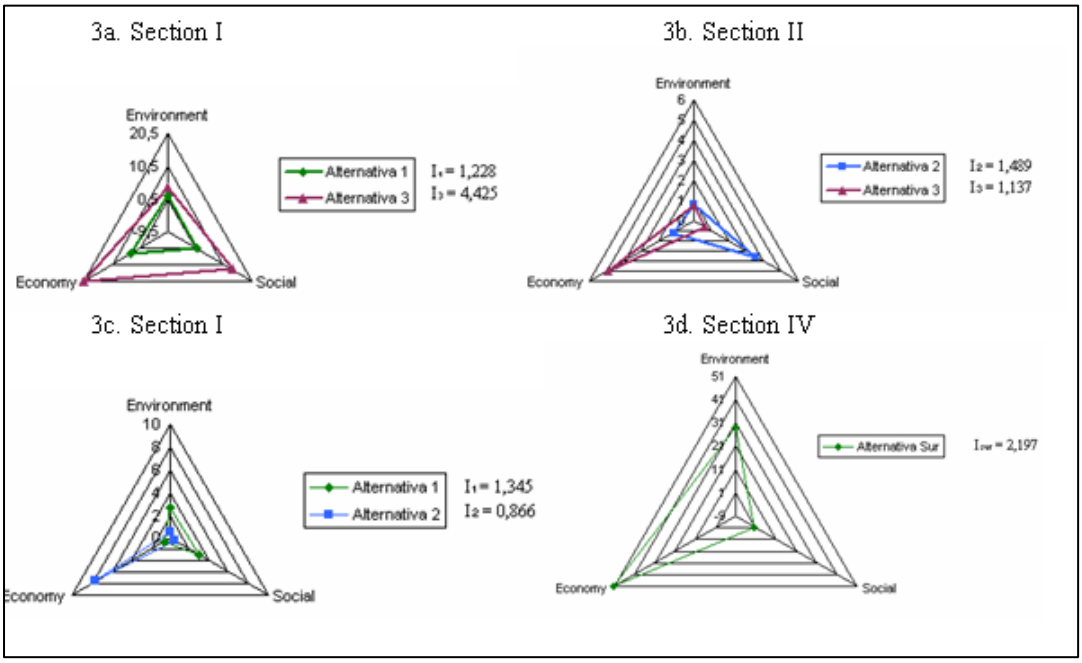

Figure 2. Comparison between the selected solution and the most sustainable alternative by the criteria proposed

3 DISCUSSION AND CONCLUSIONS

It is proposed here an indicator set for assessing the sustainability of an infrastructure project in the early stages of creation and selection of alternatives. After its application to a case study (a highway) it has been identified some limitations regarding the correct quantification of all indicators in the absence of a greater degree of definition of different alternatives proposed, resulting understandable being in such early stages of the project. For this reason, some indicators have been evaluated according to a qualitative assessment by the project authors or estimated using the pre-dimensioning according to information given in the project analyzed. Also, we should note the typical limitations of all multi-criteria analysis due to the assignment of weights and the integration of all criteria in a single value (sustainability index) and mixing units, which makes for example in section II the valuation of Alternative 2 as the most sustainable solution, while on the economic dimension has a higher score the Alternative 3 (final choice). Something similar happens in the third section, where the final selected alternative dominates in the economic dimension while sustainable solution does in environmental and social dimension. However, in the first section highlights the Alternative 3 compared to Alternative 1, since it is most valued in all dimensions of sustainability. In the last section, both solutions match.

It is considered necessary further technical development of projects in order to provide more information about the alternatives proposed and to consider more sustainability criteria in the creation and selection of alternatives to enable the empowerment and improvement of solutions towards a more sustainable construction from early stages. Applying these criteria from design phase would allow the selection of the friendliest solution with the environment. Generally, sustainability criteria such as waste management, health and safety, risk management or materials selection is carried out in later stages where the project is more rigid and change capacity is much lower. It is also noted how the technical solution chosen in the project has been the high-

est rated on the economic dimension, however not so in the other dimensions (environmental and social).

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Czech assessment system SBToolCZ

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ABSTRACT: SBToolCZ certification system comes out from the international research in sustainable building. The structure of the method and assessment procedures of each criterion was adapted to the European conditions and accords with national standards and regulations. The core indicators are incorporated according to the SB Alliance approach. SBToolCZ for residential buildings is available since June 2010.

1 INTRODUCTION

The research centre CIDEAS at the Czech Technical University in Prague (or CVUT) in cooperation with the International Initiative for a Sustainable Built Environment (iiSBE) and Technical and Test Institute for Construction Prague (or TZÚS) provides a localized version SBToolCZ for buildings certification in the Czech Republic.

2 METHODOLOGY DEVELOPMENT AND INTERNATIONAL BACKGROUND

2.1 *Review of existing tools and methods*

Several methods of complex assessment of buildings performance are available in Europe. The Czech Republic followed the international group Green Building Challenge since 2005 and participated on development of international assessment framework SBTool within the International Initiative for a Sustainable Built Environment (iiSBE).

Based on wide survey in 2008 (Lupisek et al. 2008)) focused on 17 existing methods for assessment and certification of sustainable buildings there was made a long list of all included criteria counting over 800 items. Besides the investigations of tools' structures there was made also deep analysis of the weights of particular criteria within the systems (when weighting applicable). All criteria were sorted into independent structure and the weights were put into a matrix.

It came out most of the assessment methods were in basis "green"; meaning focused primarily on the environmental impacts of building and quality of the indoor environment. Only few tools were focused wider onto the three sustainability pillars – environmental, social and economic.

Learned from this lesson when preparing certification system suitable for the Czech Republic there was selected SBTool assessment framework, which handles all the three sustainability issues.

2.2 *General information model of assessment system*

One of results of existing methodologies analysis is general information model of assessment systems. It was used in 2007 for design of a tool SBTool Core (Žďára & Vonka 2007), which stands for general software enabling simple implementation of any assessment method. SBTool

Core enables parallel assessment of one building using different assessment schemes while putting in the common parameters of building just once.

SBTool Core system also enables sensitivity analysis of any assessment method and detailed study of assessed buildings. The system works upon general database that enables quick and easy access to all data on assessment method as well as building.

2.3 *SBTool implementation in the Czech Republic*

SBToolCZ certification scheme is based on the generic framework of SBTool developed by iiSBE. Criteria benchmarks convert physical measures, indicators and levels onto unified 0-10 scale according to the SBToolCZ user guidelines containing detailed definitions and description of whole method. Criteria weights setting procedure is in concordance with the SB Method. The weights of criteria have been set by the panel of experts using SBTool localization procedures and guidance.

SBToolCZ 2010 for residential buildings in the design phase has in total 33 criteria. Set of assessment criteria is divided in accordance with principles of sustainable construction into three basic groups: Environmental, Social, Economy and Management. The three areas are complemented by a fourth group Locality.

Assessment of the locality (building site and its surroundings) is separated from the building performance evaluation in concordance with the German approach of the BNB methodology.

The criteria accord to Czech and European standardization and reflect the outputs of CEN TC 350. The core indicators of the SB Alliance are also incorporated.

2.4 *SBToolCZ structure*

SBToolCZ methodology consists of 33 criteria: 12 environmental; 11 social; 4 covering economy and management; 6 related to location. Full list of criteria is in Table 1.

Table 1. SBToolCZ criteria

ID	Criteria
E.01	Global warming potential
E.02	Acidification potential
E.03	Eutrophication potential
E.04	Ozone depletion potential
E.05	Photochemical ozone creation potential
E.06	Use of greenery on building site
E.07	Use of greenery on roofs and facades
E.08	Potable water
E.09	Primary energy consumption
E.10	Use of construction material
E.11	Land use
E.12	Rainwater utilization
S.01	Lighting comfort
S.02	Acoustic comfort
S.03	Summer thermal comfort
S.04	Winter comfort
S.05	Health safety of materials
S.06	User comfort
S.07	Accessibility for disabled people
S.08	Building security
S.09	Adaptability
S.10	Space Efficiency
S.11	Use of building exterior
C.01	Operation cost analysis
C.02	Provision of operation plans
C.03	Operation autonomy
C.04	Sorted waste management
L.01	Biodiversity
L.02	Provision of place for free time
L.03	Provision and proximity of key amenities
L.04	Public transport accessibility
L.05	Site security
L.06	Natural risks

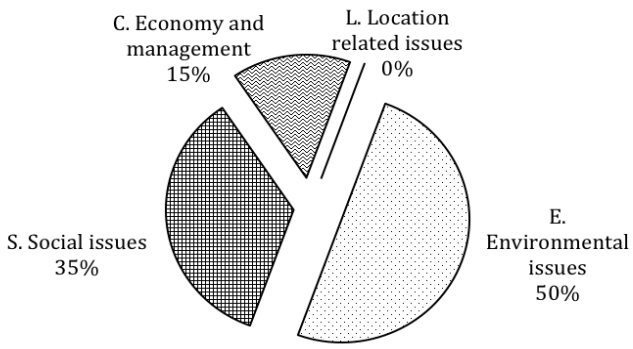

Figure 1. SBToolCZ - weights distribution.

2.5 *SBToolCZ certificate*

The output of the certification is the final certificate, which comes out along with the detailed charts of building performance stressing the three main sustainability issues – environmental, social and economic. The final result on the certificate displays not only the final score, but also building performance within the three main issues. Detailed report presenting transparently whole assessment process and details of each criteria evaluation is form of a component of a certificate.

Building performance certificate SBToolCZ is based on the total score. There are four certification levels, as follows:

- Certified building (score 0 – 3.9);
- Bronze certificate (bronze leaf, score 4.0 – 5.9);
- Silver certificate (silver leaf, score 6.0 – 7.9);
- Gold certificate (golden leaf, score 8.0 – 10.0).

2.6 *SBToolCZ certification body*

In the period 2010 – 2011 the only certification body for the SBToolCZ is TZÚS, one of the biggest testing institutes in Czech. The auditors for SBToolCZ have been educated and accredited during summer 2010. Actual list of auditors is available at www.sbtool.cz.

Current version of SBToolCZ focuses on residential buildings (more than 50 % of net floor area used as residential). The assessment is being carried out in the two phases:

- design phase (assessment of building based on the project documentation for building permit and related documents);
- assessment of finished building (assessment of the real as-built house; within the first year of operation).

Each of above-mentioned assessments results in different type of the certificate.

2.7 *First certified project X-LOFT*

The first building certified by the methodology SBToolCZ has 44 apartments, two ground floors and four standard floors and an attic. The building fills a brownfield gap in Prague 8.

Building project was optimized due to evaluation by criteria of SBToolCZ. Some of the building highlights are use of solar collectors on the roof of the building, retention of rainwater for the greenery irrigation, option to include air heat recovery system in housing units.

The following scores have been achieved:

- Environmental: 7.1
- Social: 5.8
- Economy and Management: 5.3
- Location: 7.0.

Total building´s score is 6.3, which corresponds to the silver certificate.

3 CONCLUSIONS

The SBToolCZ certification system comes out from the international research in sustainable building. The structure of the method and assessment procedures of each criterion was adapted to the European conditions and accords with national standards and regulations. The core indicators are incorporated according to the SB Alliance approach. SBToolCZ for residential buildings is available since June 2010.

Acknowledgement

This outcome has been achieved with the financial support of the Ministry of Education, Youth and Sports of the Czech Republic, project No. 1M0579. All support is gratefully acknowledged.

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Sustainability assessment of buildings and needs of stakeholders

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ABSTRACT: The paper contains first results of the international research project SuPerBuildings - Sustainability and Performance assessment and Benchmarking of Buildings. The project will develop and select sustainability indicators for buildings and provide guidance for sustainability assessments and rating methods for buildings. One of the initial project objectives was to develop understanding how to indicate social and economic sustainability of buildings, improve the logical structure of assessment systems and develop understanding about key performance indicators. During the period of June - October 2010 a wide international survey oriented on different sustainability assessment stakeholders groups and their needs has been organized. The paper summarizes overview of the survey results.

1 PROJECT OBJECTIVES

One of the project's main goals is to develop a common understanding about the potential of sustainability assessment and benchmarking methods in progress towards sustainable built environment. The project will model, study and make conclusions about the usefulness and potential of sustainability assessment and benchmarking methods in different stages and tasks of building processes and study the potential of these methods with regard to different steering mechanisms. The project considers different steering mechanisms paying attention to economic incentives and regulations.

The project will develop understanding how to indicate social and economic sustainability of buildings, improve the logical structure of assessment systems, develop understanding about key performance indicators and develop the validity and reliability of the selected key indicators. It is important to avoid overlapping indicators and ensure that all wanted aspects of sustainable buildings are measured with help of appropriate indicators.

SuPerBuildings project consortium will collect information about the performance levels of buildings with regard to key performance indicators and study how these vary in different European countries, develop knowledge about the required levels in order to achieve minimum progress required and significant advance in building stock and built environment in terms of sustainable development.

Next objective is to develop recommendations and solutions for the use of the system in different stages of building process and in steering and building regulation. The project will consider the following stages: target setting, design, construction and tendering processes, building maintenance and renovation. The project will also develop solutions for the integration of sustainability assessment systems with BIMs. The project will make guidelines in order to support the further development of existing BIM software.

One of the initial project objectives was to develop understanding how to indicate social and economic sustainability of buildings, improve the logical structure of assessment systems and develop understanding about key performance indicators. During the period of June - October 2010 there was organized a wide international survey oriented on different sustainability assessment stakeholders groups and their points of view and needs.

2 METHODOLOGY

The main information sources for the research work were results of interviews and surveys.

Surveys were organized in paper and electronic form. Paper surveys were distributed during two sustainable building conferences. The first one was "Central Europe towards Sustainable Building" conference held 30.6. – 2.7. 2010 in Prague, Czech Republic. The second conference was "SB10 Finland: Sustainable Community" held 22. – 24. 9. 2010 in Espoo, Finland. During those two events 450 paper survey questionnaires have been distributed, from which 73 were collected back (return ratio over 16 %).

In the period of July and September 2010 a call for filling the electronic version of the survey has been send out to the whole project network. There were collected 58 responses.

In the same period interviews with local stakeholders around Europe were organized. All the project partners were asked to contact local stakeholders and interview according to the interview guidelines provided by CVUT. Interviews were arranged personally, via phone or Skype. The stakeholders' answers were copied into one single file question by question.

Complete information on the survey and its results are accessible online at the project website http://cic.vtt.fi/superbuildings in session deliverables under D3.1.

3 SURVEY RESULTS

3.1 *Respondents*

The major groups of respondents were researchers (49), academics (48), architects and designers (42) and users of the buildings (35). On the other hand the groups of grant providers, insurers, banking sector, planning authorities, community representatives and estate agents were minor. This was partially caused by the fact that participants of events like conferences are mainly architects, designers, researchers and academics and that these stakeholder groups are in general more interested in sustainable building assessment issues.

3.2 *Importance of assessment for specific stakeholders' groups*

It was clear from the results that in general sustainability assessment is most important for architects and designers, authorities and planning authorities. On the other hand it seems to be of low importance for insurers, banking sector and community representatives (Fig. 1).

It was interesting this general point of view is common for the most of stakeholders' groups, however there are some exceptions:

- Clients see the assessment most important for property owners and valuers.
- Facility managers see the assessment most important for authorities, clients, contractors, and manufacturers.
- Manufacturers see the assessment most important for professional associations, researchers, planning authorities, valuers.

3.3 *Demanded level of details in assessment output*

Detailed results of the assessment are most valuable for researchers, academics, architects and designers and manufacturers. Community representatives, planning authorities, authorities (policy makers), clients and users demand partially aggregated results. Fully aggregated results are most useful for banking sector, estate agents, insurers and grant providers.

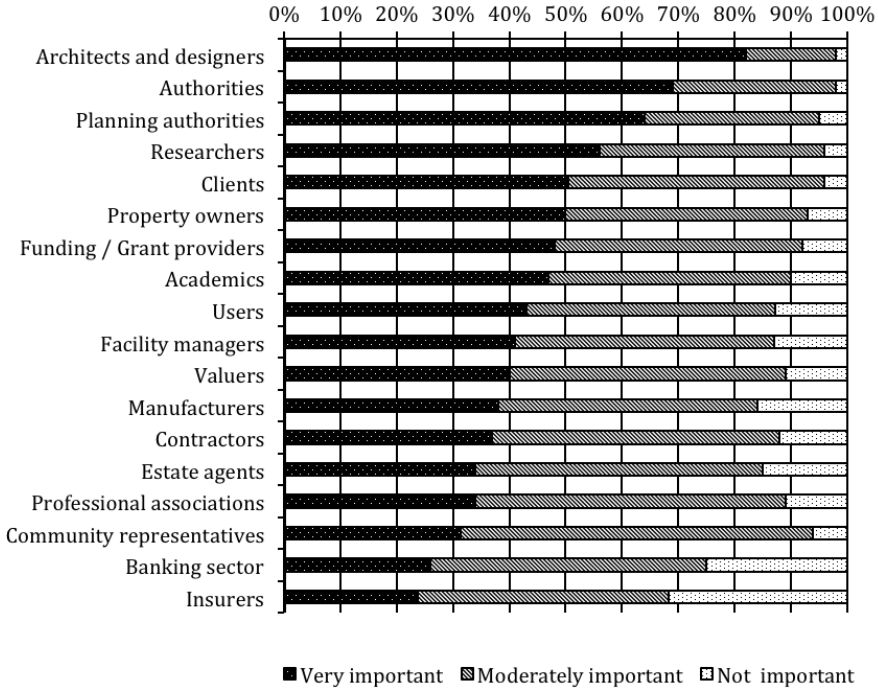

Figure 1. Level of importance of buildings sustainability assessment for particular stakeholder groups.

3.4 *Complexity of assessment tool*

Academics, researchers, valuers, users of buildings, contractors and clients find most useful comprehensive assessment tool. Architects and designers and partially property owners demand simple self-assessment tool. Community representatives and planning authorities would like to have a short checklist.

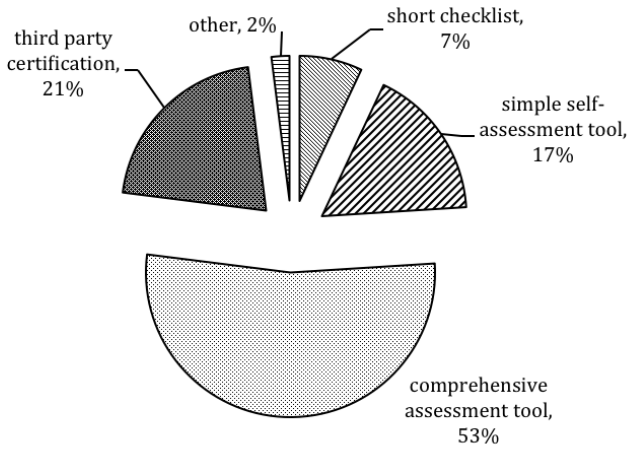

Figure 2. What type of assessment tool is the most helpful for your profession?

Third party certification is most supported by valuers, manufacturers, authorities, grant providers, planning authorities and professional associations.

Remarkable notes were in the respondents' comments:

- "Pre-*assessment tool for architects is helpful. In companies where such tool is being used, the efficiency of the design process has risen."*
- *"Third party assessment is efficient solution, because the level of quality can be easily controlled, specialization is profitable."*
- *"Suitable type of assessment depends on building type and project size."*

3.5 *Benefits of assessed buildings*

Most of the respondents (47 %) indicated that the fact the building's sustainability has been captured by an assessment could increase value of the building up to ten percent (up to five percent – 22 % respondents; five to ten percent – 27 % respondents).

3.6 *Operation costs of sustainable buildings*

Respondents indicated that the energy costs of sustainable buildings are in general more than 20% lower compared to average buildings and costs of water bills of sustainable buildings are up to 10% lower compared to average buildings.

3.7 *Impact of existing assessment systems*

Altogether 58 % of respondents feel impact of the existing assessment systems on the overall sustainability of buildings as strong (12 %) or moderate (46 %). On the other hand 41 % find the impact slight (37 %) or none (4 %).

3.8 *Roles of sustainability assessments*

According to the respondents the main roles of assessment systems are related to improvement of design process. Other important role is project quality and value assurance (project quality assurance – 15 %; valuation – 7 %; portfolio analysis – 4 %).

3.9 *Public support for incentives*

Most of respondents think there is public support for some kind of incentives for sustainable buildings. But the particular form of incentives is still for wider discussion. The possible forms of public incentives for sustainable building should be further explored.

3.10 *Benefits of integration of assessment system into one single tool*

The respondents see the multiple benefits of integration the assessment system into one single tool and slightly prefer collaborative benefits prior to ease of data maintenance.

4 CONCLUSION

Each stakeholder in the process of sustainability assessment has different needs. The future assessment systems should reflect this variety and provide support appropriate tools.
More detailed results of the survey can be found in the project deliverable D3.1. The project has a website http://cic.vtt.fi/superbuildings where all finalized deliverables will be published.

Acknowledgements

This paper presents the work and findings of the SuPerBuildings consortium, which consists of VTT, BRE, CSTB, CSTS, KIT-U, CVUT, IAO, TECNALIA-LAB, ÖGUT, YIT, VINCI, Werner Sobek, and W/E Consultants. This outcome has been achieved with the financial support of the FP7 project No. 244087 SuPerBuildings. All support is gratefully acknowledged.

Comparison of Eco-Office Buildings from the Viewpoint of Sustainability of Constructions

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ABSTRACT: Sustainable building is the process of constructing buildings with the use of materials and technologies that are environmentally responsible and environmentally friendly. Being environmentally responsible/friendly has different values such as decreasing the energy use or decreasing the CO_2 emissions of a building. Office buildings, which consume great amount of energy and produce tones of CO_2 emissions during both the construction period and the service period, become a significant building type on the sustainability of construction. Lately there are many office buildings that are designed and constructed to be ecological. They can be called as eco-office buildings. All of them have different solutions to decrease their environmental impacts. In this study, these solutions are examined and compared from the viewpoint of sustainability of constructions.

1 INTRODUCTION

"The significant problems we face cannot be solved by the same level of thinking that created them."
-Albert Einstein

Sustainable building (also known as *green building*) is the practice of creating structures and using processes that are *environmentally responsible* and *resource-efficient* throughout a building's life-cycle: from siting to design, construction, operation, maintenance, renovation, and deconstruction (EPA, 2009a). Being environmentally responsible also means being *environmentally friendly* (*eco-friendly* / *nature friendly* / *green*). The term "*eco-office building*" (also known as *green office building*) simply refers to any sustainable, environmentally responsible/friendly office building.

Sustainable buildings are designed to reduce the overall impact of the built environment on human health and the natural environment by:

- Efficiently using energy, water, and other resources
- Protecting occupant health and improving employee productivity
- Reducing waste, pollution and environmental degradation

Eco-office buildings, like any other sustainable buildings, must fulfill these qualifications.

As it is known, buildings are the biggest CO_2 emission producer (more than 70 percent) on earth. Since 1960, buildings have become the biggest carbon emission contributor, followed by the transportation sector and industry. They are also the biggest energy consumer on earth. For example: in U.S.A, buildings accounted for 72% of total electricity consumption and 43% of emitted greenhouse gases. Nearly half of that electricity consumption was attributed to commercial building usage (EPA, 2009b). Office buildings are generally large-scale buildings that

consume great amount of energy and produce tones of CO_2 emissions during construction and operation period of the building. Especially big office buildings, which accommodate many people during daytime, have become a significant building type on the sustainability of construction. There is no exact data about the total office space in the world. However, only in the EU, it is estimated that there is over 400 million square meters of office space (Rekyl project, 2004).

The implementation of eco-office building principles is based on the fact that any reduction in the *carbon footprint* of office buildings, like any other buildings, would significantly mitigate global warming.

2 EXAMINATION OF ECO-OFFICE BUILDINGS

The pioneering examples of eco-office buildings are: Willis Faber and Dumas Headquarters (Ipswich, UK, Norman Foster, 1975), which utilized a grass roof, day-lighted atrium, and mirrored windows; Gregory Bateson Building (California, USA, Sim van der Ryn, 1977) which used energy-sensitive photovoltaic (solar cells), under-floor rock-store cooling systems, and area climate-control devices. As case studies, following eco-office buildings will be considered—in a chronological order.

2.1 *The Environmental Building (BRE Building) (Garston, Hertfordshire, UK, Feilden Clegg Architects, 1996)*

The building has energy efficient building design. Energy demand and CO_2 emission of the building is 30% lower than that of a typical one. The energy consumption targets were 36 kWh/m^2 from electricity, 47 kWh/m^2 from gas and the CO_2 emissions were 34 kg/m^2. These are very low values for an office building. (Thomas, 2006, p.192)

2.2 *Helicon Building (London, UK, Sheppard Robson, designed with services engineers Ove Arup & Partners, 1996)*

The building has brought a solution to the natural ventilation of office buildings reducing the dust and noise problems. It has a double skin façade which has blinds between the two layers. These blinds protect the interior from excess sunlight. Total floor area of the building is 27.000 m^2. Annual energy use of the building is 177 kWh/m^2 while that of a typical building type is 348 kWh/m^2. (Wigginton, 2002, p.86)

When looked at energy running costs, it is about £50/m^2 per year which is significantly less than that of conventional office buildings (Edwards, 2003, p.49).

2.3 *Daimler Chrysler Building (Berlin, Germany, Richard Rogers Partnership, 1999)*

Building has been formed to optimize daylight, natural ventilation, solar control and views. The design of the building makes it environmentally friendly, using technologies such as ventilating facade complemented by nighttime free cooling, and use of atrium as thermal buffer. The modular building facade developed for solar shading with offices positioned to protect atrium from low sun. The embodied energy and CO_2 emission of the building is approximately 30% less than that for a typical office building. Facade costs 20% higher than usual (facade costs are 9% of total building cost) but help to reduce running costs 60%; annual energy consumption is approximately 75 kWh/m^2, which is a quarter of that consumed by a typical office building (Edwards, 2003).

2.4 *Condé Nast Building (New York, USA, Fox&Fowle, 2000)*

The building uses solar panel and fuel cell technology. It's the first project of its size to undertake these features in construction. Photovoltaic panels are located in the spaces between rows of windows on the southern and eastern facades on the top 19 floors of the building. The PV in-

stallation is expected to generate 15 kWh of power. Two fuel cells, located on the fourth floor, generate enough electricity to cover the building's base load during nighttime hours. Fuel cells are non-polluting, producing only hot water and CO_2 as by-products (COC, 2010). Environmentally friendly natural gas-fired absorption chillers, along with a high performing insulating and shading curtain wall, ensure that the building does not need to be heated or cooled for the majority of the year. The air-delivery system circulates 50% more indoor air than required by New York City building code.

2.5 *Swiss Re Building (London, UK, Norman Foster, 2003)*

This eco-office building was designed to admit natural ventilation through windows that open right up to the 32nd floor, when the wind speed is below 10 mph and the external temperature is between 20°C and 26°C—that is, up to 40% of the year in London (Spring, 2008). A series of rotating, radiating floors are linked by spiraling light wells that contain greenery to provide visual breaks and pressure differentials that assist natural ventilation. Fresh air is drawn in at each floor through slots in the cladding, and exhaust air is vented to the outside or recycled to provide heat to the building. Internal temperatures have been fine-tuned by adding 26 air sensors and adjusting the building management system (BMS). Advanced modeling of the building dramatically reduces energy consumption and the required scale of the mechanical plant, providing further cost savings. The building uses 50% less energy than a typical office building (Spring, 2008).

2.6 *Bank of America Tower (New York, USA, Cook+Fox Architects, 2009)*

This one billion dollar office building project has been specially designed to be one of the most efficient and ecologically friendly buildings in the world. It is also the first skyscraper designed to attain a Platinum LEED certification (BOA, 2010). Its design makes it environmentally friendly, using technologies such as floor-to-ceiling insulating glass to contain heat and maximize natural light, and an automatic daylight dimming system. The building also features a greywater system, which captures rainwater and reuses it. Air entering the building is filtered, as is common, but the air exhausted is cleaned as well (Cook, 2005).

Structural materials include steel made of 87 percent recycled content and concrete made from cement containing 45 percent recycled content (blast furnace slag) (BOA, 2010). The use of slag cement reduces damage to the environment by decreasing the amount of cement needed for the building, which in turn lowers the amount of CO_2 greenhouse gas produced through normal cement manufacturing. One ton of cement produced emits about one ton of CO_2 into the atmosphere (US Concrete, 2010).

The building produces energy on site with a 4.6 MW, natural gas burning co-generation system. This combined heat and power system provides approx. 65 percent of building's annual electricity requirements, and reduces daytime peak electricity demand by 30 percent (BOA, 2010). While generating electricity, the system will also capture almost all heat created by the process (whereas typical large power plants lose 66% of the energy they make, in the form of waste heat). Onsite power generation also reduces the significant electrical transmission losses (about 7% for United States electrical grid) that are typical of central power production plants (Cook, 2005). Waste heat from co-generation is used to provide heat in winter and cooling in summer through an absorption chiller. Ice storage system provides approx. 25 percent of the building's annual cooling requirements, reducing daytime peak loads on city's electrical grid. At night, excess electricity from co-generation system is used to produce ice, which is melted during the day to supplement the cooling system. According to Cook, building uses 50% less energy than a typical office building (Cook, 2005).

2.7 *Pearl River Tower (Guangzhou, China, SOM, 2009)*

This 71-story, zero-energy office building uses both modest energy efficiency, and a big distributed renewable energy generation from both solar and wind. Building generates nearly all the electricity that it requires.

2.8 *Energinet.dk Building (Ballerup, Denmark, Henning Larsen Architects, 2011)*

This under-construction office-building project, which will be completed in 2011, is designed to achieve the lowest energy class possible—and thus the lowest possible maintenance and operation costs. The annual energy consumption of the building is predicted as only 48.8 kWh/m^2. Incorporating solar panels, ground water cooling and heat pumps in the project would further reduce the annual energy consumption to only 35 kWh/m^2. The building meets the requirements for low-energy class 1 according to Danish building regulations even without the use of energy producing technologies (Henning Larsen Architects, 2010).

The building that covers 4,000 m^2 in two-story, has a compact shape (large volume compared to surface area) to reduce the heat loss. Integrated energy design concept of the building makes it environmentally friendly, using technologies such as three-layer low-energy windows, north-facing overhead lights, and use of green roof serving several sustainable purposes. Green roof reduces the load on the public sewage system by means of slow percolation and evaporation. In addition, the collected rainwater is used for flushing the toilets and watering the garden, which contributes to reducing the overall energy consumption for cooling.

3 DISCUSSION

Annual energy consumption is an important indicator of a building's carbon footprint. For typical (or conventional) office buildings, annual energy consumption ranges from 100 to 1000 kWh/m^2 depending on location, use, hours of operation, building characteristics and type of services (Rekyl project, 2004). For example: in a research to study the energy efficiency of office buildings in Hong Kong, between 104 actual samples, the worst performance was obtained as 582 kWh/m^2 —for every 10 m^2 of this building, annual energy consumption is equivalent to a three-member family's annual energy consumption. (WWF-Hong Kong, 2010). According to Davis, annual energy consumption values from 80 to 250 kWh/m^2 are common among traditional office buildings (Davis, 2008). Since, eco-office buildings are designed to use the energy efficiently, the main feature of an eco-office building is "low annual energy consumption". According to DETR Report 30, the target for total electricity consumption of energy-efficient offices range between 36 and 75 kWh/m^2 per year while CO_2 emissions range between 34 and 52 kg/m^2 per year (Edwards, 2003, p.12). Annual energy consumption of considered case studies ranges from 36 to 177 kWh/m^2.

Table 1. Examination of case studies(derived from above).

Name of Building	Year Completed	CO_2 Emission	Annual Energy Consumption
The Environmental Building (BRE Building)	1996	34 kg/m^2 (30% lower than a typical office building)	36 kWh/m^2 from electricity 47 kWh/m^2 from gas
Helicon	1996	-	177 kWh/m^2
Daimler Chrysler Building	1999	approximately 30% less than that for a typical office building	75 kWh/m2
Condé Nast Building	2000	-	-
Swiss Re Building	2003	-	50% less energy than a typical office building
Bank of America Tower	2009	-	50% less energy than a typical office building
Pearl River Tower	2009	-	zero-energy office building
Energinet.dk Building	2011 (estimated)	-	predicted as 48,8 kWh/m^2 (would further decrease to 35 kWh/m^2)

Electric consumption in offices is growing due to architecture with large glazed facades, increasing use of IT solutions and increasing requirements for internal air quality. Typical office buildings, heavily relying on air-conditioning systems often use 10 to 15 times more energy than the most energy efficient buildings (Baker & Steemers, 1999). Especially, the main part of the cooling demand is covered by electricity consuming installations, and about 10% of the global electricity production is used for cooling (Rekyl project, 2004).

As seen from Table 1, the annual electricity consumption of the buildings can be reached from anywhere while nearly nothing can be found about the *Carbon Footprint* of the buildings, only approximately 30% less CO_2 emission is mentioned in the literature as found. But it is the CO_2 or other greenhouse gases emission amount which helps having sustainability when decreased. Therefore it is necessary to calculate and announce this value in order to have a more sustainable future.

Towards the latest case studies, the total annual energy consumption is decreasing. It is even zero in the Pearl River Tower building. But zero-energy concept doesn't mean that the building doesn't use energy; it means energy consumption of the building is lowered to a value which can be produced only by use of green technologies—like solar panels, wind turbines, fuel cells and co-generation systems. A further step towards this concept is also possible; an office building can produce more energy than it consumes. The Energy Plus Office Building (Paris, France, SOM), which has not yet broken ground, is planning to produce up to 20% more energy than it consumes—hence the building's name. Building will hold 10,800 m^2 of photovoltaic cells on the roof—the largest building-integrated solar array in the world—and the Seine River's water will be used for cooling purposes; no air conditioner needed. Building is set to consume only 16 kWh/m^2 per year (Davis, 2008).

4 CONCLUSION

An eco-office building is constructed and operated in line with environmental factors/ecosystem. They use the energy efficiently through a cleverly integrated package of passive and active environmental controls. They reduce the energy consumption by use of sources such as natural ventilation, cool-night air, heat created by the built-in co-generation systems, and even Underground Thermal Energy Storage (UTES) using groundwater or geo-exchange systems for thermal energy. Some eco-office buildings also produce energy by use of co-generation systems, wind turbines, solar panels and fuel cells. The other eco-features of these buildings are green roof, exhausted air cleaning, greywater and rainwater systems.

It is clear that carbon footprint of the eco-office buildings is decreasing within every generation of them. The eco-office building of the future doesn't just do less harm to the environment; it improves it. It won't just use less water; it will collect and treat it. It won't just consume air; it will filter it. And it won't just save energy; it will generate it.

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Integrated design of buildings

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ABSTRACT: The paper treats the aspect of integrating the environmental impact in the usual design of buildings. Experience shows that the environmental impact of a building is very difficult to control at a macro-level (global or integrated approach). That is why, in practical applications is suggested to work on certain levels: (i) at a micro-component level, as in the case of comparing materials with the same destination in buildings; (ii) when the difference could not be made at the level of individual items, the analysis should contain components, as is the case of assemblies. This is the case for example in choosing different systems for envelopes, roofing systems, finishing layers etc. and (iii) at a macro-component level, in which the integrated analysis is made for the entire building. Considering these levels, one can easily combine the micro-components and components in order to approximate the global environmental performance of the building. The paper presents applied examples that show the methods of integrating the environmental impact aspect in usual design of buildings at different levels.

1 INTRODUCTION

In the traditional spirit of building, a frequent dispute leads to a so-called "adequate design". It includes two conditions that are somehow in contradiction:

1. *The accomplishment of design criteria related to safety and functionality.* It implies aspects related to resistance and stability under severe conditions of loading, the architectural, thermal, acoustic, hydro-insulation demands etc. that could affect the internal comfort of the inhabitants;
2. *The achievement of an economical structure*. This criterion may influence not only the choice of a structural system, but also the choice of building envelopes and other non-structural components. Mainly, it is the beneficiary who takes the principal decisions about investing more in the construction phase thus reducing the costs during exploitation or reciprocally.

In the holistic approach, applying an integrated performance design, the environmental impact should be considered as a third set of constraints.

Taking into account the fact that the first condition of safety and functionality represents a necessary condition for a building, it results that the design should be based on the following philosophy: among the solutions that assure the safety and functionality of a building, one should chose those conducting to a minimum cost and a lower impact on environment.

The present study analyses the approaches used to estimate the environmental impact on buildings in order to account the differences that could appear in the design process due to the choice of a material or another or due to choices of a certain constructive solution or another.

Sustainable development in construction assumes not only the implications in design options (the choice of building materials etc.) and the architectural aspect, but also should contain considerations on energy efficiency or the disposal scenario.

2 ENVIRONMENTAL IMPACT AS A DESIGN CONSTRAINT

Taking into account the huge amount of energy and material use for buildings, the environmental impact is more and more regarded as an additional constraint in designing. Moreover, this should be considered in all phases of the construction life, as the realisation, exploitation and at the end of life. Thus, it is recognized that Life Cycle Assessment (LCA) offers a very good tool for the determination of the environmental effects of products or processes (Braganca & Mateus 2008).

However, the intervention of this third factor in the conception of buildings will make the full equation of building conception of a higher degree. The resolution in this case first requires a full understanding of the problem by all the factors involved, but nevertheless, the choice for a final solution can draw back more or less on other criterion.

The environmental consideration will sometimes be in contradiction with traditional parameters such as the economical aspect (Block & Gervasio 2008).

In the case of buildings, in order to perform a rigorous LCA, there should be considered several phases, each of them having its influence on the global impact. Among them, at least three should be considered into an LCA:

- the erection phase;
- the exploitation phase;
- the disposal (demolition, reuse etc.).

Each of these phases could contain energy use, materials and processes. The tools that are now in use for evaluating the environmental impact strongly recommend to have clearly defined the scope and system boundaries for LCA analyses. In many situations, especially when comparisons are made, some processes and materials could be intentionally excluded from LCA analyses. This is because these materials and processes bring the same environmental impact and therefore the boundaries are set by excluding common elements.

When performing an LCA, the results are analysed by means of a certain method. In order to perform a realistic interpretation of the results, attention should be paid when choosing the right analysis in relation to the process under consideration.

3 SIMPLE APPROACH OF THE ENVIRONMENTAL IMPACT OF BUILDINGS

The simplest way of considering the environmental impact in buildings is by analysing the materials that may have the same function within a building. As an example, Figure 1 presents a simple comparison of two materials, both used in thermal insulation of walls: mineral wool vs. glass wool.

The analysis is made only for the production stage, considering 1 kg for each material, using the SimaPro software and considering the Eco-Indicator'99 as the method for the interpretation of results. These are represented per impact category in points (defined in accordance to Eco-Indicator'99 method). The scaling of points is done in such a way that 1000 Pt represents the average environmental load for one European.

Usually, the results are quite subjective and give rise to interpretations due to (at least) the following reasons:

- the input data for processes and materials are not the same in the case of a real project with the conditions of material definitions in the databases (for example the energy process is different from the European average to each European country);
- there are specific processes that should be added at each location (for example transportation to site) which is different from location to location;
- usually, the materials are considered as using an average energy and material consumption, fact that may differ from a producer to another. Anyway, it is hard to know from the beginning what producer will be the provider of a certain material;
- the weighing of results represents a very subjective way of comparing different aspects that are considered when analysing the environmental impact. For example, the single scoring will include scoring of carcinogen substances and acidification although they are not comparable and compatible in a direct way;
- the method used for the interpretation of the results may consider or not certain aspects.

Concerning the last issue, Figure 2 presents the results of the same comparison (considering the two materials listed above) analysed by two different methods:

- Eco-Indicator'99 method used also for the representation of Figure 1, and
- IMPACT 2002+ method.

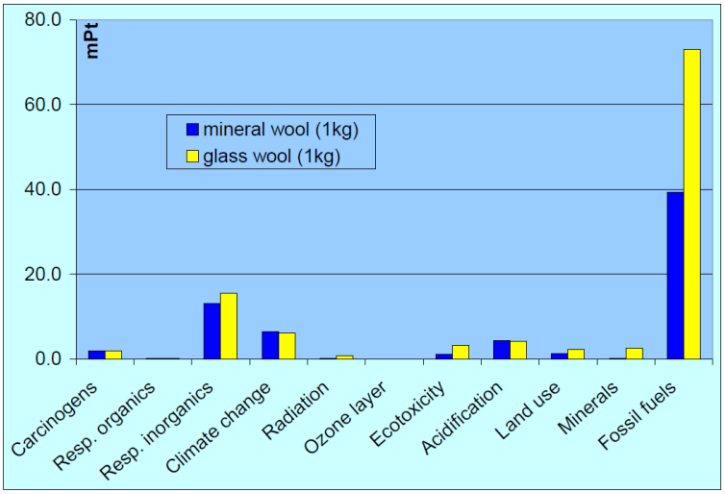
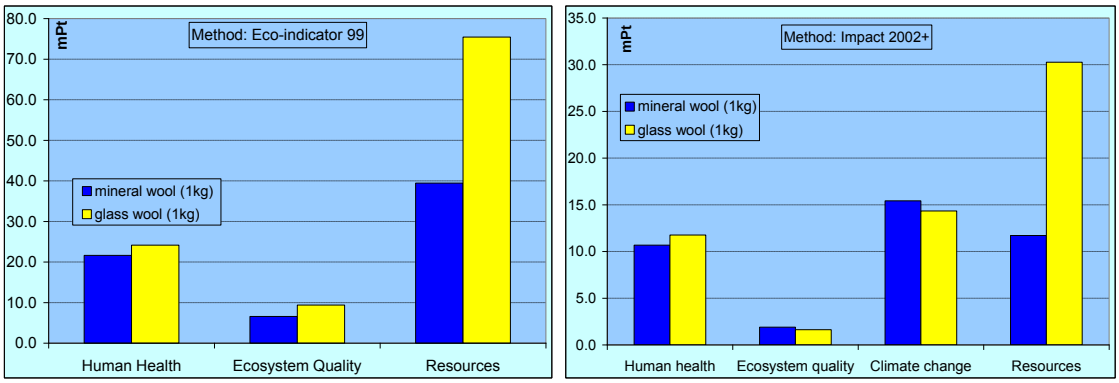


Figure 1. Environmental impact of mineral wool and mineral glass per impact category (comparison).



a) Eco-Indicator'99 b) IMPACT 2002+

Figure 2. Influence of analysis method (weighing).

These results are given in Figure 2 as endpoints. The Eco-Indicator'99 method uses as endpoints *Human Health*, *Ecosystem Quality* and *Resources*, while the Impact 2002+ method considers a supplementary endpoint (*Climate Change*).

Thus, as the main purpose is to compare relative differences between the products, the results rather help in taking up decision and not in a strict comparison of absolute value of number of points. In our example, the results significantly differ only in the case of Resources, the better score being obtained for mineral wool and this is confirmed by both methods under consideration. It must be pointed-out that the high scoring on resources is not due to the raw materials taken from the ground but due to the high quantity of fossil fuels used for energy used in material processing.

4 ENVIRONMENTAL IMPACT CONSIDERING ASSEMBLIES

The simple approach of environmental impact is of practical use in cases in which the building system is set and one of the building materials is in question. The matter becomes more complex when a building assembly could be realised in different manners. In these cases, the simple comparison of building materials is of no use as the assemblies are built in their characteristic way. In order to illustrate this, the chart from Figure 4 presents the comparison in environ-

mental impact for a flooring system (an assembly in this example) which is considered in two building solutions:

- first case, in which is considered a usual flooring system made out of a solid concrete slab, called as "traditional floor" and
- second case, in which the flooring system is built as a lightweight system, with cold-formed thin-walled steel profiles as bearing skeleton and oriented strand board plates as stiffening system and decking.

Figure 3 presents the floor layers for the two systems. In order to have an easier input of construction materials in LCA (the tool used was SimaPro), there have been computed average values for the weight of materials on square meter of flooring. These have been estimated as follows: the total weight of materials (resulted from the material lists) was divided to the total area of constructive element (in m^2). In this way, the final result represents an aggregate average per square meter of constructive element.

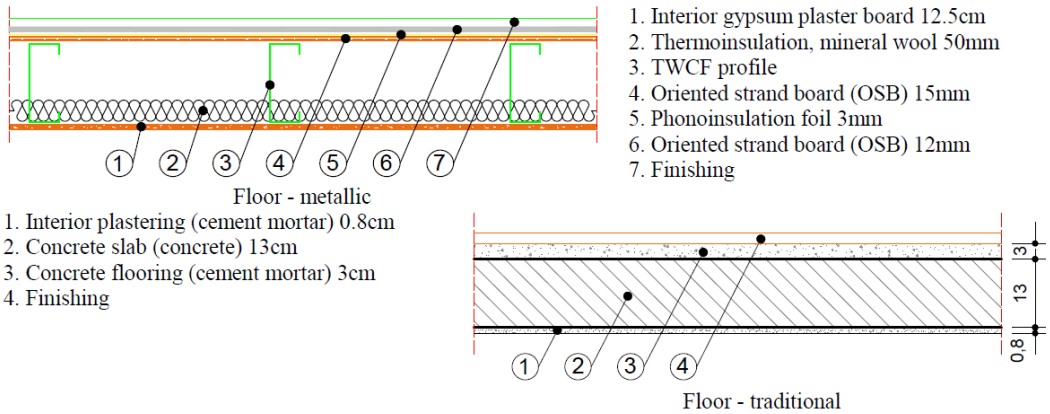


Figure 3. Layers considered for flooring systems.

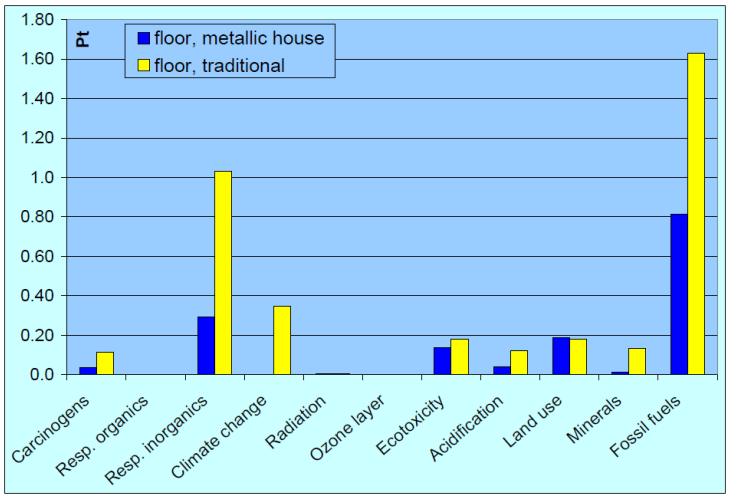


Figure 4. Comparison for two assemblies (floor systems) per impact category.

The following weights of materials were considered in the comparison (the cross-sections through floors are given in Figure 3):

a. By considering the regular construction system with a concrete floor and additional layers:

- cement-mortar: 66 kg (3 cm);
- concrete (not reinforced): 312 kg (13 cm);
- reinforcement: 16.8 kg;
- light mortar: 11.2 kg.

b. Considering a light-weight floor:

- sound - insulation foil (polypropylene): 0.1 kg;
- oriented strand board: 9.6 kg (15 mm) for top layer and 7.68 kg (12mm) for bottom layer;

- steel cold-formed C profiles: 13.61 kg (mean value per square meter);
- mineral wool: 2.25 kg;
- gypsum plaster board: 9.15 kg.

The method used in this analysis was Eco-Indicator 99. The system boundaries considered in this example ignore the common materials/resources and processes, such as:

- finishing of floor, considered as being the same in both cases;
- the transportation of materials to the site;
- the use of machines and other equipments on site, etc.

As it can be observed, for both assemblies, the highest impact categories are for the use of fossil fuels (category directly related to the use of energy), emissions causing respiratory diseases, and climate change.

Although this type of comparison is not as rudimentary as the simple approach, it may clear the choice for a certain structural system. Of course, the economical aspect should complete the reasoning for the final choice.

5 ENVIRONMENTAL IMPACT CONSIDERING BUILDING SYSTEMS

If the environmental impact analysis considers differences in all or the majority of assemblies, then the impact environmental analysis becomes generalised, analysing the entire building system. Although in this case the analysis could be conducted also on individual assemblies, only the final integration of results can help in taking a final solution of a system in the favour of another. Even if this approach represents a complete building evaluation, this kind of analysis represents a time-consuming and very complex solution due to at least three reasons:

- it needs exact (final) list of materials, classified on assemblies, that are established only at the end of the design and detailing process;
- in comparisons there are needed at least two parallel designs and detailing, from which only one will be chosen for final building;
- integration in analysis impact compiler of specific materials or adaptation of existing ones in the databases in accordance to the local conditions of construction.

The environmental impact evaluation for the building system will offer instructive results not only related to the whole building but also to assemblies (e.g. identification of the assemblies with the greatest/smaller impact on environment) or regarding the most affected impact categories. Such an analysis is to consider a building designed in two different solutions. For example a dwelling which is realised in two alternatives:

- by considering a classic solution in brick walls and a harmonized structural solution: reinforced concrete floor and wooden roofing covered with ceramic tiles and;
- a relatively novel structural solution, i.e. a cold-formed steel framed structure. In this case, the walls are stiffened by oriented strand boards, while the roof is made of cold-formed steel members and steel sheeting.

The main idea of this comparison is to obtain the same internal volumes considering a given architectural solution (Ciutina et al. 2009, Citina & Ungureanu 2009). A 3-D view of the house and the ground floor plan are given in Figure 5.

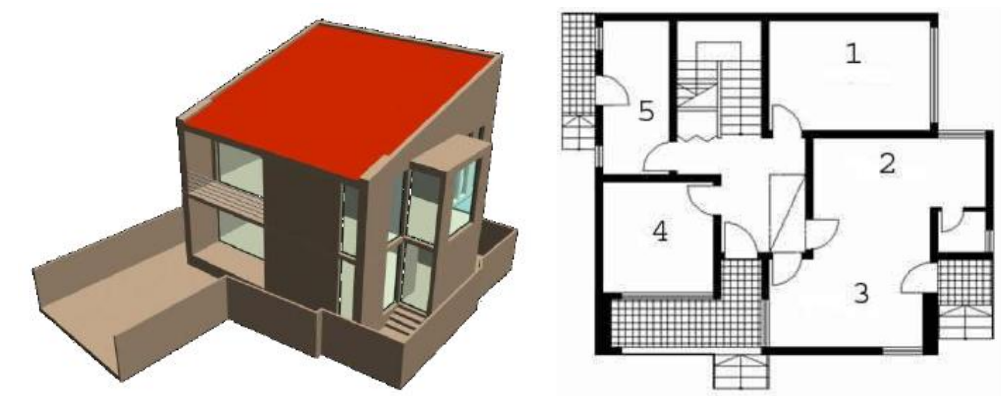
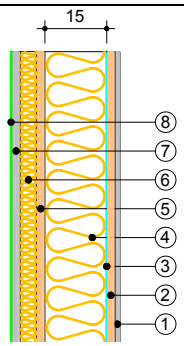


Figure 5. 3D view and ground floor plan of the house (Ungureanu & Dubina 2006).

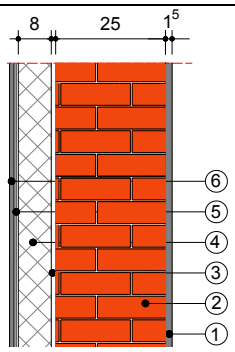
Exterior walls

TWCF house



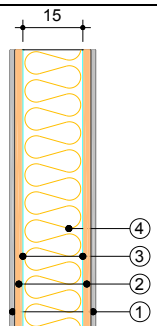
1. Gypsum plaster board 12.5cm
2. Vapour barrier (foil) 2mm
3. Internal oriented strand board (OSB) 12mm
4. TWCF profile / Mineral wool 15cm
5. External oriented strand board (OSB) 12mm
6. Thermoinsulation (polystyrene extruded) 20mm
7. Polyester wire lattice (glass fibre)
8. Exterior plastering (Baumit) 1.5cm

Traditional (masonry) house

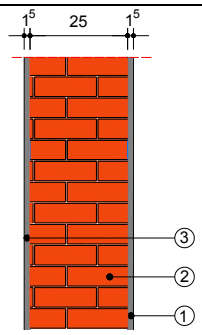


1. Interior plastering (cement mortar) 1.5cm
2. Masonry (bricks) 25cm
3. Adhesive
4. Thermo-insulation (polystyrene extruded) 80mm
5. Polyester wire lattice (glass fibre)
6. Exterior plastering (Silicone Baumit) 1.5cm

Interior walls

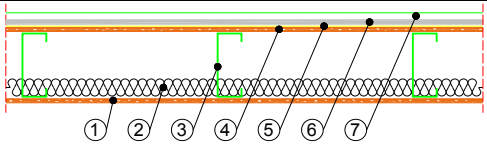


1. Internal and external gypsum plaster board, 12.5cm
2. External and internal oriented strand board, 12mm
3. Vapour barrier (foil), 2mm
4. TWCF profile / Mineral wool, 150mm



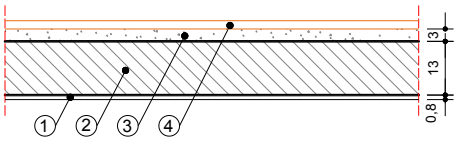
1. Interior plastering (cement mortar) 1.5cm
2. Masonry (bricks) 25cm
3. Interior plastering (cement mortar) 1.5cm

Floors

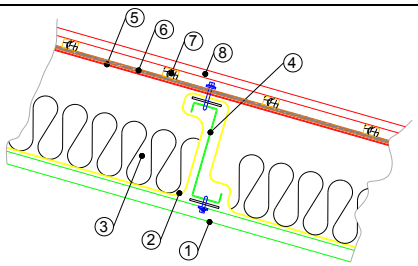


1. Interior plastering (cement mortar) 0.8cm
2. Concrete slab (concrete) 13cm
3. Concrete flooring (cement mortar) 3cm
4. Finishing

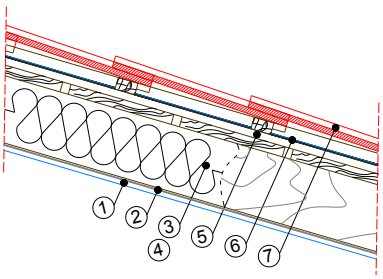
1. Interior gypsum plaster board 12.5cm / 2. Thermoinsulation, mineral wool 50mm / 3. TWCF profile / 4. Oriented strand board (OSB) 15mm / 5. Phonoinsulation foil 3mm / 6. Oriented strand board (OSB) 12mm / 7. Finishing



Roofs

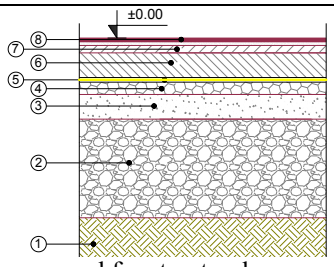


1. Inferior gypsum plaster board 12.5cm / 2. Vapour barrier (foil) 2mm, anticondense barrier 2mm / 3. Mineral wool 200mm / 4. TWCF profile / 5. Aluminium antireflex foil 3mm / 6. Oriented strand board (OSB) 15mm / 7. Timber framing (sawn timber) / 8. Steel tiled sheet (coated steel)



1. Inferior gypsum plaster board 12.5cm / 2. Vapour barrier (foil) 2mm, anticondens barrier 2mm / 3. Mineral wool 150mm / 4. Timber rafter / 5. 6. Timber framing (sawn timber) / 7. Ceramic tiles

Foundations and ground floors



1. Foundation soil
2. Compacted soil 40cm
3. Ballast 10cm
2. Thermo-insulation (polystyrene extruded) 5cm
5. Vapour barrier (foil) 2mm
6. Concrete slab 10cm
7. Concrete flooring (cement mortar) 3cm
8. Finishing

Figure 6. Layers used for structural components.

Both systems include complementary elements for thermal insulation and enveloping accordingly. In consequence, all the assemblies have different construction systems. Detailed element arrangements are given in Figure 6, for the distinct assemblies considered: (i) exterior walls, (ii) interior walls, (iii) floor over first storey, (iv) roof and (v) foundations (including the concrete ground floor).

According to these layers, Table 1 presents the complete lists of materials for assemblies. Two considerations have to be underlined concerning the lists of materials:

I. Average weights of materials.

In order to have an easier input of construction materials in the analysis tool, there have been computed average values for the weight of materials. These have been estimated for each type of constructive element as follows: the total weight of materials (resulted from the material lists) was divided to the total area of constructive element (in m^2). In this way, the final result represents an aggregate average per square meter of constructive element (e.g. in case of external walls of the traditional house the concrete resulted form the stanchions, although they are placed at each 2.5 m and at corners only). This represents in fact the inventory used in analysis. These values are then multiplied by assembly surfaces given in Table 2.

II. Boundary conditions.

In order to set the input elements (inventory), both for simplifying the model and time-saving, the inventory analysis has been done according to system boundary conditions:

- all identical components and materials which are identical as dimensions and weights for both design situations were left out of comparison, bringing the same input and output (for example wall painting or the floor finishing). Including here are the doors / windows and electrical or heating systems;
- the transportation was not taken into account, although the values (especially the weights) are much smaller in case of steel cold-formed house. However, these values may be introduced at any time in comparison;
- domestic use of the building (water / gas / electricity use), was not integrated herein, as this comparison was focused on the construction stage;
- the energy used for construction purposes (such as cranes and other technological machinery) was not integrated in comparison.

Figures 7 and 8 presents the environmental impact considering the above assumptions and input data for the building system, classified on different assemblies. All the results are presented in “Eco-points” in order to have unitary and comparably values for comparison. The method used is Eco-Indicator’99.

Figure 7 presents the impact given by the classic structural solution (masonry house – presented in the charts as the “traditional house”), classified on different assemblies. It results very clear that the highest impact is due to exterior walls and foundations. Both assemblies are high consumers of resources and of human health, mainly due to processes used in fabrication of building materials (bricks, cement etc.). As a difference, the roof has a major impact on ecosystem, mainly due to the use of important quantities of wood.

In a direct comparative impact analysis, for traditional house result higher impact values for most of the impact indicators (categories), as could be seen in Figure 8. One could realise that for both structures the major impact is for fossil fuels, as these resources are used for the fabrication of building materials at all levels. Also, important values of impact are recorded for inorganic respiratory emissions, climate change substances and land use. Although in the case of carcinogens and ecotoxicity the impacts have comparable values, large differences could be noticed in case of land use (2.5 times greater for traditional house), fossil fuels, respiratory inorganic substances and climate change (at least 2 times greater for traditional house). In a single score analysis, (see inner Figure 8), the sum of impacts is expressed in a total score of 1626 points, that less than half of the global score of the classic solution (3409 points).

Table 1. Calculated quantities of materials for construction stage.

Constructive element	Constitutive materials	Use for traditional house	Constitutive materials	Use for TWCF house
Exterior walls	Interior plastering (cement mortar)	1.5cm (21kg)	Gypsum plaster board	12.5cm (9.15kg)
	Masonry (bricks)	25cm (207.5kg)	Vapour barrier (foil)	2mm (0.1kg)
	Cement mortar	69.19kg	Mineral wool 100mm	4.5kg
	Thermoinsulation (polystyrene extruded)	100mm (3.5kg)	Internal oriented strand board (OSB)	12mm (7.7kg)
	Polyester wire lattice (glass fibre)	$1m^2$ (0.16kg)	External oriented strand board (OSB)	12mm (7.7kg)
	Exterior plastering (Silicone Baumit)	1.5cm (4.2kg)	Thermoinsulation (polystyrene extruded)	20mm (0.7kg)
	Concrete (stanchions, lintels)	66.54kg	Polyester wire lattice (glass fibre)	$1m^2$ (0.16kg)
	Reinforcing	8.14kg	Exterior plastering (Silicone Baumit)	1.5cm (4.2kg)
			Steel cold-formed profile	16.32kg
Interior walls	Masonry (bricks)	25cm (207.5kg)	Internal and external gypsum plaster board	12.5cm x 2 (18.3kg)
	Interior plastering (cement mortar)	1.5cmx2 (42kg)	Vapour barrier (foil)	2mmx2 (0.20kg)
	Cement mortar	69.19kg	Mineral wool	50mm (2.25kg)
	Concrete (stanchions, lintels)	66.54kg	External and internal oriented strand board	12mm x2 (15.36kg)
	Reinforcing	8.14kg	Steel cold-formed profile	18.33 kg
Floor	Concrete flooring (cement mortar)	3cm (66kg)	Oriented strand board (OSB)	12mm (7.68kg)
	Concrete slab (concrete)	$1m^2$ (312kg)	Phonoinsulation foil 3mm	0.1kg
	Reinforcement (steel)	16.8kg	Thermoinsulation Mineral wool	50mm (2.25kg)
	Interior plastering (cement mortar)	0.8cm (11.2kg)	Inferior gypsum plaster board	12.5cm (9.15kg)
			Oriented strand board	15mm (9.6kg)
			Steel cold-formed profile	13.61kg
Roof system	Timber framing (sawn timber)	32.7kg	Steel tiled sheet (coated steel)	5kg
	Ceramic tiles	43kg	Steel cold-formed profile	19.09kg
	Mineral wool	180mm (8.1kg)	Timber framing	5.16kg
	Vapour barrier (foil)	2mm (0.1kg)	Anticondens barrier	2mm (0.135kg)
	Anticondens barrier	2mm (0.135kg)	Oriented strand board (OSB)	15mm (9.6kg)
	Inferior gypsum plaster board	12.5cm (9.15kg)	Mineral wool	180mm (8.1kg)
	Inferior gypsum plaster board	12.5cm (9.15kg)	Aluminium antireflex foil	3mm (0.1kg)
			Vapour barrier (foil)	2mm (0.1kg)
			Inferior gypsum plaster board	12.5cm (9.15kg)
Foundation - Infrastructure	Ballast – compacted	10cm (540kg)	Ballast – compacted	10cm (320kg)
	Concrete	1752kg	Concrete	1078kg
	Reinforcement	19.12kg	Reinforcement	13kg
	Thermoinsulation (polystyrene extruded)	50mm (1.75kg)	Thermoinsulation (polystyrene extruded)	50mm (1.75kg)

Table 2. Computed surfaces for different constructive elements (in m^2).

Constructive element	Traditional house	Metallic house
Exterior walls	216.25	215.1
Interior walls	134.27	126.11
Floors	86.13	80.6
Roof system	100.11	92.54
Foundation	95.36	91.28

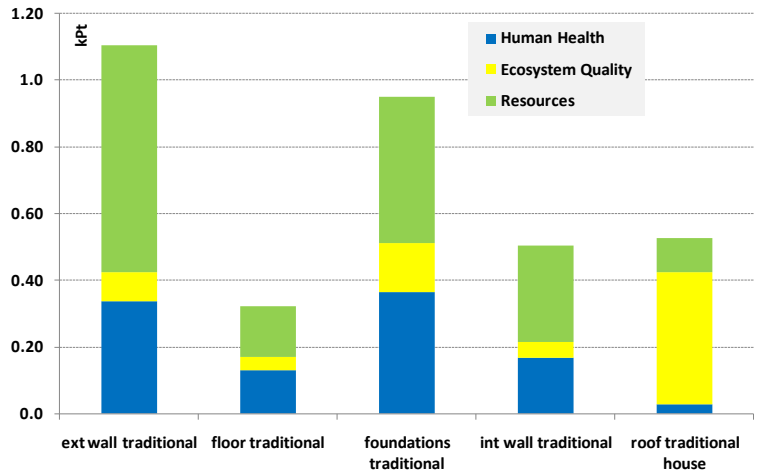


Figure 7. Environmental impact of the classic dwelling on assemblies.

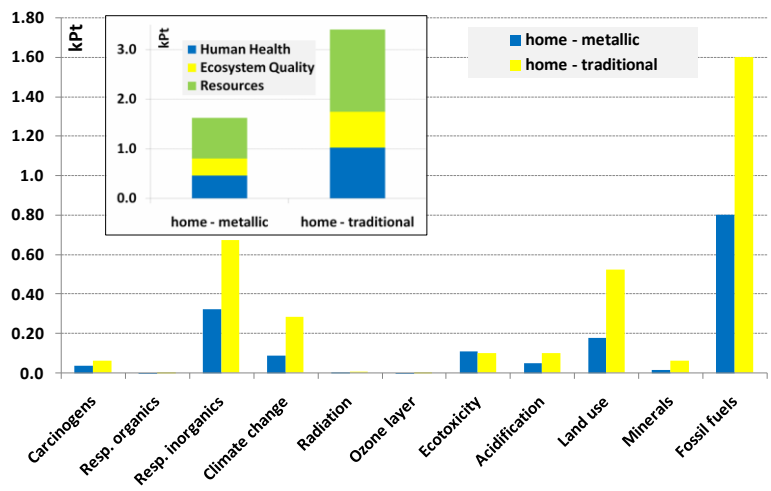


Figure 8. Comparison on environmental impact for metallic and traditional house (weighting).

6 ENVIRONMENTAL IMPACT CONSIDERING LIFE-CYCLE

When considering a building system that takes into account its entire life-cycle, the analysis and interpretation become more complex and integrate specific parameters that concern:

- the erection (including production) stage;
- the energy, material and processes employed in the exploitation period;
- the disposal scenario.

The processes integrated in the three stages listed above all have an impact on the environment, but by far the highest rate goes to the exploitation period, which results in energy use, material replacing and so on. This is partly due to the relatively large period that is considered for building exploitation (the average life-time of a regular building is 50 years). An example in this direction is presented in Figure 9. It shows that the environmental impact produced by the energy used during exploitation (natural gas for heating, electricity and water estimated for a

mean life-time of a building of 50 years) conducts to a total score of about 19000 eco-points, more than 8 times the score obtained for the building stage of steel house. Ciutina et al. (2009) and Citina & Ungureanu (2009) have presented in details the estimations of maintenance list of materials and consumable goods during the exploitation.

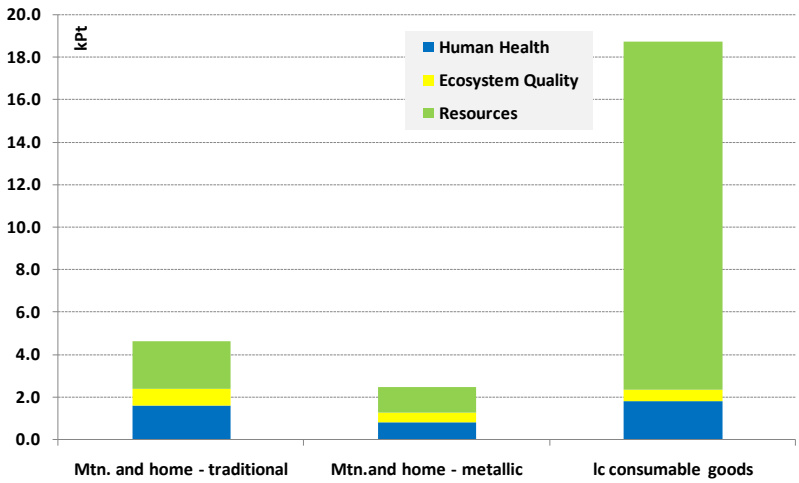


Figure 9. Single score comparison of environmental impact for building process and consumable goods.

Consequently, the general tendency in the modern approach of building construction is to aim at the reduction of energy consumption during exploitation, although the building process (use of new materials, machines and other erection processes) will imply a negative impact on the environment.

In case of buildings, a rigorous LCA should include all the processes, materials, energy, machine use etc., "consumed" during the life-time of the building. However, this kind of analyses will lead to a considerable volume of results and their interpretation could be cumbersome. Moreover, the analysis itself could be time consuming. That is why the analysers recommend, for the case of an LCA, to include only the processes that have a major contribution to the overall impact and, respectively, to ignore the processes that have an impact beyond a cut-off limit. In the case of comparisons, the analysis could be further simplified, by ignoring the common elements, as mentioned above. Thus, the analyst might only focus on the differences that exist for the subjects under comparison.

One of the difficulties that may arise in an LCA analysis is referred to conceiving scenarios for the exploitation period as well as for the disposal of materials at their end-of-life. Most of the times, these scenarios are done under the actual conditions at designing, or in the best conditions by forecasting or extrapolating the actual conditions.

For the example considered herein, in order to complete the life-cycle of analysed dwellings, there have been added two post-construction stages:

- disposal of materials at the end of building life and,
- maintenance of building.

The disposal of materials was considered according to present conditions in Romania for recycling, reuse and disposal. These are summarised in Table 3 for the main building materials considered.

Concerning the maintenance, the following forecasting was considered for a standard life-time of 50 years for both solutions considered in comparison:

i) In case of the traditional house:

- nine internal decorations (once at 5 years);
- three external decorations (once at 12.5 years);
- three changes for bathroom/kitchen sanitary (once at 12.5 years);
- one change of the electric and heating system (once at 25 years);
- one change of the roofing system (wood and cover) (once at 25 years);
- one change of the exterior thermo-system (once at 25 years).

ii) In case of the metallic house:

- nine internal decorations (once at 5 years);
- three external decorations (once at 12.5 years);
- three changes for bathroom/kitchen sanitary: (once at 12.5 years);
- one change of the electric and heating system (once at 25 years);
- one change of the steel tiled sheeting (once at 25 years);
- one change of the thermo-system (once at 25 years).

Table 3. End-of life for building materials.

Building material	Reuse [%]	Recycling [%]	Burn [%]	Landfill [%]
Steel –profiles, tiled sheets	---	100	---	---
Steel – reinforcement	---	80	---	20
Bricks, ceramic tiles	---	---	---	100
Wood	35	---	65	---
OSB	50	---	50	---
Gypsum plaster boards	30	---	---	70
Ballast	70	---	---	30
Concrete, mortar	---	---	---	100
Other inert materials	---	---	---	100
Other combustible materials	---	---	100	---

Important to notice is the fact that, in case of steel structure, only the steel skeleton remains (theoretically) unchanged, while all other elements are changed once at 50 years. For traditional house, the maintenance reduces here at the level of plastering for walls, thermo-system and part of the roof-wood supporting. For both cases, no maintenance was considered for infrastructure. In addition, for the life-cycle assessment, the same conditions for disposal at the end-of life have been considered in accordance to the previous explanations.

In a global result, summing up the impact values given by the building process, maintenance and disposal, we can observe the same tendencies as those obtained in case of the building process only, namely all the impact categories being greater for the traditional house (see Figure 10). In a single score analysis (see inner Figure 10), and taking into account the boundary conditions as explained before, the metallic house (2450 eco-points) present an important advantage in front of traditional home (4600 eco-points).

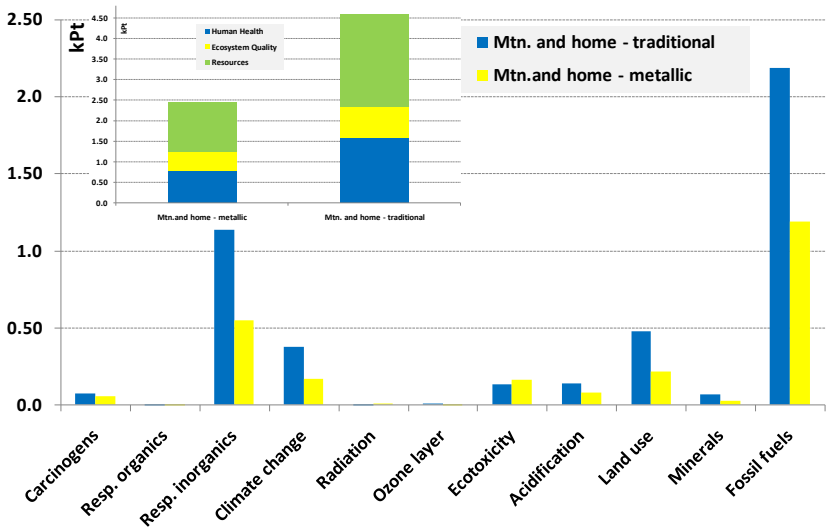


Figure 10. Single score comparison of environmental impact for building process and consumable goods.

7 CONCLUSIONS

The applied examples of this paper show that the methodology used in analysing the environmental impact of buildings, at the moment, can provide qualitative indicators for appreciating a design solution or another one.

The environmental impact considerably depends on the databases used for the analysis, the method used in appreciating the results etc. Moreover, the specificity of materials, energy and processes could differ from country to country and from location to location.

Experience shows that the environmental impact of a building is very difficult to control at a macro-level (global or integrated approach). That is why, in practical applications it could be suggested to work on certain levels:

- on a *micro-component level*, as is the case of analysing only materials with the same destination in buildings;
- when the difference could not be made at the level of individual items, the analysis should contain components, as is the case of assemblies. This is the case for example in choosing different systems for envelopes, roofing systems, finishing layers etc.;
- at a *macro-component level*, in which the integrated analysis is made for the entire building;
- however, a complete environmental impact analysis in buildings could only be realised by a life-cycle approach, on which there should be considered all the life-time processes, such as building, maintenance and disposal.

Considering these levels, one can combine the micro-components and components in order to approximate the global environmental performance of the building.

For the practical integrated design (e.g. including environmental impact), the materials should contain not only specifications on their physical and mechanical properties, but also information on the environmental impact. Within this context, the European EPD (Environmental Product Declarations) of products will be welcome. Such integrated lists for materials could make easier the choice for a material or another.

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Building sustainability theory meets practice; Opportunities and gaps: the case of GPP and examples from Slovenia and Greece

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ABSTRACT: This paper deals mainly with the problem of implementing into practice the theoretical background acquired during the last decades in the field of sustainability. The discussion is focused on the building sector. Firstly, the available theoretical means, with regard to environmental profile assessment methods and tools as well as to LCA methods/tools are shortly reviewed. The problem of implementing this theoretical knowledge into practice and the difficulty in persuading the private sector to act in an environmentally "friendly" way are discussed. Moreover, the characteristics of the methods and tools that can be applied in practice are discussed, with reference to their complexity, to their functioning based on accessible data etc. Additionally the EC policy on building sustainability is referred to, with the focus being on directives, national action plans, Green Public Procurement etc. Finally certain examples relatively to the efforts of theory implementation into practice from Greece and Slovenia are cited.

1 INTRODUCTION

Development of methods for environmental assessment of buildings made a significant progress since nineties. The first generation of assessment methods was based on LCA indicators, with significant impact of energy related impacts. Later also the economic (LCC based) and social indicators were considered. In the last decade the EU policy oriented to green public procurement and thus the need for transparent methods and tools was revealed. Standardization effort and several FP7 research projects support progress in sustainability assessment methods.

2 SHORT REVIEW OF LCA TOOLS AND ENVIRONMENTAL PERFORMANCE METHODS APPLICABLE TO THE BUILDING SECTOR

The big number of building environmental assessment tools, as well as LCA tools applicable to the construction sector, constantly increasing and including tools of varying sophistication and characteristics with regard to the extent of the analysis they perform, the criteria they use and their applicability to different cases and conditions, renders their analysis, comparison and categorization a rather difficult and time consuming task. Nevertheless, extensive reviews of such methods, tools and relative issues can be found in literature (e.g. Bribián et al. 2009; Haapio et al. 2008; Rebitzer et al. 2004; Finnveden et al. 2009; Erlandsson et al. 2003).

In the following a short review of some LCA methods and tools that can be applied in the construction sector as well as building environmental assessment tool methods and tools are shortly reviewed, aiming mainly at providing structural key features and relative bibliographic references for further research.

2.1 *LCA methods and tools*

The methods and tools for Life Cycle Analysis can be divided into two categories, with regard to their direct applicability to the building sector:

- the general LCA software, also applicable to buildings and building products/ components and
- the specific LCA tools, oriented towards the construction sector.

Several well known, widely used and sophisticated tools are included, such as SimaPro (SimaPro), TEAM (Team), Gabi (Gabi), Umberto (Umberto). These tools have a wide field of applications and can therefore be also used for buildings. An extensive catalogue of such tools can be found in a paper by Bribián I. Z. et al. (Bribian et al. 2009).

In Table 1 some LCA tools oriented towards buildings and building products/ components are cited; also relative references and a categorisation according to the ATHENA classification (Trusty 2000).

Table 1. LCA tools oriented towards buildings and building products/ components (this table is based on similar tables and information found in Bribián et al. 2009 and Haapio et al. 2008)

Athena classification	Tool	References
Level 1 *(product comparison tools and information sources)*	BEES	www.bfrl.nist.gov/oae/software/bees.html
Level 2 *(building design or decision support tools)*	ATHENA	www.athenaSMI.ca
	BeCost	www.vtt.fi/rte/esitteet/ymparisto/lcahouse.html
	Eco-Quantum	www.ecoquantum.nl
	Envest 2	envestv2.bre.co.uk
	EQUER	www.izuba.fr
	LEGEP	www.legep.de
Level 3 *(whole building assessment frameworks or systems)*	Eco-Effect	www.ecoeffect.se

Apart from the tools referred to in Table 1, other tools such as GreenCalc (GreenCalc), ECO-SOFT (ECO-SOFT), etc., can be included in the same category.

2.2 *Methods and tools for the assessment of buildings' environmental performance*

The tools belonging to this category are characterised by a wider field of analysis in comparison to the ones cited in the previous section. Specifically, they assess a rather wide range of criteria addressing several aspects of a building's environmental performance: apart from LCA aspects, issues such as indoor air quality, energy consumption during operation stage, environmental loadings resulting from operational factors are taken into consideration. As in the previous category, there is a big number of methods and tools that can be listed in this group. Some of the most widely used ones are SBTool – previously known as GBTool- (iiSBE 2004), CASBEE (CASBEE), BREEAM (BREEAM 2007), CRISP (CRISP 2004), LEED (LEED 2007; CRISP 2004), PAPOOSE (PAPOOSE 2003), DGNB (DGNB 2010), etc. Of course, the computational basis and structure is not the same for all the methods and tools. For example, LEED is more of a rating system, while SBTool is a computational tool.

A detailed insight into the most frequently used tools and related indicators is available at SB Alliance (SB Alliance 2009). SB Alliance is an international coalition of stakeholders aiming at definition of common metrics to monitor and compare building sustainability at international level. SB Alliance provided a common set of indicators addressing building sustainability in most frequently used rating tools, like DGNB, BREEAM and LEEDS.

3 POSING THE CENTRAL QUESTION: DIFFICULTIES IN IMPLEMENTING THEORY INTO PRACTICE.

The rapid progress of theory and the subsequent ongoing constant development of detailed, sophisticated and of increasing validity methods and computational tools in the field of sustainability assessment is not reflected by a similar rhythm of these methods' implementation and use in the building/construction industry and in the building/construction practice.

The difficulty in implementing this theoretical advance into practice can be attributed to several reasons, related to not only the nature and the characteristics of the above mentioned methods but also to difficulties regarding the persuasion of the practice world about such new methods' effectiveness at issues that extend beyond the scientific aspect of the matter.

In this section an effort is made to present systematically some of the major difficulties in implementing the acquired theoretical background into practice. It should be noted that this effort is not aiming at providing an extensive, full and detailed catalogue of such factors; however, it aims at pointing out some of the major issues contributing to the very slow acceptance and use of new methods and tools in practice.

A central group of factors leading to the divergence between theory progress and practice is related to the structure and the functioning of the sustainability assessment methods and tools. More specifically, extended catalogues of complex criteria, which often are the central core of environmental performance methods, demand a significant effort to be dealt with. The use of such methods and tools is a time-consuming task and cannot be easily implemented as an inseparable part of the design and construction process, already integrating a plethora of other types of studies and processes. The same logic applies to extended and time and effort demanding complex life cycle assessment analyses (the level of activity demanded in this case can be estimated on the basis of the complexity of LCA for a single product; a building, or a construction, being an ensemble of materials, which are combined to form the building components and assemblies, are subject to different types and levels of loadings, have different characteristics, different life durations, and fulfil varying performance demands, is a much more complex case to study).

Another problematic aspect of theory's implementation into practice is related to the lack of readily available data (databases) required for such methods to be applied. The big number of criteria taken into consideration and assessed leads to the requirement of using a big number of data of various categories. Data related to environmental performance and sustainability issues are not easily accessible, and in several cases, not even available for all the materials, systems, components and functions that must be assessed.

Another crucial point is the availability of data and the use of criteria that are adapted to the regional/local conditions. As an example the use of wood in structures can be referred to. In several countries of northern Europe, the use of wood in structure is considered to be environmentally friendly. In the countries like Slovenia, where almost 56% of the country is covered by forests, recently revealed environmental benefits of wood in construction may influence the perception of sustainable building. Due to long historic tradition in use of local wood in construction, a more recent challenge of economic benefits prioritized other less sustainable materials and construction techniques. Transparent criteria are needed to justify the selection of wood as a green preference due to the strong competition with other materials. Nevertheless, in countries such as Greece, in which structural timber is generally not produced, the use of wood in structure is not necessarily the considered environmentally friendly: for such a conclusion to be drawn, also the environmental impact of transporting appropriate for structural elements wood from other countries should be co-calculated. Moreover, the construction industry in Greece is not, in its large proportion, oriented towards wood-based construction. All these mean that, even such a criterion was included in a tool for direct use in Greece, keeping the respective benchmark or relative weight at the same level as e.g. in Norway, would make no sense either for the actual ecological profile drawn for the constructions under study, or for the practical applications.

Apart from issues relative to the structure and the function of the developing methods, there are problems that are related to the persuasion of the practitioners, especially of the private sector, to implement such methods in their activity. Two of the most important are the following:

1. the need of proving, beyond any doubt, that the theoretical methods' application will be effective not only in what regards the ecological profile of the constructions but also in economical terms (short term or long term return of the money invested etc.).
2. the difficulties related to the costs of implementing new methods and technologies into every-day practice (technology, software, personnel training, etc.).

Several actions are taken worldwide for the implementation of theoretical achievements into practice. In the following section the EC activity towards this aim is presented.

4 POLICIES - APPROACHES IN EC

The European society is facing a challenge of implementing sustainable building into daily life. This challenge emerged in the context of the rapid climate changes, increasing energy dependency, limited natural resources, raising awareness of the importance of preserving natural and healthy environment, the impact of globalisation and ageing of the population.

Buildings account for around 42% of all energy consumed in Europe, whereas construction activities account for about 5% of energy used, including construction related transport (ECTP SRA 2005); moreover 36% of greenhouse gas emissions in the EU arise from the building sector. Buildings also represent a large part of EU economy, as about 9% of EU GDP and 7-8% of EU employment is connected with buildings and construction sector. Construction sector is expected to increase its contribution to the competitiveness of the European industry as well as to improve the quality of life and reduce the impact to the environment. Buildings and construction sector in general are therefore integrated in the policies of Directorate General (DG) Enterprise and Industry, DG Environment and DG Energy.

4.1 *Sustainable building and competitiveness of EU economy*

EC policy in the field of construction industry planned several activities to support sustainable building. The European Commission adopted in Dec. 2007 the Communication on the "Lead Market Initiative" (COM (2007) 860 final SEC (2007) 1730), where sustainable construction has been identified as one of six areas with the highest potential for competitiveness and innovation. Base on that the action plan for sustainable construction was developed, aiming at several tasks to be completed in the period 2008-2011; among them several priorities refer to building sustainability and sustainability assessment methods:

- the adoption of performance based approach in the national buildings regulation,
- the upgrade the public procurement with the LCC based guidance to select on the basis of economically most advantageous tender instead of the lowest price tender, as well as to promote LCA for construction products via increased implementation of Environmental Products Declaration (EPD) in public procurement,
- the development of a framework for certification of sustainability criteria of innovative products,
- further development of Eurocodes in order to integrate the sustainability aspects in construction design, such as energy and environmental aspects,
- the development of voluntary performance targets for sustainable building, integrated in the national system of incentives for sustainable building, and
- the definition of assessment methods and benchmarks for assessing sustainable buildings.

Moreover, DG Enterprise and Industry is currently changing the Construction Products Directive (CPD) into a harmonized Construction Products Regulation (CPR). The draft from 2008 defined also the seventh basic requirement (former six essential requirements), called "sustainable use for natural resources" for the construction works; due to that in future the manufacturer will have to provide the sustainability information on the environmental performance of the construction product (i.e. EPD).

4.2 *From green to sustainable public procurement in EU*

As public procurement in EU covers 16% of the GDP, the procurement criteria have significant impact on the market, i.e. on the supplied technologies, on innovation in environmental technologies, products and services and on knowledge of stakeholders in sustainable building. EC defined green public procurement (GPP) as a voluntary instrument, which means that individual Member States and public authorities can determine the extent to which they implement it. In practice, the ambitious national targets related the implementation of EU climate and energy policy, committed the public sector to implement GPP rules.

DG Environment defined the important role of Green Public Procurement (GPP) in the Communication (COM (2008) 400) "Public procurement for a better environment". The document addresses the barriers and stresses the need for common EU GPP criteria and information on LCC of products, as well as for legal and operational guidance and political support. EC encouraged the Member States to prepare national action plans for GPP. Currently 17 countries prepared the GPP action plan, and 5 more are in preparation (National 2010).

EC strongly supported GPP by the preparation of Training Toolkit on GPP (Training 2008), that provided the first set of common GPP criteria for 10 products, including construction with criteria focused mostly at a building level. The purchasing guidelines are provided at two levels, i.e as core criteria, which only cause minimum additional verification effort and cost increase and as the comprehensive criteria for more ambitious procurers that want to purchase the best products on the market and may therefore request additional verification effort. The second set of criteria for additional 8 products has been prepared in the mid 2010. Among them there are also criteria for products relevant for sustainable building, like: windows, thermal insulation, hard floor coverings, wall panels and combined heat and power.

The second set of GPP criteria correspond to the key environmental impacts of the particular product through its life time, and for instance in order to reduce: the impacts of a window related energy use, the environmental impact of the window construction materials and waste burden the GPP criteria for windows aim at promoting the following approach in window selection: the purchase of thermally efficient glazing, the use of frames with higher thermal efficiency and lower impacts (using LCA), the use of appropriate glazing – in consideration of climatic conditions, effective maintenance of windows to extend useful life, end of life management (e.g. take back schemes / re-use / recycling), products designed to be easily dismantled and recycled, use of recycled and environmentally sound materials. The GPP policy supports mainly the environmental criteria, while the final goal of the EC policy is to upgrade the environmental criteria with the economic and social ones in order to cover all three sustainability elements. Such a strategy clearly exhibits the need for practical adaptation of scientific methods for assessment of building sustainability.

In 2003 DG Environment presented the Communication on Integrated Product Policy (IPP) - Building on Environmental Life-Cycle Thinking (COM/2003/0302 final), that stresses the fact that the producers should share a responsibility of the impact of their products up to their end of life. IPP is supported by environmental information on products and eco-labels, respectively; according to the ISO 14000-series standards the following types of labels exist: Type I labels are awarded to the products with above average environmental performance, by a third party and based on multiple criteria (i.e. EU Eco-label); Type II labels are self-declared environmental claims based on the consideration of the life cycle and issued by a producer; Type III labels are environmental product declarations (EPD), based on the LCA of a product, issued by an independent body and verified by a third party for high level of credibility. Environmental labels are part of the voluntary environmental labeling system defined by ISO 14040, moreover these are based on ISO 14021 standard (Type I and II) as well as on ISO 14025 (Type III - EPDs) and ISO 21930 (EPDs for building products) (Peters 2009). However, EPDs are gaining the importance by being referred to in draft CPR and in GPP criteria for construction.

More recently, the afore mentioned standardization at a product level is being complemented by the standardization for assessing building sustainability performance in the framework of ISO TC59/SC17 and CEN/TC 350. This standardization aims at development of environmental, economic and social indicators for assessment of sustainable buildings, while setting the benchmarks and weighing of indicators remains the national task.

4.3 *Buildings as a part of EU climate and energy policy*

In March 2007 EC developed an integrated approach to climate and energy policy in order to combat climate change and increase the EU's energy security while strengthening its competitiveness. The climate and energy targets, known as the 20-20-20 targets by 2020, aim at reduction of EU greenhouse gas emissions of at least 20%, reaching 20% share of renewables (RES) in EU energy consumption and 20% reduction of primary energy use by improved energy efficiency. The climate and energy package became an EU law in June 2009, where also the national binding targets are set for the share of RES (i.e. following the RES Directive (2009/28/EC) in Greece 6,9% RES in 2005 shall be increased to 18% of final energy use in 2020, and in Slovenia RES share must be increased from 16% to 25%), and for the reduction of greenhouse gas emissions. The buildings are represented in the targets for the 2013-2020 period in the so-called »Effort Sharing Decision«) (i.e. emissions limit in 2020 compared to 2005 for Greece is -4% and for Slovenia +4%). EC plans to set indicative national targets for energy efficiency (instead of the binding ones) in the revised EU energy efficiency action plan.

Energy efficient buildings are a key priority of the climate and energy policy. The Directive EPBD – Recast (2010/31/EU) has defined a number of measures for construction of energy efficient new buildings as well as for retrofitting of existing buildings. Energy performance calculation methodology, minimum requirements and above all obligatory energy performance certificate (EPC) play an important role in GPP. Slovenia and Greece have just recently completed the formalities for the implementation of EPCs (Implementation 2008); so only the experiences based on the use of pilot EPCs for the GPP purpose are available (Low Carbon 2009).

State of the art in setting the criteria for sustainable building in practice revealed (Training 2008) that the requirements related to building energy efficiency, share of RES and reduction of carbon emissions represent the core set of criteria for sustainable building and GPP. Often the energy criteria are upgraded with the criteria for the environmental quality of the construction products (i.e. EPDs). Thus the parts of the building life-cycle of production of building materials and products and building operation are considered in assessment while the construction and the end of life are not included. Comprehensive methods and tools for assessment of LCA at a building level and methods and tools for assessment of building environmental / sustainable quality are the challenge for the near future.

5 DESIRABLE CHARACTERISTICS OF TOOLS TO BE USED IN PRACTICE

The features of theoretical means (methods and computational tools) – relative to their structure and function – contributing to the delay of their implementation into practice, pointed out in section 3 provides a rough context, in general terms, of the characteristics of a tool destined for general use in practice. These characteristics include, among others, the following:

- a relatively low level of complexity (given that such a tool would be applied by professionals who are not necessarily specialised in the sustainability field and that such studies would be performed in the context of a much broader study – design, etc. – including several levels and kinds of calculations),
- function on the basis of existing and available data, accessible at the first stages of design (since several critical decisions are taken at the first stages of design and also the procedure should be facilitated),
- integration of relatively simple simulation tools if necessary,
- formation of realistic benchmarks and
- adaptation to the local factor, considering local and regional conditions, priorities, needs and special characteristics (an approach for the selection of the appropriate indicators is presented in Malmqvist & Glaumann 2007).

Of course, the above listed characteristics are not the only ones demanded for the formulation of tools appropriate for direct implementation and use into practice; nevertheless, they form an axis of sufficiently clear direction for the future efforts towards the discussed aim.

6 DISCUSSION ON GAPS AND OPPORTUNITIES: SLOVENIAN / GREEK SITUATION

The level of implementation of theoretical advancements into practice in different countries varies intensely due to differentiation in national conditions and priorities. In this section, a short – but not exhaustive – review of actions taken towards this direction in Slovenia and Greece is made.

The rhythm of implementation of sustainability principles and the relative computational methods in Greek practice is relatively low. As also pointed out (Kontoleon et al. 2008) in contrast to the academic achievements and advances at a theoretical level, the steps taken in the direction of implementing theory into practice in Greece are slow; this can be attributed to, among others, gaps and shortages of the required statistical/technical substructure for the development of an easily usable tool in practice (Giarma et al. 2005). Nevertheless, a series of efforts towards the enhancement of theory's implementation into practice has been undertaken:

- -Approximately 150 Greek products have been awarded the European Ecolabel (http://gpp.itcilo.org)
- 9 hotels have been awarded with the Ecolabel (http://gpp.itcilo.org)
- 61 organizations with 821 sites are EMAS registered (http://gpp.itcilo.org)

A recent development in Greece in the sustainability field is the new buildings' energy efficiency regulation. Working on the basis of primary energy consumption and being of an obligatory nature, this new regulation can not only lead to a significant improvement of buildings' energy performance, but also form the basis for the fixation of benchmarks in the context of environmental performance assessment methods and tools.

Several laws and ministerial decisions, not only during the current decade but also in previous years, implement relative EU directives and contribute to the direction of sustainable practices' promotion and enhancement. The regulations, laws and decisions are related to several issues such as solid waste management, greenhouse gases emission reduction (atmosphere quality), reduction of buildings' energy consumption, energy inspection, etc.

Some more information about sustainable approaches in Greece can be found in a paper by Kontoleon et al, 2008. As for Green Public Procurement, in Greece there is no national GGP Policy to date (http://gpp.itcilo.org). There are some examples of GPP in some sectors of public administration (e.g. http://www.procuraplus.org/).

Slovenia intensified the efforts towards the implementation of GPP in 2009 with adoption of national action plan on GPP (target of 30% of GPP in construction by 2012) and with drafting of the related regulation on GPP, put into public consultation process in Jan. 2010. The core and comprehensive criteria for GPP in preliminary design, detailed planning and building refurbishment are defined, similar to the first set of EU criteria for GPP (Training 2008).

Recently upgraded Slovenian building codes PURES 2010, based on EPBD Recast, imposed ambitious low energy requirements including 25% coverage of energy needs with RES at a buildings level and 10% better energy performance in case of public buildings. National incentives are available for passive house standard and for RES.

In order to support sustainable decision in selection of the building products, the voluntary "Quality label in building and civil engineering" was introduced in Slovenia in 1997. Over 120 national ZKG labels were awarded since to building products that passed the pre-defined threshold and were ranked among top 15% in the relevant category. One of the categories developed to support GPP comprises the assessment of sustainability of apartment buildings (Šijanec Zavrl et al. 2009). EIE Buy Smart (http://www.buy-smart.info) developed several check-lists and protocols for GPP in building sector, that are linked as voluntary tools to GPP portal.

GPP in Slovenian construction sector is primarily focused on environmental issues, where energy related impacts of building operation play prevailing role, currently the integration of EPDs in GPP is encouraged in order to cover LCA of building materials (no EPD data base available yet). In spite of using LCC on the demonstration public buildings and in spite of preliminary experiences with ZKG labeling of sustainable building, the wider consideration of economic and even social impacts in Slovenia is still lacking of proper assessment criteria.

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Life-Cycle Assessment of Residential Buildings

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ABSTRACT: The quantification of the environmental impacts of a building can help decision-makers to identify processes of major environmental impacts. Therefore it can be used since the early stages of design to support decision makings which aim to promote lower environmental impacts and, as a result, more sustainable buildings. Life Cycle Assessment (LCA) is considered the most adequate method for evaluating the environmental pressure caused by materials, building assemblies and the whole life-cycle of a building. Nevertheless this method is not widely used in the building sector. This paper aims to present the main constrains that are hindering the use of LCA in the building sector. Moreover, it presents a solution to overcome the indentified barriers and to promote the use of LCA methods since the earlier phases of the design process.

1 INTRODUCTION

Construction is not an environmentally friendly process by nature. The cumulative environmental impacts of construction processes have been increasing in the world due to a large number of ongoing construction projects. Most of these impacts are related with the operation and maintenance phases of a building. A recent study (EPA, 2009) shows that construction is the third largest industry sector in terms of contributions to greenhouse gas emissions in the United States.

In Portugal, most of the impacts of the built environment in the sustainable development are related to the residential sector (Mateus, 2009). At the environmental level this sector is directly and indirectly linked to the consumption of a great amount of natural resources (energy, water, mineral, wood, etc.) and to the production of a significant quantity of residues. For example, although Portugal has a mild climate, residential sector accounts for about 17% of the total national energy consumption (DGGE, 2005). Additionally, it uses a considerable amount of water resources, about 132 l/inhabitant/day of potable water, being a significant part of this capitation used in toilets (INAG, 2005).

The use of improved materials and building technologies can contribute considerably to better environmental life cycle and then to the sustainability of the constructions.

Life Cycle Assessment (LCA) is a usable approach to evaluate the environmental impacts of products or processes during their whole life-cycle. It is basically quantitative, and it considers the material and energy flows. The methodology has been developed and used for tens of years, but it was only standardized in the mid-to-late 1990s', by the International Organization for Standardization (ISO14040-42). The LCA fits at best to the level of single product or material, but it is generally accepted to be applied for construction products and whole building, too. Environmental performance is generally measured in terms of a wide range of potential effects, such as global warming potential; stratospheric ozone depletion; formation of ground level ozone (smog); acidification of land and water resources; eutrophication of water bodies; fossil fuel depletion; water use; toxic releases to air, water and land.

It is widely recognised in the field of Building Sustainability Assessment that LCA is a much more preferable method for evaluating the environmental pressure caused by materials, building assemblies and the whole life-cycle of a building. Although there are several recognized LCA tools, these tools are not extensively used in building design and most of building sustainability assessment and rating systems are not comprehensive or consistently LCA-based. Reasons for this failure are above all related to the complexity of the stages of a LCA. Besides of being complex, this approach is very time consuming and therefore normally used by experts at academic level. For these reasons most of the building sustainability assessment methods are relied on singular material proprieties or attributes, such as recycled content, recycling potential or distances travelled after the point of manufacture (Carmody, et al, 2007).

The adoption of environmental LCA in buildings and other construction works is a complex and tedious task as a construction incorporates hundreds and thousands of individual products and in a construction project there might be tens of companies involved. Further, the expected life cycle of a building is exceptionally long, tens or hundreds of years. For that reason LCA tools that are currently available are not widely used by most stakeholders, including those designing, constructing, purchasing or occupying buildings. Due to its complexity most of LCA tools are used and developed only by experts, most times only at academic level.

In order to overcome this situation, most popular rating systems simplified LCA for practical use. The simplified LCA methods currently integrated in rating systems are not comprehensive or consistently LCA-based but they are playing an important role in turning the buildings more sustainable. Nevertheless, the LCA approach is not the same in the different sustainability assessment methods and therefore the results of the environmental performance assessment are not the same nor comparable. The integration of more accurate environmental assessment methods is needed to verify if the required performance has really been achieved, to accurate compare solutions and to compare the results from different rating systems (Bragança et al, 2008).

In order to standardize, facilitate the interpretation of results and comparison between different building sustainability assessment methods developed within the European Countries, in 2005 CEN (European Centre of Normalization) set up the Technical Committee 350 (CEN/TC 350), "Sustainability of Construction Works". This Technical Committee aims to develop voluntary horizontal standardization of methods for the assessment of the sustainability aspects of new and existing construction works and standards for the environmental product declarations (EPD) of construction products (CEN, 2010). As a result of the work carried out to date the following pre-standards and standards have been produced:

- EN 15643-1:2010, Sustainability of construction works - Sustainability assessment of buildings - Part 1: General framework;
- CEN/TR 15941:2010, Sustainability of construction works - Environmental product declarations - Methodology for selection and use of generic data;
- prEN 15643-2:2009, Sustainability of construction works - Assessment of buildings - Part 2: Framework for the assessment of environmental performance;
- prEN 15643-3:2008, Sustainability of Construction Works - Assessment of Buildings - Part 3: Framework for the assessment of social performance;
- prEN 15643-4:2008, Sustainability of Construction Works - Assessment of Buildings - Part 4: Framework for the assessment of economic performance;
- prEN 15978:2010, Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method.

Based in the work of CEN TC 350 and in the work of iiSBE Portugal in the development of the Portuguese rating system for residential buildings SBTool^{PT} - H, this paper will present and discuss the development of a method to simplify LCA for effective used during the design phase. The presented method is based in the developed of an LCA database that covers much of the conventional and non-conventional building technologies used in residential buildings in Portugal.

2 THE LIFE CYCLE ASSESSMENT APPROACH

LCA is a systematic approach to measure the potential environmental impacts of a product or service during its lifecycle. LCA considers the potential environmental impacts throughout a product's life cycle (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal.

LCA is very important to compare several possible alternative solutions, which can bring about the same required performance but that differ in terms of environmental consequences. For constructions, such bridges, the embodied environmental performance of the building materials as well the construction impacts on landscape and biodiversity will often dominate the construction's life-cycle environmental impacts. For buildings, such as dwellings and offices, life-cycle environmental impacts are often dominated by energy consumption, in space heating or cooling, during the operation phase: it is estimated that the operation phase in conventional buildings represents approximately 80% to 94% of the life-cycle energy use, while 6% to 20% is consumed in materials extraction, transportation and production and less than 1% is consumed through 1% end-of-life treatments (Berge, 1999). In buildings, design teams should seek for more energy-efficient alternatives, while in other constructions, like for instance dikes and bridges, priority should be given to eco-efficient materials. Nevertheless, with the development of energy-efficient buildings and the use of less-polluting energy sources, the contribution of the material production and end-of-life phases is expected to increase in the future.

There are two combined standards developed specific to set the framework and requirements of a LCA that replaced the former four LCA standards (ISO 14040, ISO 14041, ISO 14042, ISO 14043) in 1st July 2006: ISO/FDIS 14040 2006-07-01 Environmental management – Life cycle assessment – Principles and framework; and ISO/FDIS 14044 2006-07-01 Environmental management – Life cycle assessment – Requirements and guidelines.

According to ISO 14040, framework for LCA includes:

- Goal and scope definition of LCA;
- Inventory analysis (LCI);
- Impact assessment (LCIA);
- Interpretation;
- Reporting and critical review;
- Limitations;
- Relationships between the LCA phases, and
- Conditions for use.

As presented in Figure 1, LCA is essentially an iterative process.

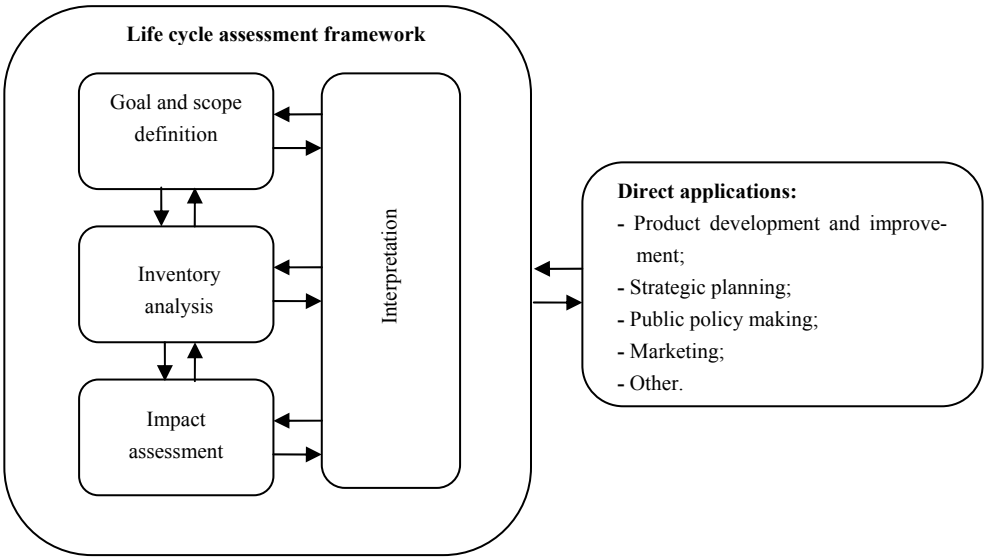


Figure 1. Stages of an LCA in ISO 14040:2006.

LCA can be applied to a single product or to an assembly of products, such as a building. For building and other constructions (B/C) the general framework for LCA involves the following goals and LCA steps (Kotaji, Schuurmans & Edwards, 2003):

1) The lifecycle of the B/C is described. What is included in the study will depend on the scope. It may include how the B/C is constructed, used, maintained and demolished and what happens to the waste materials after demolition. These are processes that contribute to the life-cycle performance of a B/C, but which will not be included in all studies.
2) The B/C is "broken down" to the building material and component combinations (BMCCs) level. This is the composition of the B/C to be analysed. The way in which the BMCCs are defined is not necessarily important; what matters is that the B/C is completely described through the addition of the BMCCs.
3) For each BMCC, the LCA of the production process (cradle-to-gate) is carried out. Their LCAs may include the transport processes to the B/C site, the construction process, the operation and maintenance processes, the demolition processes, and the waste treatment processes for each of the waste materials defined in the B/C model. This would be a cradle-to-grave analysis.
4) The BMCC-LCA results are added together, resulting in the LCA of the B/C. The various BMCC-LCAs should be carried out consistently according to the goal and scope.

3 THE DEVOLOPMENT OF THE LCA DATABASE

3.1 *Environmental impact categories*

Sustainability assessment systems are the tools normally used by project teams to support decision making which aim to lower the environmental impacts of buildings. Nevertheless, the number and type of environmental impact category indicators are different in the several sustainable assessment methods. There is a wide range of impact category indicators, normally categorized according to the endpoints or the midpoints. Endpoints are also known as damage categories and express the effect of the product in the Human Health, Ecosystems Quality, Climate Change and Resources. LCA methods that use this type of impact categories are damage oriented and they try to model the cause-effect chain up to the endpoint, or damage, sometimes with high uncertainty. The midpoints, also referred as indicators, are the measures between the emissions and resource extraction parameters from life-cycle inventory (LCI) and the damage categories. These impact categories are used in the classic impact assessment methods to quantify the results in the early stage in the cause-effect chain to limit the uncertainties. Midpoints uses to group LCI results in the so-called midpoint categories according to themes as "destruction of the stratospheric ozone layer", "acidification of land and water resources" or "global warming".

LCA can be incorporated into rating systems for buildings to quantify environmental burdens associated with the manufacture of building products. Such burdens include the consumption of primary resources and the output of gaseous, liquid, and solid wastes. Most of the rating systems use midpoint impact categories but do not assess the B/C's environmental performance in a LCA consistent way, because they do not include LCA-based indicators.

The differences between the environmental impact assessment approach in the several rating methods – because some of them are not LCA-based, not based in a reliable LCA method (because do not integrate the most common impact categories) or do not share the same impact categories – difficult the comparison of results from different rating systems.

The goal of the work undertaken by CEN/TC 350 standardization mandate is to overcome this problem at the European level, through the development of an approach to voluntary providing environmental information for supporting the sustainable works on construction. The document prEN 15643-2:2009 sets the environmental indicators that should be used in the European building sustainability assessment methods. The aim of the list of the impact categories is to represent a quantified image of the environmental impacts and aspects caused by the object of assessment during its whole life cycle. As referred in Table 1, according to the future CEN standard the assessment of the environmental performance of an building should be made through the evaluation of five quantified indicators for environmental impacts expressed with

the impact categories of the life cycle impact assessment (LCA) and nine quantified indicators for environmental aspects expressed with data derived from LCI and not assigned to the impact categories of LCA.

The assessment approach of this future CEN standard is applicable to new and existing buildings. It provides a calculation method that covers all stages of the building life cycle (assembly, operation and disassembly phases) and the list of environmental indicators is developed in such way that potentiates the use of the LCI data issued from Environmental Product Declarations (EPD).

Table 1. Quantified indicators for environmental impacts/aspects assessment according to prEN 15643-2:2009.

Environmental impacts expressed with the impact categories of LCA	Environmental aspects expressed with data derived from LCI and not assigned to the impact categories of LCA
• Climate change expressed as Global Warming Potential; • Destruction of the stratospheric ozone layer; • Acidification of land and water resources; • Eutrophication; • Formation of ground level ozone expressed as photochemical oxidants.	• Use of non-renewable resources other than primary energy; • Use of recycled/reused resources other than primary energy; • Use of non-renewable primary energy; • Use of renewable primary energy; • Use of freshwater resources; • Non-hazardous waste to disposal; • Hazardous waste to disposal; • Nuclear waste (separated from hazardous waste).

In future, all standardized European sustainability assessments should consider the same list of indicators, the new sustainability rating systems should be consistent with it and it is expected that the existing ones will be adapted to this new approach. The Portuguese building sustainability assessment method (SBTool^{PT}) it is already updated according to the requirements of this future standard. Therefore the developed LCA database covers the five environmental indicators expressed with the environmental impacts of LCA together with the embodied energy in the materials and construction technologies.

3.2 *Considered life-cycle phases*

A typical life cycle of a building can be separated into three distinct phases, each consisting of one or several life cycle stages, as illustrated in Figure 1. The assembly phase refers to the collection of raw materials through resource extraction or recycling, the manufacture of these raw materials into products, the assembly of products into a building, the replacement of building products and assemblies, and intermediate transportation. The operation phase refers to heating and electricity requirements, water services and other services excluding material replacement. The disassembly phase refers to the decommissioning and demolition of the building, the disposal/recycling/reuse of building products and assemblies, and intermediate transportation steps. Each life cycle stage can consist of many unit processes.

The LCA database for building technologies covers the “cradle-to-gate” impacts, i.e. the environmental impacts from the raw material extraction to the manufacturing of building products and assemblies and the disassembly phase. Additionally the database covers the environmental impacts derived from the transport of the demolition waste to the treatment units and with its treatment. The considered processes are highlighted in Figure 2.

3.3 *Quantification of the environmental indicators*

The two most important barriers to the quantification of the environmental indicators and therefore to the incorporation of LCA in rating systems are: a lack of LCI data for all building products and the inherent subjectivity of LCA. Environmental Product Declarations (EPD) are a good source of quantified information of LCI environmental impact data. In order to potentiate

their use, rating systems should be based in the same LCA categories, as stated in the future CEN standard. Nevertheless, at the moment, there are important limitations on this approach, since there is only a small number of companies either having or making publicly the EPD of their products. The solution proposed to overcome this problem is to develop and use databases with the LCA data of the most used building materials and components. The developed database is continuously updated and covers common building technologies for each building element (floors, walls, roofs and windows, doors) and the most used building materials

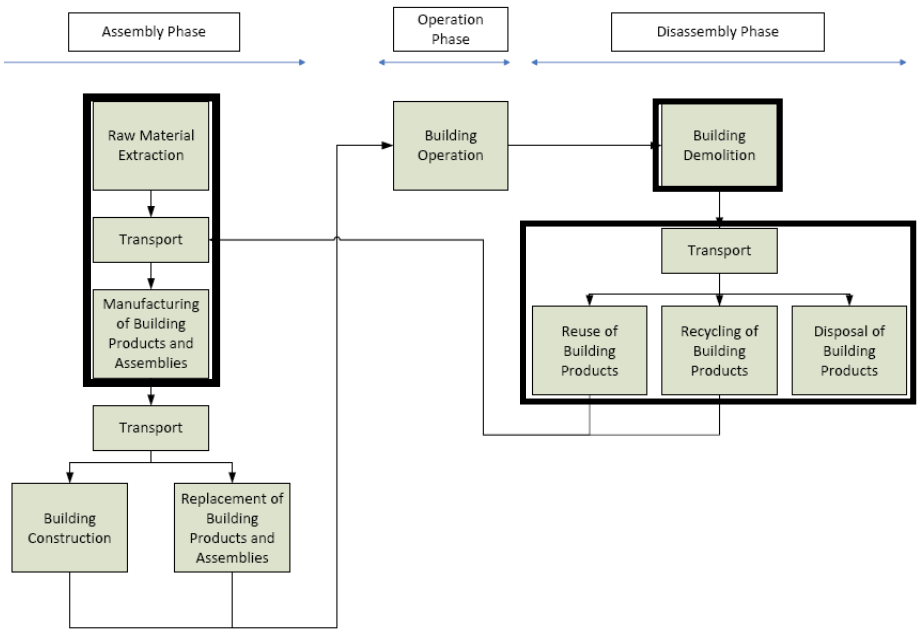


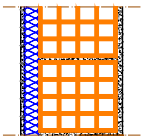
Figure 2. Life cycle of a building (Optis, 2005).

The environmental indicators were quantified using the SimaPro software and several LCI databases with the average environmental impacts of each used building material (e.g. EcoInvent, IDEMAT 2001, etc.). Table 2 shows the six environmental impact categories covered by the database and the LCA methods used to quantify the environmental categories.

Table 2. Environmental impact categories declared in the built-in LCA database for building technologies

Environmental impact categories	Unit/declared unit	LCA methods
Depletion of abiotic resources	[kg Sb equiv.]	CML 2 baseline 2000
Global warming potential (GWP)	[Kg CO_2 equiv.]	IPCC 2001 GWP 100a
Destruction of atmospheric ozone (ODP)	[KgCFC-11 equiv.]	CML 2 baseline 2000
Acidification potential (AP)	[Kg SO_2 equiv.]	CML 2 baseline 2000
Eutrophication potential (NP)	[Kg PO_4 equiv.]	CML 2 baseline 2000
Photochemical Ozone Creation (POCP)	[Kg C_2H_4 equiv.]	CML 2 baseline 2000
Non-renewable primary energy	[MJ equiv.]	Cumulative Energy Demand
Renewable primary energy	[MJ equiv.]	Cumulative Energy Demand

Figure 3, presents how the information is organized in the LCA database for a building component and the list of environmental indicators and LCA methods used to quantify it. In the database of the building components the quantification is presented per each component's unit of area (m^2) and in the materials database values are available per each unit of mass (kg). Quantification is presented for two life-cycle stages: "cradle to gate" and "demolition/disposal". SBTool^{PT} uses a bottom-up up approach in the quantification of the whole building environmental performance. The quantification begins at the level of the embodied environmental impacts in building materials and ends at the whole building scale. Figures 4 e 5 illustrates the calculation method of the whole life-cycle environmental impact of a building using the data from the SBTool^{PT}'s LCA database.

Building component:	Hollow brick single wall (11cm) with an external thermal insulation composite system								Ref: Wall 3
	Life cycle stages	Environmental impact categories of LCA						Embodied energy	
		ADP[1]	GWP[2]	ODP[3]	AP[4]	POCP[5]	EP[6]	NR[7]	R[8]
	Cradle-to-gate	2,48E-01	5,00E+01	3,02E-06	1,16E-01	1,23E-02	1,45E-02	5,63E+02	5,39E+01
	Dismantling and disposal	1,12E-01	1,65E+01	2,67E-06	7,60E-02	2,90E-03	1,58E-02	2,57E+02	1,57E+00
	Total	3,60E-01	6,65E+01	5,69E-06	1,92E-01	1,52E-02	3,03E-02	8,20E+02	5,54E+01
	Comments:	**Considered materials:** Hollow brick, Portland reinforced mortar (external and internal finishing and brick joints), EPS (thermal insulation) **LCA methods:** CML 2 baseline 2000 method (version 2.04, to quantify the environmental impact categories of LCA) and Cumulative Energy Demand (version 1.04, to evaluate the embodied energy) **LCI librarie(s):** Ecoinvent system process							

Notes:

[1]Abiotic depletion potential in kg Sb equivalents;

[2]Global warming potential in kg CO_2 equivalents;

[3]Ozone depletion potential in kg CFC-11 equivalents;

[4]Acidification potential in kg SO_2 equivalents;

[5]Photochemical ozone creation potential kg C_2H_4 equivalents;

[6]Eutrophication potential in kg PO_4 equivalents;

[7]Non-renewable embodied energy in MJ equivalents;

[8]Renewable embodied energy in MJ equivalents.

Figure 3. Part of the SBTool[PT] LCA database.

The quantification of the environmental impacts using the LCA database is divided in two phases: i) quantification of the global embodied environmental impacts (Figure 4); and ii) quantification of the whole building's life-cycle impacts (Figure 5). In the first phase, using the above-mentioned bottom-up approach, the global embodied environmental impacts per square meter and year are quantified. This process is based in the contribution of each material and building element (available in the database) for the total embodied impact. In the second phase, the result from the previous phase is summed up with the impacts related to the maintenance scenarios, resulting in the whole building's life-cycle impacts.

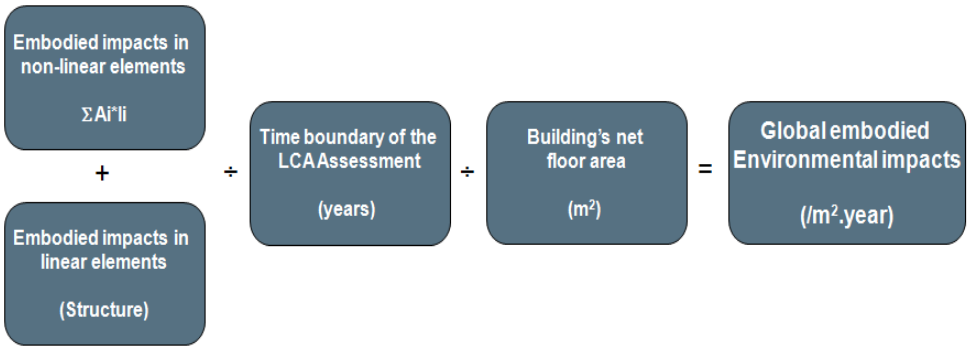


Figure 4. Phase 1 – quantification of the global embodied environmental impacts.

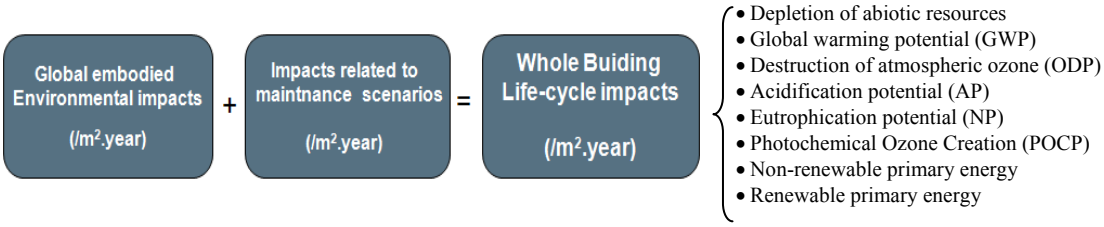


Figure 5. Phase 2 – quantification of the whole building's life-cycle environmental impacts.

4 CONCLUSIONS

Although, LCA is considered the best method available to assess the environmental performance of a product, its application in construction is very complex. This is because the huge number of different materials, products, actors, processes and also the wide life cycle span of a construction product.

Based in the work of CEN TC 350 and in the development of the Portuguese sustainability rating system (SBTool^{PT}), this paper presented some solutions to overcome the difficulties in using an LCA-based approach to support decision-making which aims at promoting lower environmental building design since the earlier design phases. The development by experts of databases with the LCA data of the most used building technologies and materials is a good solution to overcome some of the presented barriers that are hindering the widespread use of the LCA-based approaches by the design teams.

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LCA of building envelope components - Part 1. A database for Greece

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ABSTRACT: This paper is the first of two papers focused on the LCA of building envelope components, which are representative of the current practice in Greece, and on the use of these analyses' results for the selection of the least burdening solutions at the design phase with the help of a new computational tool developed in the context of this study. In this paper, the structure of the components that have been analysed with the use of Sima Pro is presented. For some of these components, certain indicative results are also cited. The focus is on the layout and on the materials used for the examined components. In the second paper (Part 2), a new computational tool that works on the basis of the LCA results previously mentioned is presented.

1 INTRODUCTION

During the last decades, numerous methods for buildings' and, generally, constructions' environmental performance assessment have been developed internationally. Based on different philosophies, using various criteria for the evaluation of the constructions' environmental profiles, employing different assumptions and simplifications and allowing varying levels of subjectivity in the assessments they perform, those methods form a rather wide and interesting, for a researcher as well as a practitioner, spectrum to investigate. The use of many of these methods is thought to provide reliable results and, in spite of their debatable accuracy in terms of exact calculations and of their inherent problems concerning the parameter of time and lifetime (Safouri et al. 2005), to lead to safe conclusions. Internationally, there is an ongoing effort towards the improvement of such methods reliability and accuracy and towards the enhancement of those tools' application in every-day practice.

LCA of building materials and components, as well as of building-related products, is closely related to the afore-mentioned assessment. Indeed, the results of building components' LCA could either serve as input to holistic buildings' environmental performance assessment methods or as autonomous data, giving an analytical image of various materials and components environmental impacts. The application of thorough life cycle analyses, compiling an inventory of relevant positive and negative flows (inputs and outputs) for any system and then evaluating the potential environmental impacts associated with those flows (Blok et al. 2007), to building components (and much more to buildings) is a rather complex process. The variety of building materials, having different properties, characteristics and life durations, attacked by different aggressive agents and produced through different production lines are difficult to be evaluated in the same analysis, and especially as parts of the functional system of adequately performing building components and, in a broader scope, adequately performing buildings.

Nevertheless, several life cycle assessment methods and tools applicable to building components and buildings, characterized by different levels of complexity and sophistication, have been developed in the recent years. Reviews of such methods can be found in several papers e.g. (Bribián et al. 2009); (Haapio et al. 2008).

This paper is the first of a series of two papers dealing with the Life Cycle Analysis of building components in Greece. In the first part (Part 1), the focus is on the LCA of building envelope components, which are representative of the current practice in Greece. More specifically, the layouts of the building envelope components that were analysed with the help of a well known LCA software, Sima Pro (Sima Pro), are presented and some results are cited. This way, an image of which components are included in the developed database is acquired. Apart from the formation of a database with LCA results, this study was extended to the development of a computational tool that works on the basis of these results. This tool developed as a Visual Basic Application and functioning on the basis of LCA results for the main environmental impacts of several envelope components (database presented in Part 1), is introduced in the second paper of this short series (Part 2).

2 LCA ANALYSIS OF BUILDING ENVELOPE COMPONENTS

2.1 *Introductive discussion*

The LCA analysis of building envelope components was conducted with the use of Sima Pro, a well known and widely acceptable software, in the context of a diploma thesis (Pelekas et al. 2010).The analyses were conducted with the use of Ecoinvent database and with the application of Eco-Indicator 99 method. The layouts of the components that were selected to be studied are considered representative of the current construction practice in Greece. For some of these components, different layouts were examined. For example, for the outer wall brick construction four alternatives were analysed:

- brick construction with insulation at the exterior surface of the brick layer,
- brick construction with insulation at the exterior surface of the brick layer assuming an end-of-life scenario of bricks reuse,
- brick construction with insulation between two brick layers and
- brick construction with insulation between two brick layers assuming an end-of-life scenario of bricks reuse.

Exactly the examination of those alternatives is the basis of the computational tool that will be presented in another paper (Part 2). In the following sections, the layouts that have been analysed will be shortly presented. In this presentation, also the components, for which only one layout has been examined, are also included for reasons of clarity and completeness.

A big number of results have been produced for every layout examined. In the tool presented in Part 2, only the results referring to the 11 main impact categories are used. Such results are indicatively presented in the following for only one component, due to the limited available space.

2.2 *Concrete wall components*

2.2.1 *Typical concrete wall*

The layout and the layers of the typical envelope concrete wall are presented in Fig. 1 and in Table 1 respectively. In Fig.2 the results calculated for the 11 main impact categories are shown.

2.2.2 *Concrete wall with thermal plaster*

The difference of this layout with the one previously presented is that the exterior plaster is replaced with one having better insulating capacities and the width of the insulation layer is reduced, so that the total components' insulation capacity remains the same. The layout and the layers of this concrete wall are presented in Fig. 3 and in Table 2 respectively.

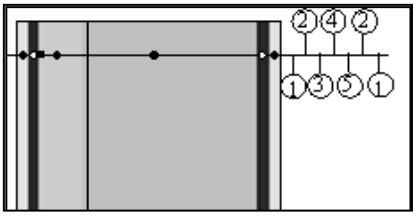

Figure 1. Layout of the typical concrete wall (see Table 1 for the specification of the component's layers).

Table 1. Layers of the typical concrete wall (Fig. 1)

Nr	Layer		Material (Ecoinvent data-base)	Width (m)
1	Paint		ALKYD PAINT, WHITE 60% IN H_2O, AT PLANT / RER S	0,002
2	Plaster		BASE PLASTE, AT PLANT CH/S	0,025
3	Glass fibre		GLASS FIBRE, AT PLANT / RER S	0,0008
4	Insulation		POLYSTYRENE FOAM SLAB, AT PLANT / RER S	0,050
5	Reinforced concrete	Concrete	CONCRETE NOT REINFORCED ETHS	0,250
		Reinforcing steel	REINFORCING STEEL, AT PLANT / RER S	

Impact category /	Unit	life cycle of toixeio
Total	Pt	40,2
Carcinogens	Pt	13,2
Resp. organics	Pt	0,015
Resp. inorganics	Pt	4,67
Climate change	Pt	3,12
Radiation	Pt	0,0221
Ozone layer	Pt	0,00219
Ecotoxicity	Pt	10
Acidification/ Eutrophication	Pt	0,447
Land use	Pt	1,3
Minerals	Pt	0,2
Fossil fuels	Pt	7,18

Figure 2. Results for the impact per m^2 of the typical concrete wall in the 11 main impact categories (Pelekas et al, 2010).

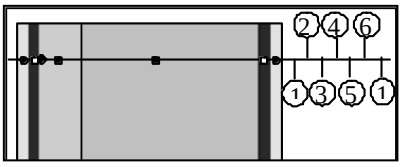

Figure 3. Layout of the concrete wall with thermal plaster (see Table 2 for the component's layout).

2.3 *Exterior brick wall components*

2.3.1 *Brick wall with exterior insulation*

The layout and the layers of the brick wall with exterior insulation are presented in Fig. 4 (right) and in Table 3 respectively.

2.3.2 *Brick wall with exterior insulation - brick reuse scenario*

The layout and the layers of this component are the same as previously, with the end of life

scenario being differentiated. This component is not separately illustrated (same as Fig. 4 (right) and Table 3).

2.3.3 *Brick wall with insulation between the two brick layers*
The layout and the layers of the brick wall with insulation between the two brick layers are presented in Fig. 4 (left) and in Table 4 respectively.

2.3.4 *Brick wall with insulation between the two brick layers - brick reuse scenario*
The layout and the layers of this component are the same as previously, with the end of life scenario being differentiated. This component is not separately illustrated (same as Fig. 4 (left) and in Table 4).

Table 2. Layers of the concrete wall with thermal plaster (Fig. 3)

Nr	Layer		Material (Ecoinvent database)	Width (m)
1	Paint		ALKYD PAINT, WHITE 60% IN H2O, AT PLANT / RER S	0,002
2	Plaster (exterior)		THEPMAL PLASTER, AT PLANT / CH S	0,025
3	Glass fibre		GLASS FIBRE, AT PLANT / RER S	0,0008
4	Insulation		POLYSTYRENE EXTRUDED (XPS) , AT PLANT / RER S	0,040
5	Reinforced concrete	Concrete	CONCRETE NOT REINFORCED ETHS	0,250
		Reinforcing steel	REINFORCING STEEL, AT PLANT / RER S	
6	Plaster (interior)		BASE PLASTER, AT PLANT / CH S	0,025

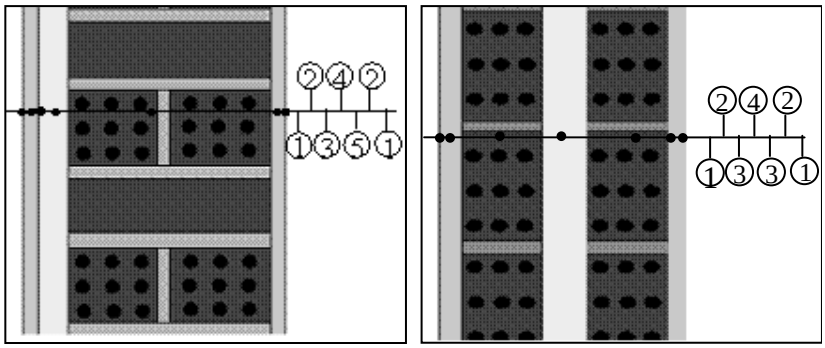

Figure 4. Right: Layout of the brick wall with exterior insulation (see Table 3 for the component's layers)- Left: Layout of the brick wall with insulation between two brick layers (Table 4 for the component's layers)

2.4 *Basement concrete wall*

For this type of component, only one layout was examined and analysed with the use of Sima Pro. This layout and the layers it includes are presented in Fig. 5 and Table 5.

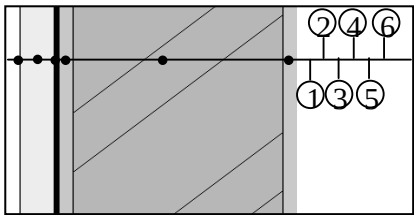

Figure 5. Layout of the basement concrete wall (see Table 5 for the component's layers)

Table 3. Layers of the brick wall with exterior insulation (Fig. 4-right)

Nr	Layer		Material (Ecoinvent data-base)	Width (m)
1	Paint		ALKYD PAINT, WHITE 60% IN H2O, AT PLANT / RER S	0,002
2	Plaster		BASE PLASTER, AT PLANT / CH S	0,025
3	Glass fibre		GLASS FIBRE, AT PLANT/RER S	0,0008
4	Insulation		POLYSTYRENE FOAM SLAB, AT PLANT / RER S	0,050
5	Brick con-struction	Bricks	BRICK, AT PLANT / RER S	0,190
		Mortar	LIME MORTAR AT PLANT / CH S	0,002

Table 4. Layers of the brick wall with insulation between two brick layers (Fig. 4-left)

Nr	Layer		Material (Ecoinvent da-tabase)	Width (m)
1	Paint		ALKYD PAINT, WHITE 60% IN H2O, AT PLANT / RER S	0,002
2	Plaster		BASE PLASTER, AT PLANT / CH S	0,025
3	Brick con-struction	Bricks	BRICK, AT PLANT / RER S	0,090×2
		Connecting mortar	LIME MORTAR AT PLANT / CH S	0,002
4	Insulation		POLYSTYRENE FOAM SLAB, AT PLANT / RER S	0,050

Table 5. Layers of the basement concrete wall (Fig. 5)

Nr	Layer		Material (Ecoinvent data-base)	Width (m)
1	Granulate		PROPYLENE GRA-NULATE AT PLANT RER /S	0,002
2	Insulation		POLYSTERENE EXTRUDED AT PLANT /RER S	0,050
3	Bitumen sealing		BITUMEN SEAL-ING V60 AT PLANT / RER S	0,007
4	Mortar		LIME MORTAR AT PLANT / CH S	0,020
5	Reinforced concrete	Concrete	CONCRETE NOT REINFORCED ETHS	0,250
		Reinforcing steel	REINFORCING STEEL, AT PLANT / RER S	
6	Plaster (interior)		BASE PLASTER, AT PLANT / CH S	0,025

2.5 *Roof*

Only one layout for the building's roof has been examined (Fig. 6 –right and Table 6).

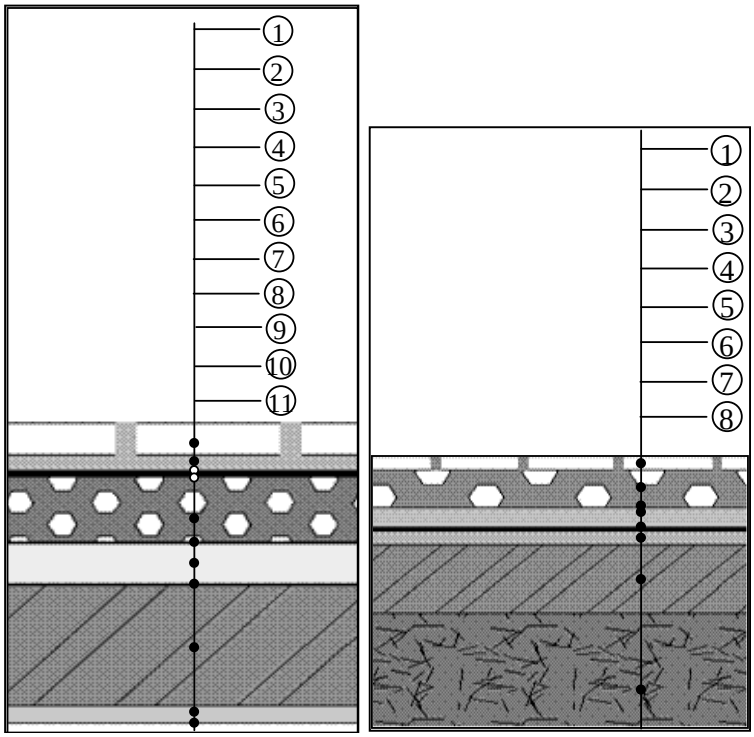

Figure 6. Right: Layout of the building's roof (see Table 6 for the component's layers)-
Left: Layout of the building's basement floor (see Table 7 for the component's layers)

Table 6. Layers of the building's roof (Fig. 6-right)

Nr	Layer		Material (Ecoinvent data-base)	Width (m)
1	Stone plates		NATURAL STONE PLATE CUT AT REGIONAL STO-RAGE/ CH S	0,040
2	Cement mortar		CEMENT MORTAR AT PLANT / CH S	0,020
3	Granulate		PROPOPYLENE GRANULATE AT PLANT / RER S	0,002
4	Bitumen sealing		BITUMEN SEALING V60 AT PLANT / RER S	0,007
5	Poor concrete		POOR CONCRETE AT PLANT / CH S	0,080
6	PVC		PVC	0,002
7	Insulation layer		GLASS WOOL MAT AT PLANT / CH S	0,050
8	PVC		PVC	0,002
9	Reinforced concrete	Concrete	CONCRETE NOT REINFORCED ETHS	0,150
		Reinforcing steel	REINFORCING STEEL, AT PLANT / RER S	
10	Plaster		BASE PLASTER, AT PLANT / CH S	0,020
11	Paint		ALKYD PAINT, WHITE 60% IN H2O, AT PLANT / RER S	0,002

2.6 *Basement floor (lower floor)*

The basement floor analysed is presented in Fig. 6-left and in Table 7.

Table 7. Layers of the building's basement floor (Fig. 8)

Nr	Layer		Material (Ecoinvent database)	Width (m)
1	Stone plates		NATURAL STONE PLATE CUT AT REGIONAL STORAGE/ CH S	0,030
2	Poor concrete		POOR CONCRETE AT PLANT / CH S	0,080
3	PVC		PVC	0,002
4	Insulation layer		GLASS WOOL MAT AT PLANT / CH S	0,050
5	Bitumen sealing		BITUMEN SEALING V60 AT PLANT / RER S	0,007
6	Cement mortar		CEMENT MORTAR AT PLANT / CH S	0,030
7	Reinforced concrete	Concrete	CONCRETE NOT REINFORCED ETHS	0,150
		Reinforcing steel	REINFORCING STEEL, AT PLANT / RER S	
8	Gravel		GRAVEL ETH S	0,025

2.7 *Column (envelope component)*

Also for the column (belonging to the building's envelope), only a case was examined. This layout is presented in Fig. 7 and in Table 8.

Table 8. Layers of the column component (Fig. 4)

Nr	Layer		Material (Ecoinvent database)	Width (m)
1	Paint		ALKYD PAINT, WHITE 60% IN H2O, AT PLANT / RER S	0,002
2	Plaster		BASE PLASTE, AT PLANT CH/S	0,025
3	Glass fibre		GLASS FIBRE, AT PLANT / RER S	0,0008
4	Insulation		POLYSTYRENE FOAM SLAB, AT PLANT/ RER S	0,050
5	Reinforced concrete	Concrete	CONCRETE NOT REINFORCED ETHS	0,300
		Reinforcing steel	REINFORCING STEEL, AT PLANT / RER S	

2.8 *Components not belonging to the envelope (interior surfaces)*

Apart from the envelope components, also some interior components were analysed (Pelekas et al, 2010):

- Interior brick construction (width:0,244m)
- Interior brick construction (width:0,144m)
- Horizontal component (plate) between two successive floors (stone floor)
- Horizontal component (plate) between two successive floors (wooden floor)

Detailed description of these components is not given here due to not only the fact that the paper is focused on envelope components but also to the limited available space.

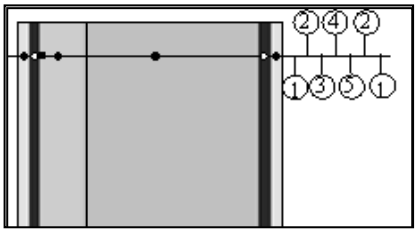

Figure 7. Layout of the column component (see Table 8 for the specification of the component's layers)

3 DISCUSSION AND CONCLUSIONS

The development of a database of typical components' impacts with the use of LCA analysis is a useful step towards the selection of least burdening components at the stage of design, or even of pre-design. Such a database, derived with the use of Sima Pro, for building components' layouts that are representative of current construction in Greece was presented in this paper. Of course, this database can be considered as a first step towards the formation of a more extensive and detailed database of components. Such databases can be constantly enriched. In the second paper of this series (Part 2), a computational tool working on the basis of this database will be presented.

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Sima Pro: http://www.pre.nl

LCA of building envelope components - Part 2. The computational tool BEnICa

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ABSTRACT: This paper is the second of two papers focused on the LCA of building envelope components, which are representative of the current practice in Greece, and on the use of these analyses' results for the selection of the least burdening solutions at the design phase with the help of a new computational tool developed in the context of this study. In this paper, the new computational tool BEnICa (Building Envelope Impact Calculation) that works on the basis of the LCA results described in Part 1 is presented. Specifically, the first limited version of the currently developed tool is analysed. The structure, the algorithm and the mathematical background of the tool under study are presented. Finally, indicative results derived from the so far developed version of the tool are presented and discussed.

1 INTRODUCTION

This paper is the second of a series of two papers dealing with the Life Cycle Analysis of building components in Greece. In the first part (Part 1), the focus was on the LCA of building envelope components, which are representative of the current practice in Greece. More specifically, the layouts of the building envelope components that were analysed with the help of a well known LCA software, Sima Pro (Sima Pro), were presented and some results were cited (Pelekas et al., 2010). The database acquired with the conductance of the afore-mentioned analyses is the main source of data for the new computational tool presented in this paper. This tool is named BEnICa (Building Envelope Impact Calculation); it is developed as a Visual Basic Application and functions on the basis of the LCA results described in Part 1. The application of this tool contributes to the investigation of the best possible selection of the components' layouts, in terms of LCA. The mathematical background and the algorithm of this tool are presented analytically. Apart from the description of BEnICa's structure, some indicative results derived from BEnICa's application are cited and discussed. It should be pointed out that these results were derived from the application of a first, short version of BEnICa, currently functional. BEnICa is currently under development in its full form.

Before the presentation of BEnICa it should be stressed that the aim of this tool is not the proposal of a new method for LCA, such as the numerous currently available methods, applicable to building components and buildings, characterized by different levels of complexity and sophistication (Bribián et al. 2009; Haapio et al. 2008). BEnICa aims at using the results of LCA methods (in this version of BEnICa Sima Pro was used for building components' LCA) for the selection of the least burdening combination of building envelope components at initial stages of design, depending on their area on the building envelope and on the relative impor-

tance of environmental issues for every region. The structure and the mathematical background of BEnICa leading to the achievement of this target are described in the following sections.

2 THE COMPUTATIONAL TOOL BENICA

2.1 *Introductive discussion*

The analysis of the afore-mentioned components led to the development of a database containing the basic impacts of each case (per m^2). Of course, this database can by itself be used for the formation of an image about the relative aggravation caused by the areal unit of the examined components. This image, as illustrative it may be, is not very clear when the envelope of a whole building is considered. The relative area of the components on the envelope of the building can lead to significant differentiation in the results, with regard to the contribution of each component to every impact category, in comparison to what is derived from the developed database. Furthermore, in case that certain environmental issues are considered more important than others, due to regional priorities or needs, then the relative weight of every impact category is differentiated, creating this way an additional difficulty in the direct estimation of a potential selection's influence on the total environmental impact of a building.

In the context of this problem, the computational tool BEnICa (Building Envelope Impact Calculation) was developed. This tool is developed as a Visual Basic application (form) in an Excel environment. The application (user form and code) benefits both from the development of an autonomous user form (user-friendly interface, avoidance of multiple references to cells, etc.) and from its development in Excel environment (the structure of Excel spreadsheets is taken advantage of, with the creation of tables, the use of ready, implemented functions in Excel for the calculation of intermediate results and thus avoidance of the syntax of very complicated and extremely extensive code). This tool, the function of which is presented in the following section, is based on the results of the LCA analyses referred to in the previous section.

2.2 *Logical and mathematical background of BEnICa*

For each one of the components analysed with the use of Sima Pro, a big number of results is produced. One of the basic sets of results is illustrated in Fig. 2 of Part 1. Analytically, Sima Pro (Eco-Indcator 99 method) calculates the impact of a m^2 of each component in the following impact categories:

1. Carcinogens
2. Respir. organics
3. Respir. inorganics
4. Climate change
5. Radiation
6. Ozone layer
7. Ecotoxicity
8. Acidification
9. Land use
10. Minerals
11. Fossil fuels

BEnICa works on the basis of these eleven impact categories. More specifically, for each type of component (e.g. concrete wall), there is available a set of options of layouts (e.g. typical concrete wall and concrete wall with thermal plaster). Also the possibility of implementing the area of each component on the examined building's envelope is given. Moreover, the relative weights of the eleven impacts categories are set by the user. The course of calculations is described roughly in the following steps:

1. Selection of the layout for each envelope component
2. Input of each component's area on the examined building's envelope
3. Input of relative weights for the 11 impact categories
4. For each one of the 11 impacts: calculation of total impact according to the inputted areas and to the available layouts

5. For each one of the 11 impacts: calculation of total impact for the selected combination of the components' layouts (given of course the previously inputted areas)
6. For each one of the 11 impacts: Application of a normalization scheme, so that a number between 0 and 1 is assigned to each impact category for the selected combination of the components' layouts. For each one of the categories, the normalization scheme applied is the one given by equation (1):

$$IC_{i\text{-}norm}=\frac{IC_i-IC_{min}}{IC_{max}-IC_{min}} \quad (1)$$

where $IC_{i\text{-}norm}$ is the normalized value for the i-th impact category (i=1,..,11) as it is derived for the examined combination,
IC_i is the value calculated for the i-th impact category (i=1,..,11) as it is derived for the examined combination (step 5),
IC_{max} is the maximum value for the i-th impact category (i=1,..,11) among the values calculated for all the possible combinations of the available layouts of the components (given the areas of each component on the building's envelope) and
IC_{min} is the minimum value for the i-th impact category (i=1,..,11) among the values calculated for all the possible combinations of the available layouts of the components (given the areas of each component on the building's envelope)
7. Weighted sum (relative weights of the impact categories as inputted in step 3) of the above mentioned normalized numbers for the 11 impact categories.

With the application of the previous steps, a grade between 0 and 1 is assigned to the building's envelope consisting of the selected combination of layouts for its components. Specifically:
- 0 is assigned to the least aggravating envelope construction among the available combinations (areas of the components and impact categories relative weights being taken into consideration) and
- 1 is assigned to the most aggravating envelope construction among the available combinations.

This way, a first estimation of what the impact of certain selections, in regard to selection among typical layouts for envelope components in Greece, to the whole envelope's environmental impact might be can be derived, for any combination of impact categories relative weights. In Fig. 1 the algorithm of BEnICa is schematically illustrated.

2.3 *Application of the first version of BEnICa*

The algorithm described in the previous section is the basis of the computational tool named BEnICa, which is currently under development. At this point, a first version of this tool is functional. In this version, data about two components have been implemented:
- Concrete wall
  - Typical concrete wall
  - Concrete wall with thermal plaster
- Exterior brick wall
  - Brick wall with exterior insulation
  - Brick wall with exterior insulation – brick reuse scenario
  - Brick wall with insulation between two brick layers
  - Brick wall with insulation between two brick layers – brick reuse scenario

A small, indicative parametric study is conducted with this version of BEnICa. The variables of this study are the layouts of the two components and the relative weights of the 11 impact categories. In all the cases of this parametric study, the areas of the two components are set to (indicative values):
- Concrete wall: $30m^2$
- Exterior brick wall: $150m^2$

In the first group of analyses, the relative weight of "carcinogens" impact category is set to 100%- the rest of the relative weights are of course set to 0%. For the selection of layouts:
- concrete wall: typical concrete wall
- exterior brick wall: brick wall with exterior insulation,

the final grade derived for the envelope is 1.

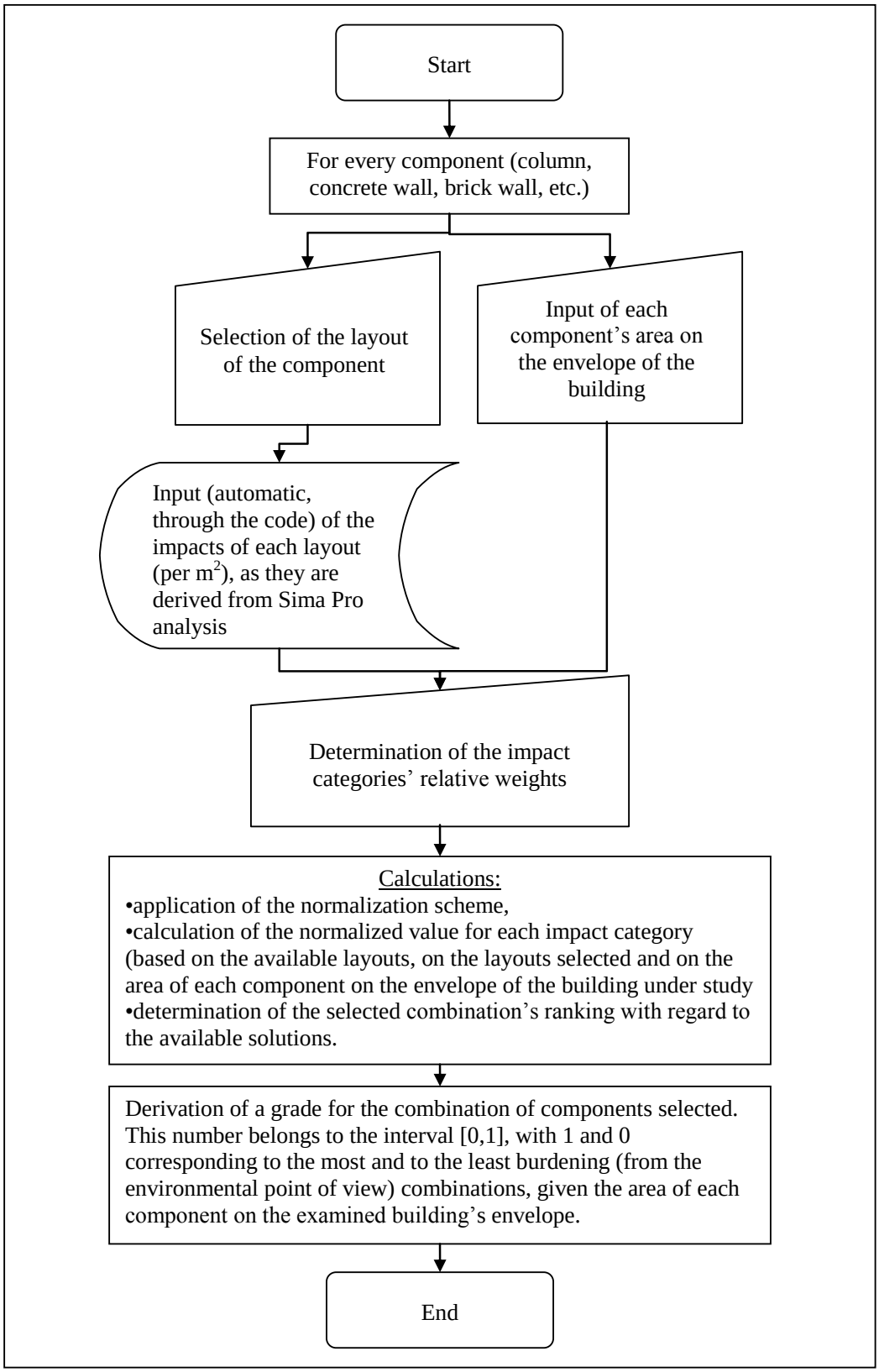

Figure 1. Schematical illustration of BENICA algorithm.

For the selection of layouts:
- concrete wall: typical concrete wall
- exterior brick wall: brick wall with exterior insulation – brick reuse scenario,

the final grade derived for the envelope is 0,726.
For the selection of layouts:
- concrete wall: concrete wall with thermal plaster
- exterior brick wall: brick wall insulation between two brick layers– brick reuse scenario,

the final grade derived for the envelope is 0.

In the second group of analyses, the relative weights of "ozone layer" impact category and of "land use" impact category are both set to 50%- the rest of the relative weights are of course set to 0%. For the selection of layouts:
- concrete wall: typical concrete wall
- exterior brick wall: brick wall with exterior insulation,

the final grade derived for the envelope is 0,750.
For the selection of layouts:
- concrete wall: typical concrete wall
- exterior brick wall: brick wall with exterior insulation – brick reuse scenario,

the final grade derived for the envelope is 0,532.
For the selection of layouts:
- concrete wall: concrete wall with thermal plaster
- exterior brick wall: brick wall insulation between two brick layers – brick reuse scenario,

the final grade derived for the envelope is 0,661.

In the third group of analyses, the relative weights of each of the first 4 impact categories, as they are cited in 2.2., are set to 5%, the relative weights of the next 4 categories are set to 20%; consequently, the relative weights assigned to the rest of the categories are 0%. For the selection of layouts:
- concrete wall: typical concrete wall
- exterior brick wall: brick wall with exterior insulation,

the final grade derived for the envelope is 0,894.
For the selection of layouts:
- concrete wall: typical concrete wall
- exterior brick wall: brick wall with exterior insulation – brick reuse scenario,

the final grade derived for the envelope is 0,674.
For the selection of layouts:
- concrete wall: concrete wall with thermal plaster
- exterior brick wall: brick wall insulation between two brick layers – brick reuse scenario,

the final grade derived for the envelope is 0,448.
It is obvious that there is a very big number of analyses that can be conducted, even with the use of this limited version of BEnICa.

3 DISCUSSION AND CONCLUSIONS

The computational tool BEnICa, currently under development (a first -limited- version was presented in this paper) permits the estimation of the whole impact of a building envelope, with regard to the 11 main impact categories considered in Eco-Indicator 99, when the relative weights of the impacts, as well as the area of each component in the building under design are considered. This tool, providing a user-friendly interface and easy to interpret results, also provides a base for further and constant development and enrichment in terms of the analysed components. The LCA results used in this version of BEnICa were derived with the use of Sima Pro software. The database created with the use of BEnICa was presented in the first paper of this series (Part 1).

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Life Cycle Impacts Assessment of Steel, Composite, Concrete and Wooden Columns

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ABSTRACT: This paper presents a comparative study showing the environmental profile of structural members used in the construction domain. The functional unit is a column that is realistic in terms of dimensions and load bearing capacity, made of steel or high strength steel sections, steel and concrete (composite), reinforced concrete, solid wood and glue-laminated wood. The design of the columns is made following the Eurocodes. Several environmental impacts are assessed, such as the global warming potential and energy consumption while also focusing on the acidification potential. The results are presented in the forms of bar charts for each considered column. For steel and concrete, depending on the source of information, the inventory can vary substantially e.g. the CO and CH_4 emissions. Several sources of information are provided and used to perform a brief sensitivity analysis. The influence of the recycling of steel taking into account the IISI methodology will also be discussed.

1 INTRODUCTION

This paper presents the outcomes of a comparative cradle-to-gate impacts assessment (LCIA) of different types of columns showing the most important drivers for environmental impacts as for instance the influence of the end-of-life scenario for steel. The columns are made of different materials and are chosen with respect to a design load. In LCA, the choice of the functional unit is very important for making a meaningful comparison. A realistic design compressive load was thus estimated for a particular building configuration with particular number of stories, dimensions of the room and occupancy. Traditionally, the embodied energy and CO_2 emissions are chosen as the most important parameters for the environmental profile evaluation. These impacts are usually calculated as cradle to gate although, in some cases, the transport from the factory to construction site is also provided as well as downstream processes for steel or concrete construction (Gervásio & Simões da Silva 2007). In more complete research, several scenarios

for the end-of-life stage are also considered especially for wood which can be recycled with energy recovery (Manthey et al. 2010) and for concrete which can be recaptured, crushed and recycled as aggregate (Marinkoviæ et al. 2008). Most of these studies however provide few impact categories and are often supporting one material among others. In this study, not only are several impacts assessed but they are also studied in a brief sensitivity analysis taking into account the variability in the data sources such as the life cycle inventory (LCI) data for concrete.

2 LIFE CYCLE IMPACTS ASSESSMENT (LCIA)

2.1 *Principles*

The LCA is generally cited as the most important method in the construction domain for the long-term measurement of sustainability. Herein, environmental midpoint impacts (such as global warming potential, acidification or ozone layer depletion) are used to compare the columns to be able to choose the least burdensome. The level of this analysis is beyond the basic life-cycle thinking that is just a qualitative discussion underlining the important issues of the analysis but remains a simplified LCA since it assesses a limited amount of environmental impacts and does not take into account several steps of the life cycle such as the transportation part and use.

2.2 *Functional unit*

An attempt is made to achieve a fair comparison between the columns considered in the present research. For that purpose, the compressive load and bending moment are calculated on the basis of a realistic building configuration. The slab of the building consists of a profiled steel panel filled with concrete acting as a composite decking. The weight of the slab was taken from the specification for this slab and a 10 by 20 meters panel dimensions was considered. The imposed dead and live loads were taken from the appropriate Eurocode and the load, transferred from the slab to the beams and to the columns, was estimated to be equal to 1874kN which equals 5622kN for a three-storey building. By way of conclusion, the load bearing capacity was chosen to be equal to 5000kN plus an arbitrary constant bending moment of 100kNm (around the strong axis for profile columns) which is consistent with a simply supported column located in a frame at the end of which the joints allow the rotations to develop. The length of the column equals 5 m. In this study, the strength, stability and stiffness conditions according to Part 1-1 of Eurocode 3 and Eurocode 4 were taken into account for the design of the steel and composite columns. For the concrete and wooden column, Eurocode 2 and DIN 1052:2008 were respectively used.

2.2.1 *Steel columns*

Table 1. Case studies for steel columns

CHS	S355	S690			
	CHS508x10	CHS355,6x10			
H profile	S355				
	L=5m				L=2.5m
	1	2	3	4	5
	N=5000kN M= 300kNm HD 400x187	N=5000kN M= 100kNm HD 360x179	N=2500kN M= 300kNm HD 360x147	N=2500kN M= 220kNm HD 360x127	N=5000kN M= 300kNm HD 360x162
	S460				
	HD 360x179	HD 360x147	HD 320x127	HD 320x127	HD 360x147

For the steel columns, two types of profiles are considered: traditional H (namely profile) and circular shaped (namely circular hollow section CHS, see Figure 1). The steel yield strength equals 355, 460 or 690MPa and the Young's modulus is 210GPa. Several designs were made for the profile column considering two lengths and several loading configurations (see Table 1), the dimensions of the profiles are taken from ArcelorMittal catalogue. In the sense of ISO 14040 standards, the columns functions are different and thus not comparable. The different de-

signs are only used for the sake of sensitivity analysis. For CHS, standard dimensions of Vallourec and Mannesmann tubes manufacturer were considered.

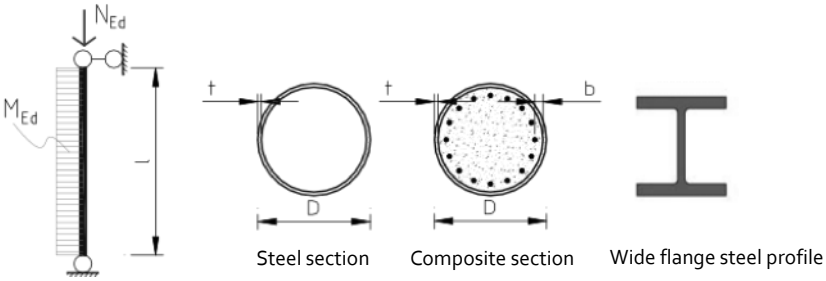

Figure 1. Steel and composite circular columns – Types and loading condition (Hoang et al. 2010). A empty circular hollow steel section, a wide flanges steel profile and a concrete filled section were considered.

2.2.2 *Composite columns*

Table 2. Case studies for composite columns

	S355	S460
CHS	Steel tube: CHS406,4x6,3 *As* = 45,17cm^2 (~ 4% of the conc. area)	Steel tube: CHS355,6x10 *As* = 26,38cm^2 (~ 4% of the conc. area)

The composite column is made of a CHS (made of traditional construction steel and high strength steel) filled with reinforced concrete (*As* is the area of reinforcement) as depicted in Figure 1. The dimensions of the column using standard tubes are provided in Table 2.

2.2.3 *Concrete column*

The concrete column design was carried out with reference to Eurocode 2, and the required properties of the column are provided in Table 3. The totals volumes of concrete and steel are also reported in Table 3. The upper part of the column (lapping of vertical reinforcement) intended to allow for the next floor was ignored in the analysis.

Table 3. Concrete column

Exposure Conditions	Internal- Mild XC1
Concrete	f_{ck} =35 N/mm^2
Steel	f_{yk} = 500 N/mm^2
Cover C_{nom} (1,5H of fire résistance, Category 1 (dry) durability)	35mm
Width	50cm
Depth	50cm
→ Total volume of concrete	1,25 m^3
Required *As*	3150mm^2
→ Corresponding to 8 H25 rebars (*As*=3930 mm2)	l= 6000mm (including lap)
→ Total volume of reinforcing rebar	VH25=0,02358m^3
→ Additionally, 17 R10 links are required	Spacing = 300mm, l=1850mm
→Total volume of links	VR10=0,00247m^3
→ Total weight of steel rebar	Ws=204,5kg

2.2.4 *Wood column*

In the present research paper, two section types are considered: (1) Solid tree section: diameter = 660mm, volume 1.711m3, weight = 855kg; and (2) Standard glue laminated timber (GL28h): Round section: outer diameter = 640mm, volume 1.608m3, weight = 804kg.

2.2.5 *Shortcomings concerning the functional unit*

The limitations related to the definition of the functional unit are the followings: (1) It is important to underline that the column considered is a single column simply supported at both ends. In real building configuration, this constitutes a relatively unrealistic case. Indeed, in reality, the columns are connected with other members composing the structure and an interaction exists

with the rest of the structure, meaning that the support conditions are different; (2) Although based on a realistic building configuration, only one design is made per considered column. It is thus difficult to draw any general conclusions although it is thought that they are nevertheless relatively reliable for a certain range of column designs; (3) Moreover, still about the design, accordingly to the member type, the whole structural system type and behaviour as well as method of analysis (joints, wind bracing, plastic hinges, plastic mechanism, etc) vary a lot and should be taken into account for the design of the columns; (4) Last, in the present research, the design of the columns including the strength, stability and stiffness conditions according to the appropriate Eurocodes was achieved at ambient temperature. No fire resistance of the columns was evaluated nor robustness against accidental loading quantified.

2.3 *System boundaries*

The study is a cradle-to-gate study. It covers all the production steps from raw materials "in the earth" (i.e. the cradle) to finished products ready to be shipped from the factory (i.e. the gate of the steel work for instance). It also includes the credits associated with the steel recycling (IISI 2002). The finishing of steel structures (cutting, shot blasting, welding) is not included but, is equals to 10 kg CO_2-eq. / ton of steel according to steel producers. For concrete, the LCI data are divided by sub-components and the total result for 1 m^3 of concrete production, excluding the transportation from the production plants of the material inputs to the production plant of the final product. The transportation of steel and concrete to the construction site are also excluded. For the transport of hot rolled steel sections and rebar, the average European value for transport to the site is generally chosen equal to 30 kg CO_2-eq. / ton of steel according to steel producers, being less or more for specific cases. For sake of consistent system boundaries, the LCA takes into account the Production phase (raw materials, manufacturing, transport) and disregards the Building site operations (transport to the site, shot blasting, painting, assembling, formwork...), Use and Maintenance or Repair, End-of-life (disassembling, demolition, disposal, recycling of concrete).

2.3.1 *Life cycle inventory of steel*

Steel is produced using two process routes. The main one is the blast furnace (BF) route (basic oxygen furnace), whereas secondary steel production process uses the electric arc furnace (EAF) route. Both processes recycle a certain amount of scrap that is melted in the furnace making steel a recyclable material. The absolute recycling rate (RR) of steel is 100% but, in reality, it depends on the considered application. For construction steel, one can point the recycling rate of rebar that more or less equals 60% while for profiles, it can be up to 100%. Nowadays, industries have resolutely worked to influence the methodology and include the end-of-life (EOL) treatment (IISI 2002, Rossi 2010). LCI data are calculated for the BF route (based on iron ore and steel scrap) and the EAF route (mainly based on steel scrap) on the basis of World or European averages. These data can be obtained via the online request facility on the International Iron & Steel Institute (IISI) website (worldsteel.org). It is possible to specify the RR or use the average RR for the considered sector.

2.3.2 *Life cycle inventory of wood products*

Data for wood products are taken from the Ecoinvent database (Werner et al. 2007). Forestry processes are considered; harvesting and disbranching with chainsaws as well as energy (diesel) for the transport to the forest road (an average transport distance of 40 km is assumed to the next sawmill). For glue-laminated timber (GLT), energy for planning, drying and laminating as well as the use of resin is inventoried. The inventory of the GLT, board for both the outdoor and the indoor board, is estimated for a three layered laminated timber.

2.3.3 *Life cycle inventory of concrete*

Table 4. Outcomes for impact assessment of concrete C30/35 (Stripple 2001). RE=Renewable energy, NRE=Non Renewable energy (E=RE+NRE).

	Consumption per m^3 of concrete	Diesel (per m^3 of concrete)	Per kg of crushed aggregates	Per kg of gravel/sand extraction	Per kg of cement	Total per m^3 of concrete
RE (MJ)	7,86		0,01	0,001127143	0,18325	93,95
NRE (MJ)	0,669	55,3	0,00085	9,57143E-05	3,875	1607,06
Emissions to air, g						
CO	0,0351	4,14	0,001491667	7,35714E-05	0,00082	6,3446
NO_x	0,154	34,6	0,01225	0,000597143	2,0025	850,872
SO_x	0,112	1,85	0,0007875	4,67143E-05	1,0025	403,9397
CH_4	0,00234	0,00243	3,81667E-06	3,75714E-07	0,0000545	0,031413
CO_2	63,5	3850	1,425	0,072714286	807,5	328674,4
N_2O	0,00702	0,0779	3,60833E-05	0,0000023	0,00016375	0,19533

The evaluation of the environmental impacts is highly determined by the quality of the available data. Unlike steel, there is no standard data for all the components used in a concrete mix. Table 4 provides the necessary data for the impacts assessment of the production of 1 m^3 concrete following the information of (Stripple 2001) and considering 1200kg of crushed aggregates, 700kg of sand and 400kg of cement. It is also possible to find other sets of data in (Simapro 1998, Buzzi Unicem 2007, Marinkoviæ 2008, Stripple 2001). Those data were used to set up the minimum and maximum values of the impacts later used in the sensitivity analysis.

2.3.4 *Shortcomings concerning the cradle-to-gate data*

Some shortcomings of the LCA can be pointed: (1) No end-of-life scenario is considered for concrete making the comparison quite unfavorable seen that the recycling of concrete would reduce the use of virgin aggregate and its associated environmental impacts; (2) The system boundaries are cradle-to-gate meaning that the transportation step is reduced to transport during the production of material inputs, not to the production plant of the final product or to the construction site and the downstream processes are not assessed; (3) The composition of concrete does not take into account the additives nor the processes related to the making of the column such as formworks; (4) During the life cycle of the columns, neither painting nor protection is taken into account nor replacement or refurbishment of concrete wood.

2.4 *Characterization factors*

Herein, midpoints impacts such as the Global Warming potential (kg CO_2-eq.), Terrestrial acidification (kg SO_2-eq.) and Photochemical oxidation (kg C_2H_4-eq.) are calculated and the characterization factors are taken from (CML 2002). Different references were also analyzed concerning these factors and their influence on the impacts is provided later.

2.5 *Normalization*

Table 5. Normalization factors (CML 2010).

Terrestrial Acidification/Nutrification	16828871825,0	kg-eq sulfur dioxide/yr
Photochemical oxidation	2656769435	kg-eq ethylene/yr
Global Warming	5,21223E+12	kg-eq carbon dioxide/yr
Non-renewable energy	3,51217E+13	MJ/yr

The normalization step can place the LCA results in a larger context, for instance geographical and permits a comparative study of all the considered impacts. The reference values for the normalization step are taken from (CML 2010) and correspond to the total impacts of the considered geographical area, presently Europe.

3 IMPACTS ASSESSMENT RESULTS

In regard to the total European emissions, Figure 2 shows that the energy consumption and GWP are the greatest impacts in the environmental profile (at least compared to POCP and AP). The column comparison indicates that, within the steel columns, high strength steel tubes are definitely providing the lowest environmental profile regarding those four impacts. Moreover, the profile column comparison given in Figure 4 indicates that high strength steel can, in most cases, significantly decrease the environmental profile. In this range of columns, it seems that composite columns lead to higher impacts compared to the high strength steel or concrete columns. Although the concrete column option should be treated with care seen the following sensitivity analysis. The wooden columns show very low GWP (even negative seen the CO_2 uptake during the tree growing), POCP and AP but these options consume more energy (even more non renewable energy resources than the high strength steel column for the GL28h option). Nevertheless, no end-of-life scenario with energy recovery was considered for wood products and one could thus claim that this conclusion could be reversed. It is also important to note that the wooden columns attain very high cross-sectional dimensions, a factor that is not discussed herein. The impacts of the different profile columns (Table 1) depicted in Figure 4 also indicate that, seen the fact that only discrete geometries are allowed in catalogues, sometimes even if the required carrying capacity decreases, the impacts remain the same.

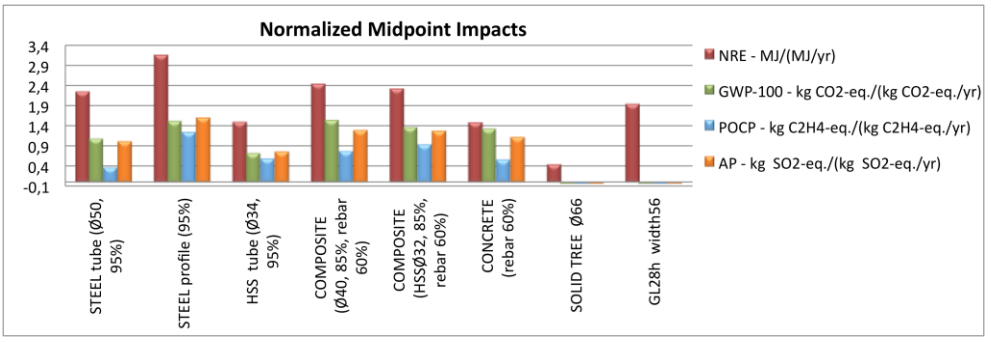

Figure 2. Normalized NRE, CO2 emissions eq. (GWP), Photochemical oxidation (POCP) and Terrestrial Acidification (AP). N=5000kN + M=100kNm case study, only steel S355, RR=95% for profiles and CHS, RR=85% when in contact with concrete, RR=60% for rebar (namely "Main case studies").

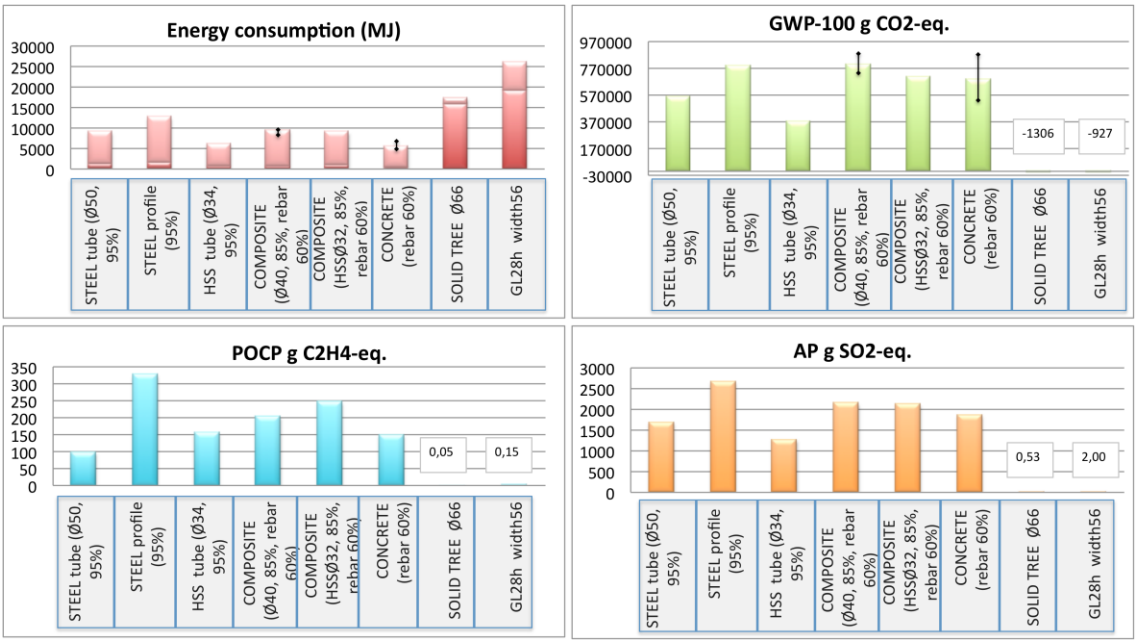

Figure 3. Demand in primary energy (RE=lower part of the bar, NRE=upper part of the bar), GWP, POCP and AP (Main case studies).

3.1.1 *Sensitivity analysis*

Last, what we call sensitivity analysis is, in fact, a study of how the variation in the output of the analysis (impacts) can be linked, qualitatively or quantitatively, to the variation of the inputs.

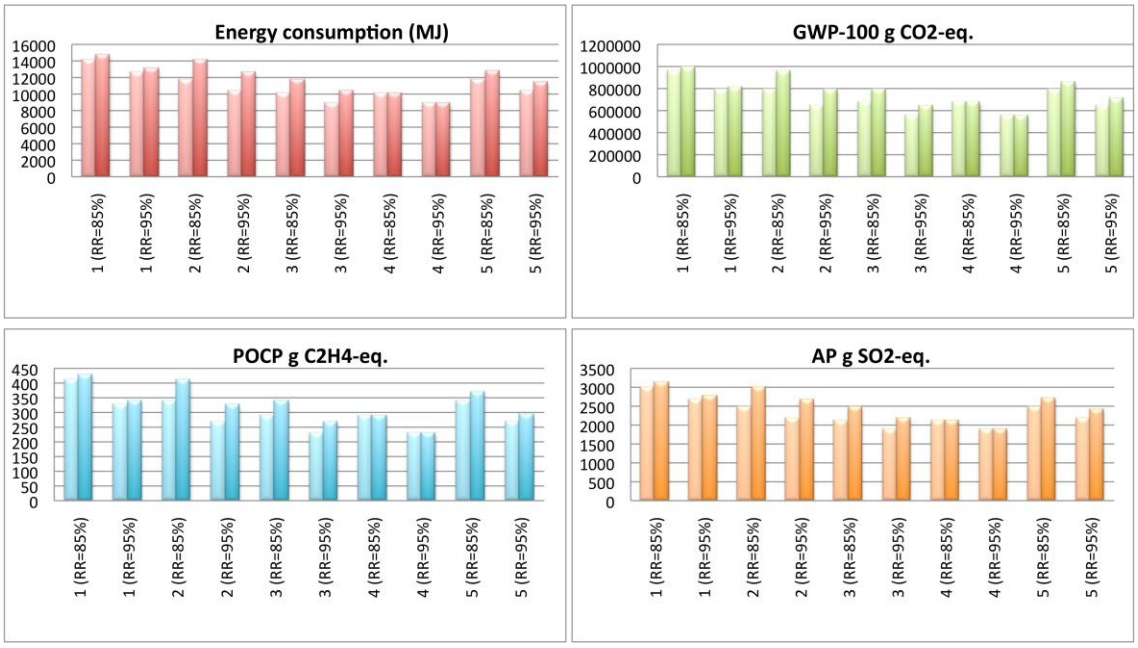

Figure 4. E, GWP, POCP and AP. Profile column case studies of Table 1, steel S355 and S460 (lighter bar), RR=85% and 95%.

This analysis is made in order to be able to comment on the reliability of the results, especially, when several options were available during the study. Nevertheless no statistical distribution was chosen for the variables, the conclusions of the sensitivity analysis should thus be considered with care. The uncertainty of several sources was considered as follows:

(1) As a key step in LCIA, during the characterization procedure, science-based conversion factors are used. However, the environmental experts often encounter problems with the way LCIA deals with specific issues, such as the non-linear dose response relationships, dynamic variations of concentration of pollutants, regional and local conditions (Heijungs & Koning 2004), making uncertain the characterization factors. When using two sources, (CML 2002) and (IEC 2008) respectively, it was found that the GWP remains stable, while the AP and POCP impacts decrease when employing the factors from (CML 2002). The relative difference in the results for the AP can attains 15%.

(2) The product manufacture is regional distinctive, thus the LCI data, if not Europe or World average, are influenced by the region. Several sources of data from different regions were considered for the LCI of concrete: Australia, Italy, Serbia and Sweden (Simapro 1998, Buzzi Unicem 2007, Marinkoviæ 2008, Stripple 2001). They allow an average to be calculated as well as a minimum and a maximum on the basis of a reference that is chosen to be the Swedish data herein. For energy consumption, it was stated that the output can range between -6% to +55% while for CO_2 emissions, the range lays between -35% to +47% (see the thin vertical lines indicating this variability in Figure 3). For steel, some other environmental product declarations (Contiga AS 2007, IBU 2010) were also compared to the IISI data (date of issue 2005) and it was found that the impacts were generally very similar or even decreased.

(3) The LCI data for steel with 60%, 85% and 95% of recovery rate (RR) are available from the IISI LCI database. Thus, it is possible to assess whether the RR influences a lot the impacts. In was stated that, when considering steel columns, the Energy consumption and GWP could be respectively decreased by more than 10 and 20% if RR increases from 85% to 95% (see Figure 4 for profile columns for instance). Besides, for concrete columns, if the reinforcement is recaptured to 95% instead of 60%, E and GWP vary substantially (up to 30%). For composite columns (hollow steel tube filled with concrete), this gain reaches 15%.

4 MAIN CONCLUSIONS

In this study, four impacts corresponding to the cradle-to-gate assessment of different types of columns are calculated: Demand in primary energy (E), CO_2 emission equivalent (GWP), Photochemical oxidation (POCP) and Terrestrial Acidification (AP), shown in Figure 2, Figure 3 and Figure 4. The analysis allows the least burdensome option to be underlined, presently high strength steel column. The most important conclusion of the following brief sensitivity analysis is that the variability in the data for concrete is of high influence on the outcomes of the impacts assessment.

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Environmental Performance of Contemporary Multi-storey Timber Buildings

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ABSTRACT: This study is intended to deal with the ecological efficiency of contemporary multi-storey wooden constructions, which are located around Germany and Switzerland.
The targeted objects consist of practical and realised timber buildings, including residential houses, offices and schools. These inspected buildings are classified into three categories according to their structural systems. As the classification, the multi-storey wooden buildings comprise board-to-board system, wooden frame system and compound system.
The environmental performance of each building is estimated by means of life cycle assessment. It reveals the resources inputs and environmental outputs caused during early life cycle.
The appraisal consequence demonstrates that which type of timber construction may be relatively eco-friendly in terms of energy consumption and global warming potential. Meanwhile, the life cycle inspection helps discover the critical points about impact generation during constructing phase. The conclusion provides architects and engineers a guidance to adopt sustainable wooden structures and even eco-friendly building processes.

1 INTRODUCTION

Environmental issue has arisen as an immensely concerned subject in the latest decades. Diverse sectors develop in a sustainable way and attempt to provide eco-friendly products and services. In this trend, minimizing energy consumption and global warming potential is the most intensively pursued target.

Building industry, as a sector consuming plenty of energy and generating bulk greenhouse gases, accounts for enormous environmental burden among human society. Numerous efforts are dedicated into enhancing the ecological efficiency of buildings. This may reduce the environmental impacts significantly and lead to a more eco-friendly human environment. In order to do so, the main task is to improve the building industry in ways of:

- choosing adaptive building materials;
- adopting eco-efficient structural systems;
- refining critical constructing processes.

Wood is considered as a sustainable building material. Compared to concrete, ceramic and steel, wood exhibits better environmental performance in terms of energy consumption and global warming potential. Due to the manufacturing process, concrete and steel are relatively energy intensive and may inevitably emit a huge amount of CO2. In the other hand, wood is a carbon-free material in a scope of life cycle, since the forest plays a role of carbon fixing. The more the wooden materials are adopted, the more significantly the forest's function may be highlighted.

In practice, however, wood may consist of certain limits for application, especially in huge dimension, mega structure and extreme height.

In recent decades, engineered wood has been developing considerably. Glue laminated timber, stack-of-planks and profiled wood are the influential products and result in extensive application of wood. These make huge dimension and mega structure possible. Among the contemporary developments, multi-storey timber construction is a notable consequence.

Since 2006, some remarkable multi-storey wooden houses have been established, which demonstrate the progress and possibility of engineered wooden products. In Steinhausen, Switzerland, a six-storey wooden house was carried out in 2006. In 2008 and 2009, eight-storey and seven-storey timber house were established in Sweden and Germany, respectively. Recently, the tallest wooden house, which is nine-storey high, was completed around the city center of London in UK.

Figure 1. 6-storey timber house in Steinhausen.

Figure 2. 7-storey housing in Berlin.

Those building projects prove that wood is feasible for high-rise buildings and this constructions are adaptive in urban context.

Although the application of wood is a trend toward sustainable prospect, the quantitative exploration and evidence remain scarce. It is still hard to determine how ecologically efficient the wooden constructions are. Few researches have carried out certain quantitative analyses to evaluate the sustainability of timber structures. With regard to prerequisite and system boundary, however, these studies are based on artificially assumed models and restrict to their presumption. Even some researches dealt with practical building projects, the inspected samples are not sufficient enough. Thus, the consequence may not be compatible for wide range of wooden constructions.

In order to complement the deficiency of previous researches, this study is intended to investigate the realized multi-storey timber buildings around Germany and Switzerland. By means of life cycle assessment, this study evaluates the sustainability of the chosen building projects. The focus of the assessment is mainly on the harvesting and manufacturing phases. By doing so, the consequence reveals which structural type and which kind of wooden products may cause less environmental impact in the early life cycle.

2 2. METHODOLOGY

The research process and basic framework is illustrated in Figure 3.

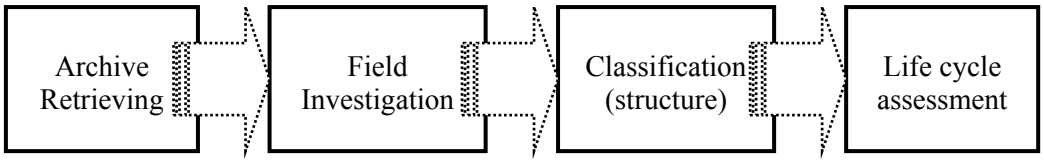


Figure 3. Research process and basic framework.

2.1 *Archive Retrieving*

In order to carry out LCA based on practical timber constructions, the first task is to find out the adaptive building projects. Retrieving archives, such as magazines, research papers and technical reports, is an efficient access. Some literatures introduce the contemporary multi-storey wooden buildings, which are:

1. located around Germany and Switzerland;
2. completed in the latest one or two decades;
3. considered as typical building projects.

After the collection of samples, however, the questions about which building is feasible arise. It is controversial to define the real timber structures, since many building complexes are composed of various materials. Sometimes, it is also questionable that if the wooden elements play the structural role in one house. To determine and find out the real wooden constructions, it is necessary to set up some principles to sieve.

In this study, the proportion of structural wood is the criteria to select compatible building samples. Firstly, the entire volume of structural wood, so-called V, is calculated. Secondly, the floor area of using space, except for the basement, is figured out and set as A. The unit of V is cubic meter, while the A is shown as square meter. When the V/A ratio is higher than 0.1, this building is considered as a timber house and chosen for the analyses hereafter.

2.2 *Field Investigation & Classification*

The field investigation plus design drawing helps verify the structural system of each wooden building. These inspections:

- confirm that a building is supported by wooden structural components, and
- define to which structural type a building belongs.

2.3 *Life Cycle Assessment*

LCA is a reliable and persuasive method to evaluate the environmental performance of a product or service in a universal way. By defining each process in the life cycle, this method helps explore the resource depletion and environmental impact based on the input-output inventory. Depending on the concept, this paper is to estimate the sustainability of multi-storey wooden houses with the support of SimaPro developed by PRé Consultants. With enormous database, SimaPro helps evaluate the environmental performance of the assigned assemblies. By inserting the amount of involved materials and processes, the program calculates the environmental outcome.

Within this study, the appraisal takes only the structural wooden elements into account. The structural wood consists of three sorts: sawn wood, stack-of-plank and glue laminated timber. The amount of diverse wooden components is calculated and inserted individually and then integrated comprehensively. The scope of LCA is thus focused on the early phases in the life cycle, i.e. harvesting and manufacturing processes. The using phase and the disposal in the end are simply eliminated in order to infer a convergent consequence.

3 BUILDING SAMPLES

The 15 houses listed below are the appropriate building projects for subsequent analyses of eco-efficiency. The detail information, such as buildings' function, number of the storey and V/A ratio, is plotted in table 1 and 2. For convenience, this paper may simply refer to the serial numbers, B01 to B15 in the first column of table 1, for each building hereinafter.

Table 1. Basic information of all building projects

Building	Location		Completed	Function	Storey
B01	Arlesheim,	Switzerland	1998~1999	housing	2+1
B02	Berlin,	Germany	2009	housing	7
B03	Lausanne,	Switzerland	2003~2004	housing	4
B04	Schaanwald,	Liechtenstein	1996	housing	4
B05	Steinhausen,	Switzerland	2005~2006	housing	6
B06	Lugano,	Switzerland	2007~2008	housing	5
B07	Coldrerio,	Switzerland	2005~2006	office	3
B08	Zollikofen,	Switzerland	2007	office	3
B09	Koeniz,	Switzerland	2004~2005	housing	3+1
B10	Givisiez,	Switzerland	2006~2007	office	3
B11	Bulle,	Switzerland	2007	mix	4
B12	Wil,	Switzerland	2001~2004	education	4~2
B13	Ossingen,	Switzerland	2005~2006	Education	3
B14	Kemptthal,	Switzerland	2006~2007	office	3
B15	Grosswil,	Switzerland	2006~2007	housing	3

Table 2. V/A ratio of each building project

Building	Function	Volume of Wood	Floor Area	V/A Ratio
B01	housing	2,830.00 M^3	9,540.00 M^2	0.30
B02	housing	225.46 M^3	1083.60 M^2	0.21
B03	housing	6,273.00 M^3	8,513.58 M^2	0.74
B04	housing	348.40 M^3	1,609.91 M^2	0.22
B05	housing	184.00 M^3	1,647.00 M^2	0.11
B06	housing	162.80 M^3	600.00 M^2	0.27
B07	office	1,180.00 M^3	9,332.32 M^2	0.13
B08	office	285.00 M^3	1,842.00 M^2	0.15
B09	housing	242.00 M^3	1,764.00 M^2	0.14
B10	office	134.20 M^3	1,299.00 M^2	0.10
B11	mix	278.00 M^3	1,322.55 M^2	0.21
B12	education	2,1880.00 M^3	14,743.00 M^2	0.15
B13	education	250.00 M^3	2,062.02 M^2	0.12
B14	office	251.40 M^3	1,454.00 M^2	0.17
B15	housing	248.00 M^3	2,316.26 M^2	0.11

As instructed in previous paragraphs, the volume of wood refers only to the structural wooden elements. All structural woods are summed into one value and listed in the third column of table 2. In the sequential calculation, however, the structural wood is further classified as sawn wood, stack-of-plank and glue laminated timber etc. These wooden products are the most common and general categories in timber constructions. This individual calculation and comprehensive summation lead to a precise appraisal of the environmental impact caused by each building during manufacturing phase, since different wooden products consist of distinct embodied energy and environmental output.

Figure 4. B01 - Settlement in Arlesheim.

Figure 5. B03 - Student's dormitory of EPFL.

Figure 6. B04 - Housing in Schaanwald.

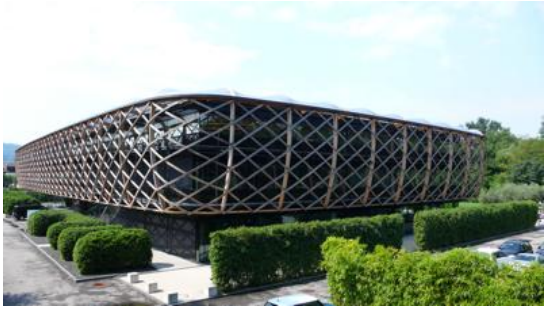


Figure 7. B07 - Office building of Hugo Boss.

Figure 8. B08 - Administration office in Zollikofen.

Figure 9. B09 - Housing in Koeniz.

Figure 10. B10 - Green office in Givisiez.

Figure 11. B11 - Multi-function building in Bulle.

Figure 12. B12 - State school in Wil.

Figure 13. B13 - Elementary school in Ossingen.

Figure 14. B14 - Support office in Kemptthal.

Figure 15. B15 - Housing in Grosswil.

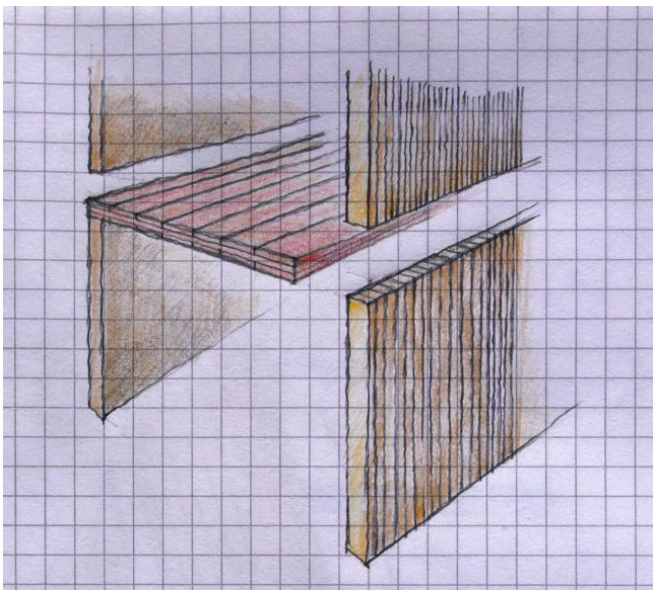
4 RESULT

As classification, the inspected multi-storey wooden buildings comprise three structural types:

1. board to board system
2. wooden frame
3. compound system.

The board-to-board system is composed of certain structural wooden elements in forms of panels and plates. The vertical boards support the construction and resist to the lateral force, while the horizontal boards offer not only spaces for utilization but also rigidity for horizontal twist. Among the investigated building projects, this kind of structural system accounts for the majority of timber buildings. The profile and further instruction are seen in table 3.

Table 3. Structural system - board-to-board

	Board to Board
	
vertical element:	wooden board[1)] / RC board[2)]
horizontal element:	wooden board[3)] / plus rigidity[4)]
comments: 1)	stack-of-plank, glue laminated timber
2)	most likely as staircases
3)	stack-of-plank, glue laminated timber, shaped wood
4)	cement board, in-situ concrete
building projects:	totally 7 B01, B04, B05, B06 B09, B11, B15

Wooden frame is another typical form of multi-storey wooden structures. Although accounting for a less proportion of modern timber buildings, this structure is feasible for extreme height and huge volume, such as B02 and B12, respectively.

Wooden frame is composed of vertical and horizontal posts which afford the normal and transverse loading. With regard to horizontal impact upon the entire structure, wooden frame needs the joints to provide certain rigidity. These connections possess steel fasteners to make them at least semi-rigid or almost rigid. In practice, these connections are carried out in various ways. The structural profile and detail information about wooden frame are seen in table 4.

The compound structure systems consist of not only wood but also alternative materials adopted for structural elements. Steel column is a typical element in compound structures. In B07 and B14, steel columns play an important role as load-bearing component. In the other hand, RC and wooden walls support the structure simultaneously in B13. The general structural profile and further information are plotted in table 5.

No matter which kind of structure a building is, staircases made of reinforced concrete are basic constructions within the whole house. With concrete staircases, all timber building may be considered as compound structures. For classification, this concrete part is not taken into account.

Table 4. Structural system - wooden frame

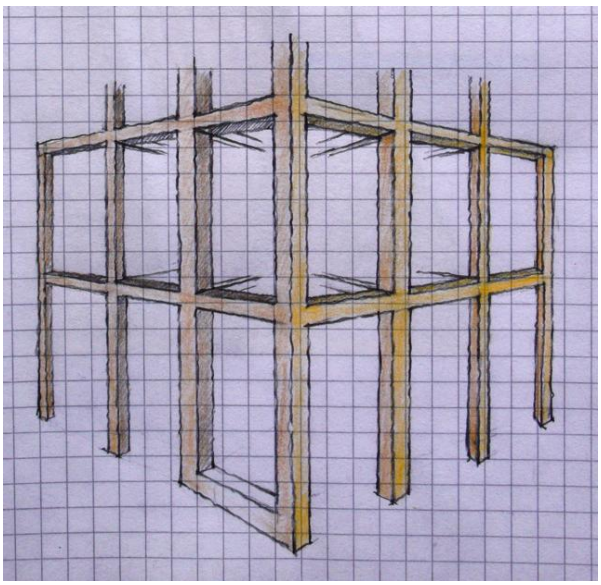
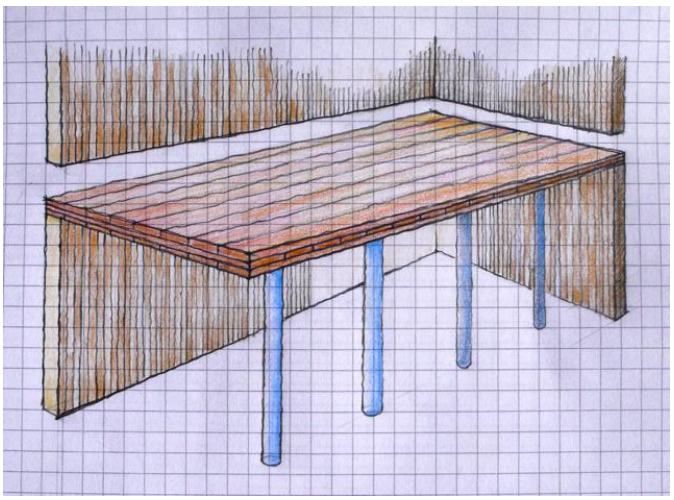
	Wooden Frame
	
vertical element:	wooden post[1)] / plus rigidity[2)]
horizontal element:	wooden post[1)] / plus rigidity[2)]
comments: 1)	stack-of-plank, glue laminated timber, sawn wood
2)	complemented by wooden panels or RC plates
building projects:	totally 3 B02, B10, B12

Table 5. Structural system - compound

Compound



vertical element:	wooden board[1)] / wooden post[2)] / steel column
horizontal element:	wooden board[1)] / plus rigidity[3)]
comments: 1)	stack-of-plank, glue laminated timber, sawn wood
2)	glue laminated timber, sawn wood
3)	cement board, in-situ concrete
building projects:	totally 5 B03, B07, B08, B13, B14

Based on the SimaPro, the estimation of ecological efficiency of the selected building projects is carried out. In this study, the most concerned impact category is the global warming potential. According to the picked analysis method in SimaPro, GWP100 is adopted as the benchmark. As general researches, the CO2-equivalent is chosen as the indicator for global warming potential. For comparison, the CO2-equivalent per square meter is the functional unit and criteria to represent the sustainability of each single building. The appraisal consequence is listed in table 6 and the CO2-equivalent/M2 is shown in the fifth column.

Table 6. GWP 100 of each building project

Building	Structure	CO_2 equivalent	Floor Area	Performance
B01	b-to-b	-1,836,785.10 kg	9,540.00 M^2	-192.54 kg/M^2
B02	frame	-146,332.71 kg	1083.60 M^2	-135.04 kg/M^2
B03	compound	-4,042,152.45 kg	8,513.58 M^2	-474.79 kg/M^2
B04	b-to-b	-226,125.77 kg	1,609.91 M^2	-140.46 kg/M^2
B05	b-to-b	-110,454.41 kg	1,647.00 M^2	-67.06 kg/M^2
B06	b-to-b	-110,577.93 kg	600.00 M^2	-184.30 kg/M^2
B07	compound	-749,665.80 kg	9,332.32 M^2	-80.33 kg/M^2
B08	compound	-182,216.02 kg	1,842.00 M^2	-98.92 kg/M^2
B09	b-to-b	-159,505.53 kg	1,764.00 M^2	-90.42 kg/M^2
B10	frame	-93,792.33 kg	1,299.00 M^2	-72.20 kg/M^2
B11	b-to-b	-191,398.38 kg	1,322.55 M^2	-143.63 kg/M^2
B12	frame	-1,371,033.15 kg	14,743.00 M^2	-93.00 kg/M^2
B13	compound	-161,695.64 kg	2,062.02 M^2	-78.41 kg/M^2
B14	compound	-160,551.52 kg	1,454.00 M^2	-110.42 kg/M^2
B15	b-to-b	-168,548.65 kg	2,316.26 M^2	-72.77 kg/M^2

Not as alternative building materials, like concrete and steel, the wooden houses possess a negative GWP effect. In fact, it is a positive influence upon the environment, since the wood

absorbs the carbon dioxide and fixes the carbon in forest. Then, it is possible to calculate the average value of CO2 equivalent / M2 of the three types of structures. As far as the compound structure is concerned, the consequence of B03 is eliminated, since it exhibits an extraordinary outcome. Therefore, the mean value of the compound system represents the performance of 4 buildings. The calculation results are shown in table 7.

Table 7. Average performance of each structural type

Structure	CO_2 equivalent per M^2
Board to Board	-99.81 kg / M^2
Wooden Frame	-100.08 kg / M^2
Compound	-92.02 kg / M^2

Among the three structure systems, the wooden frame exhibits the best environmental performance in terms of CO2 equivalent per M2, although the deviation between wooden frame and board-to-board system is absolutely subtle. In contrast, the compound wooden building is relatively worse. Furthermore, the compound structure inevitably consists of other building materials. Thus, the environmental performance of this structure may become more sever when other materials are taken into account.

5 CONCLUSION

The contemporary multi-storey timber buildings comprise three structural types, i.e. board-to-board complex, wooden frame and compound system. An interested designer is able to construct a wooden house in various forms

With regard to GWP100, the board-to-board system and wooden frame are almost equivalently sustainable, although tiny discrepancy exists between them. By adopting wooden buildings, architects and engineers may develop our surroundings in an ecological way. It is not hard to imagine that more consumption of other building materials leads to higher environmental burden. Using wood for structures is an eco-friendly way to conform human environment.

With regard to the presumption, however, this appraisal is probably too simple. Firstly, the utilized structural wooden products may be complicated and request more deliberate setups. Some building projects may apply specific wooden elements and constructing methods. Secondly, the amount of building projects remains insufficient for further and wider application. Third, the system boundary has to be precisely defined while the LCA is performed. For example, choosing wood in SimaPro has to be more sophisticated for practical situation. Further studies and explorations are necessary in order to get aware of the sustainability of multi-storey timber buildings

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Comparative Study of the Life Cycle Profile of Residential Masonry and Steel Framed Buildings in Belgium

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ABSTRACT: This research is based on a dissertation by Coelho and Andrade (2010) in which a modular building is studied in two different locations (Coimbra and Lulea) under an environmental point of view. After studying several scenarios for both case studies and comparing the CO_2 emission, it was concluded that: 1) The energy consumption is the major source of impacts; 2) The Product Stage is the most harmful period during the building's life cycle for Lulea case study and for Coimbra case, the Use Stage (Energy) is the most harmful; 3) Despite Lulea energy consumption being higher, the CO_2 emissions are lower than for Coimbra due to the better efficiency of the energy production. Starting from these premises, the goal was to ascertain whether these conclusions could be drawn for traditional constructions in Belgium. This study presents the life cycle assessment (LCA) of two buildings similar in dimensions, orientations, climate and purpose but designed for Belgium using two different construction systems: traditional masonry made of concrete blocks, insulation and ceramic bricks and light gauge steel framing as the load carrying component. The comparison between the LCA focuses on the CO_2 emission equivalent for each building's life cycle. Two tools used for the assessment are presented: the software Equer and an excel file created by prof. Mauritz Glaumann (University of Gävle/KTH, Sweden). The first one employs the 1996 EcoInvent database and provides results separated by stage of life. The second tool is a more basic one which allows access to all cell content. In this case, the database comes from different sources (EcoInvent, EcoEffect, SBI, worldsteel, IVL). The house design, which is based on typical Belgian homes, has a total area of 250m² and is composed of 2 floors, an attic and a basement. Both the masonry and the steel framed house have the same basic layout. After a short sensitivity analysis to chosen parameters, the results of the assessment are compared against each other and the conclusions are presented.

1 INTRODUCTION

The sustainability factor presents an ever-growing concern worldwide. In the building sector, this concern is translated in the search for new materials and methods providing better efficiency, if not to build a zero energy house, at least to diminish its energy needs and, therefore, contribute to a greener solution. From the perspective of sustainable development, performance of buildings should be analyzed on their entire life cycle, taking into account the design, construction, in-use, renovation and deconstruction stages. A Life Cycle Assessment (LCA) is the investigation and evaluation of environmental impacts of a given product, system or service, over its entire life cycle. It quantifies the resources use and environmental emissions associated with the system evaluated (ISO 14040 & 14044 2006).

This research is based on a dissertation (Garcia de Campos Coelho 2010) in which a modular building is studied in two different locations (Coimbra and Lulea) under the environmental point of view using the LCA method. The modular building is destined to accommodate 51 students in 5 floors in a total surface of approximately 4000m². The main conclusions of this study were that: (1) the energy consumption is the major source of impacts; (2) the Product Stage is

the most harmful period during the building's life cycle for Lulea case study contrarily to Coimbra case for which it is the Use Stage; (3) despite Lulea energy consumption being higher, the CO_2 emissions are lower than for Coimbra thanks to the better environmental profile of the energy production (energy mix).

Starting from these premises, the goal of this study is to ascertain whether these conclusions (especially the first two ones) could be drawn when comparing traditional detached houses in Belgium, similar in dimensions, orientations, climate and purpose but designed using different construction systems: one using traditional masonry made of concrete blocks, insulation and ceramic bricks and one using light gauge steel framing as the load carrying component.

The life cycle assessment (LCA) of both buildings is first carried. The comparison between the LCA focuses on the CO_2 emission equivalent for each case study. The CO_2 emission equivalent was chosen as the comparison unit because, besides being the major responsible for global warming, it is one of the most evaluated, documented and determined parameter when it comes to environmental assessments. A short sensitivity analysis is also performed in order to evaluate whether the conclusions of the comparative analysis could be drawn with a relatively high degree of certainty.

2 FUNCTIONAL UNIT

For the purpose of the study, a house was designed based on a typical detached Belgian house. Typical Belgian dwelling has more than one floor, plus a basement and an attic. Generally, this house accommodates a garage big enough for one car, one kitchen, one living room/dining room, one bathroom, two WCs and two to four bedrooms, depending on the size of the house. In some cases the insulated attic is later used as a room or a studio, while the basement is used as a laundry room, a storeroom or to shelter a central heating system.

The designed house is a two floors dwelling with two bedrooms, one bathroom, one kitchen, one living room, one WC and a one car garage. The attic has enough space to accommodate two more bedrooms and the basement is big enough to fit the central heating system and a laundry room. In all, the house surface is about 250m² in which approximately 75% is heated.

The description above is valid for both steel and masonry houses. Even though the construction systems are very different, efforts were put to keep both designs as similar as possible. Therefore, both houses have very similar dimensions and differ only in order to better accommodate the components of each construction system. The steel frame was based on the European Light Steel Construction Association recommendations and (Scharff 1996) while the masonry building was based on Belgian traditional common rules of construction. The design of the house leads to a quantity of steel (required to transfer all the loads to the ground) of 60kg/m^2. Figure 1 shows the architectural plan for the two main floors of the steel house. It is worth pointing that the influence of the quantity of steel used is assessed in the short sensitivity analysis that will follow.

Figure 2 shows generic cuts of both construction systems (only the external walls) illustrating their main differences. The thicknesses of the wall are not included in these schemes but Table 1 indicates the composition of the envelope for the steel framed house and the masonry house and provides the U-value for each wall. The thicknesses of Table 1 are to be understood with care seen that, for steel or wood purlins, the quantity of material is somehow transformed into an equivalent thickness during the manual calculations. Thus, the number of purlins per meter must be mentioned during the evaluation. If we consider a lipped channel profile of 260mm height which is quite high, the total thickness of the walls are 32cm for the steel house and 39cm for the masonry house, while the roof is 29cm for the steel house and 30 cm for the masonry house. The dimensions are thus very similar although those could be somewhat reduced (lets say optimized) by considering sandwich panels in the roof and less high profile in the walls, but this is not the scope of this research.

For the assessment, both houses were considered to have a single reinforced concrete foundation with thermal insulation, double glazed PVC windows and wooden insulated doors. The necessary moisture and air barrier are not indicated in the present research nor taken into account in the LCA.

Table 1. Composition of the envelope for the steel framed house and the masonry house.

	Steel house (SH)		Masonry house (MH)	
	Material	Thickness (mm)		Thickness (mm)
Basement slab	Reinforced concrete	120	Idem	
(U_{SH}=0,33W/m^{2}K)	Insulation	100		
(U_{MH}=0,33W/m^{2}K)	Reinforced concrete	50		
	Wood particle board	18		
Exterior wall	PVC siding	10	Clinker masonry	90
(U_{SH}=0,19W/m^{2}K)	Wood particle board	18	Insulation	100
(U_{MH}=0,20W/m^{2}K)	Insulation	160	Concrete block	190
	Steel Studs	260	Plaster	15
	Wood laths	19		
	Gypsum board	18		
Roof	Steel roof tiles	1,25	Ceramic roof tiles	18
(U_{SH}=0,18W/m^{2}K)	Insulation	200	Wood particle board	18
(U_{MH}=0,16W/m^{2}K)	Steel Studs	260	Insulation	160
	Wood laths	19	Wood purlins	230
	Gypsum board	18	Wood laths	19
			Gypsum board	18

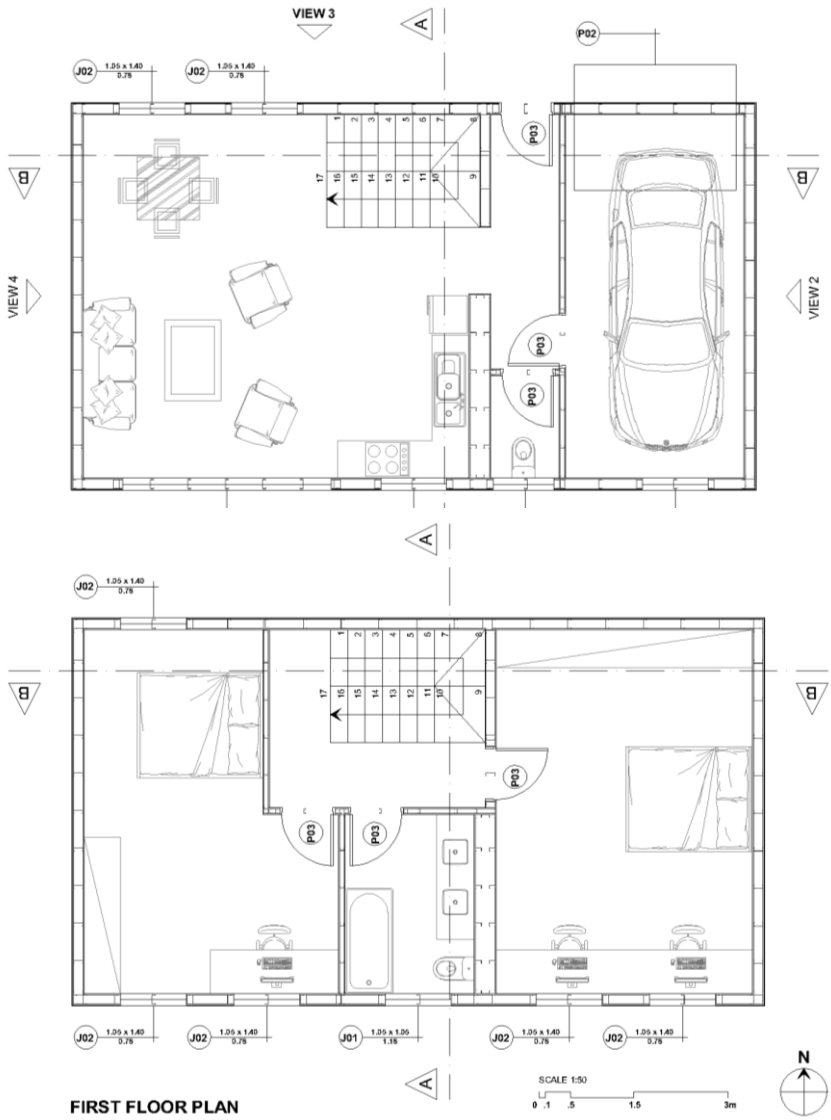

Figure 1. Ground and first floor architectural plans of the steel framed house.

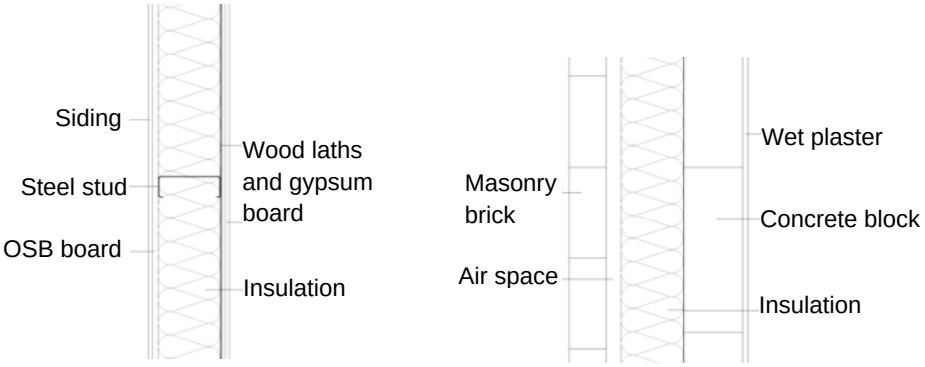

Figure 2. Generic cuts from the masonry house and the steel framed house exterior walls.

3 CALCULATION TOOLS

3.1 *Equer*

Equer is a life cycle simulation tool developed by Izuba Energies that is based upon a building model structured in objects. This tool is connected to the thermal simulation tool Pleiades+Comfie. It performs a dynamic simulation of the building thermal performances combined with a life cycle analysis. It considers the functional unit as the whole building over a certain duration, using for its calculations the EcoInvent database (EcoInvent 1996). This tool provides the user with the results of the whole assessment and also at four different stages of life: construction, use, renovation and demolition. The output from the software is also given in an ecoprofile including various indicators such as primary energy consumption, water consumption, global warming potential (GWP100), etc.

3.2 *Manual calculations*

The assessment was also made using manual calculations on the basis of an excel file developed by Prof. Mauritz Glaumann from the University of Gävle/KTH. This initial tool that assessed two life cycle stages (construction and use stage) was slightly modified: (1) the insulation resistance used for calculating the thermal transmittance (W/m^{2}K) was verified against Belgian rockwool producers; (2) the energy demand for space heating evaluation, previously based on a average temperature all over the year, was modified to take into account a scenario in which a) each month is characterized by a minimum and a maximum temperature lasting twelve hours a day, b) this temperature is decreased by an internal heat gain depending on the month and the time of the day, c) the required indoor temperature is considered different during the night and the day and during business days, only four hours of heating are demanded, after this, the evening is supposed to start, and d) if negative, the energy demand was not considered in the total required energy. The energy losses (kWh/yr) through the building envelope is finally provided in Equation 1 below:

$$\begin{aligned} E = & \sum_i \left\lfloor U_i A_i \right\rfloor \sum_{month} \Big[\left(\Delta T_{conf-day}.h_b.j_b\right) + \left(\Delta T_{conf-night}.(12-h_b).j_b\right) \\ & + \left(\Delta T_{conf-day}.12.(j_{month}-j_b)\right) + \left(\Delta T_{conf-night}.12.j_{month}\right) \Big] \end{aligned} \quad (1)$$

where U_i = heat transfer coefficient of wall *i* (W/m^{2}K); A_i = surface of wall *I* (m^2); $\Delta T_{conf-day/night}$ = demanded temperature during the day/night (K); h_b = number of hours of occupation during business days (h) and $j_{b/month}$ = number of business/month days.

The calculation of the energy demand for ventilation and hot water consumption is taken from (Garcia de Campos Coelho 2010). The envelope thermal properties and energy consumption of the house is verified against the Belgian regulations (PEB 2010).

Multiple databases are used in the excel file (EcoInvent, EcoEffect, SBI, Worldsteel, IVL) for the calculation of the materials embodied emissions. The impacts generated by the energy mix, however, were deduced from Equer database and then assumed the same in the excel file. The

excel file enables the user to calculate the materials embodied energy and CO_2 emissions, the yearly energy use and the related CO_2 emissions.

3.3 *System boundaries*

Herein, the results of the construction and use stages are analyzed. The system boundaries considered were: material use (cradle-to-gate analysis); energy consumption, in which is considered the energy mix for base production as well as for water and central heating (transmission and ventilation losses, human heat production and solar gains are included); water use (hot and cold water used in the building); electricity use (building and user electricity); production of waste (only for Equer), in which is defined how much waste is generated by each inhabitant of the house with a recycling rate (the percentage of the waste that is recycled).

3.4 *Working hypotheses*

Both houses were supposed to be built in Brussels. This city was chosen because, besides being the Belgian capital, there are plenty of useful data to conduct the research. According to Meteonorm software, the temperature in this region varies from -8°C in the winter to 25°C in the summer, with an average temperature of 10,7°C. The monthly temperatures were used in this analysis for calculating the thermal losses.

As for the recycling rate of the waste, the values adopted were of 85% for glass products and 55% for paper. Additionally, the incineration rate equals 40% and 85% of the incineration energy is recovered.

The global efficiency of the water system attains 80%.

An important input in this study was the energy mix, which in this case was gathered from official Walloon statistics. It is composed of 75% of nuclear energy, 15% of natural gas, 6% from hydroelectric powerplant and 4% from coal (EuroStats 2008). In the assessment, 9% of energy grid loss was also considered.

Finally, the water and central heating systems were supposed to be fueled with natural gas, since this solution is very popular in Belgium, according to the background research.

In this research, the presence of local heat/electricity production or energy saving equipment is not included.

3.5 *Limitations of the analyses*

To the best knowledge of the author, the tools used in this study are based on some assumptions such as:

- Concerning Equer: The material database library cannot be changed; the same is true for the energy mix, it is only possible to define the energy mix using the types of production available within the software; it is not possible to make the calculations without some assessments regarding the transport of material and domestic waste which might complicate a comparative analysis;
- Concerning the manual calculations: the thermal behavior is assessed on the basis of the U-values (W/m²K) for the walls, roofs and floors; for the CO_2 emissions, only cradle-to-gate data are considered.

4 RESULTS

The Equer software presented significantly unrealistic results for which no plausible explanation was found yet. For instance, the materials embodied CO_2 emissions calculated by the software for the masonry house was found to be unreasonable, reaching 300% of the embodied CO_2 emissions obtained by manual calculations. An analysis is currently carried on in order to find the reason of these discrepancies, a human error of use is expected but, it is already important to underline that this tool is quite difficult to use especially when it appears that the user must reach hidden values in order to understand the results.

Comparing the results from each tool to reference values found in the literature (Trocmé & Peuportier 2008) it was concluded that the manual calculations were in the expected range of results. The next paragraphs will thus focus on the manual calculations.

As stated before, the excel file is a basic tool enabling the user to calculate the materials embodied CO_2 emissions, the yearly energy use and the related CO_2 emissions. Figure 3 shows

these results for the masonry house while, in Table 2, a comparison between both houses is provided. As both case studies were analyzed in the same conditions (the scenarios created and working hypotheses are identical), the differences between the results can be attributed to the difference in the construction systems and not to other factors.

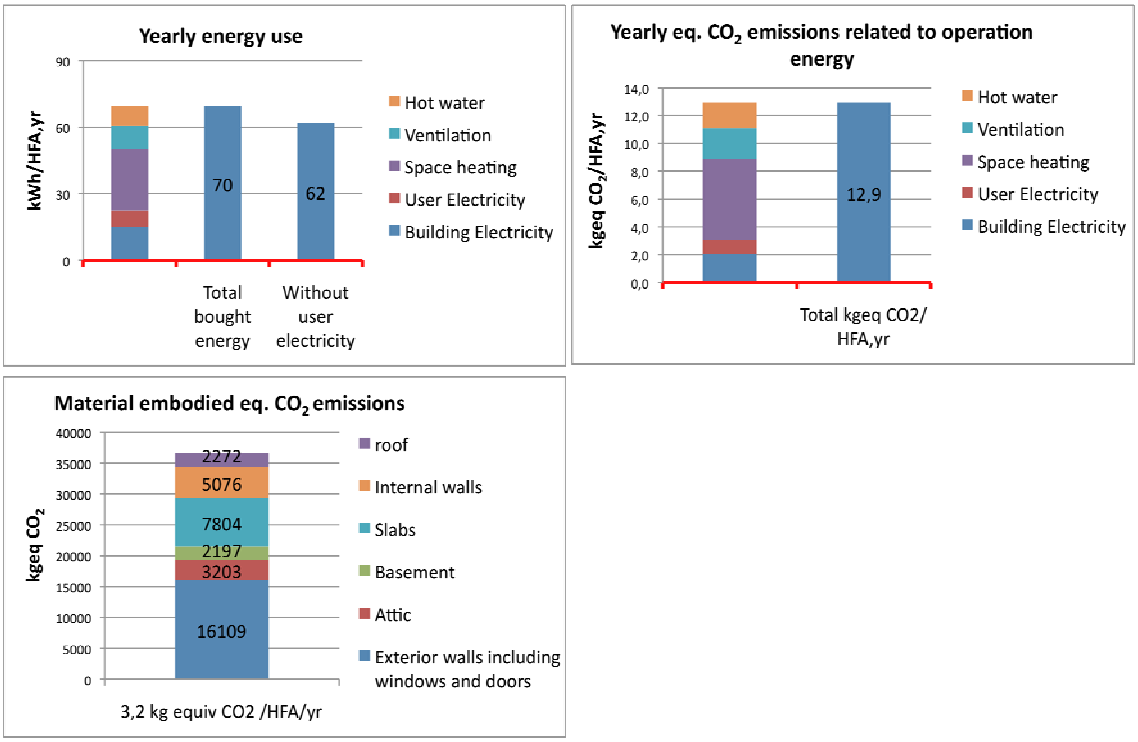

Figure 3. Results of the manual calculations – The Belgian masonry house. (HFA=heated floor area).

Table 2. Comparison between the steel framed house and the masonry house.

		Masonry house	Steel house
kg eq. CO_2 / HFA	Materials embodied eq. CO_2 emissions	162	142
kg eq. CO_2 / HFA.yr	Yearly eq. CO_2 emissions for use phase	12,9	13,1
	Total yearly energy use	70	
	Yearly energy use without user electricity	62	
kWh/HFA.yr	Space heating	27,7	28
	Ventilation	10,4	10,3
	Hot water	8,9	9
	Human heat production	-4,2	-4,5
	Building electricity	15	15
	User electricity	7,5	7,7

The only constraint was that the architect must respect the Belgian regulations for new buildings and reach the demanded minimum bought energy. The main conclusion is that, on the basis of the materials embodied CO_2 emissions presented in Table 2, it is possible to reach the legislation requirements with less materials emissions for the steel framed house. It is worth pointing that the HFA is slightly different for the two houses.

5 SHORT SENSITIVITY ANALYSIS

In order to be able to draw general conclusions, it is first necessary to conduct a sensitivity analysis of the results to chosen parameters to truly understand their influence on the final values. Herein, the goal is to compare a steel-framed house with a masonry house. The following parameters (inputs) are thus not included in the sensitivity analysis seen the fact that they don't change the conclusion of the comparative analysis, although having (for some of them) a strong

influence on the final results: (1) the energy mix: natural gas was used for heating while Belgian electricity mix was used for the electricity, this choice has of course a strong influence on the yearly eq. CO_2 emissions for use phase; (2) the scenario: naturally, if the occupation scenario or demanded temperature are modified for both cases, the indicators of Table 2 change consequently; (3) the house configuration, the percentage of glazed façades, the house plan, the envelopes composition are of course of great influence on the final results; (4) the presence of local heat/electricity production or energy saving equipment was not investigated in the present paper. In further research, the influence of these parameters will be studied for the same house but located in different regions of the globe.

Now, the influence of two important parameters was assessed since they might have an influence on the main conclusion stated before: (1) The database for steel embodied emissions, initially taken as EcoInvent, was replaced by the Worldsteel database (IISI 2002) taking into account the recycling of steel at the end of its life. This was done to verify if the database choice could have a meaningful influence on the results. It could be pointed that the new database had a positive influence on the embodied CO_2 emissions of the steel framed house. The results consequently lead to the same conclusions; (2) It was found that the quantity of steel used per HFA, that was initially evaluated as 60 kg/m^2, can be increased to 30% of its value, and that in order to reach the embodied CO_2 emissions of the masonry house. It is thus concluded that the design of the house presented in this analysis, although simplified, does not affect the final conclusion of the paper.

6 SECOND CASE STUDY

As a second step, the same constraint was still respected (the Belgian regulations) but, for the steel frame house, we assumed more insulation in the walls such that the materials embodied CO_2 emissions almost reach the masonry house ones (see Figure 4), and that in order to decrease the energy consumption of the steel framed house.

Doing this, it can be concluded that ifthe roof and exterior walls can reach a lower U-value, the heat losses are even more decreased for the steel framed house. For instance, the space heating demand is decreased to 85% of its previous value that equaled 28kWh/HFA.yr if the insulation thickness in the exterior walls is increased to 280mm (75% more) while, in the roof, the thickness is 240mm (20% more).

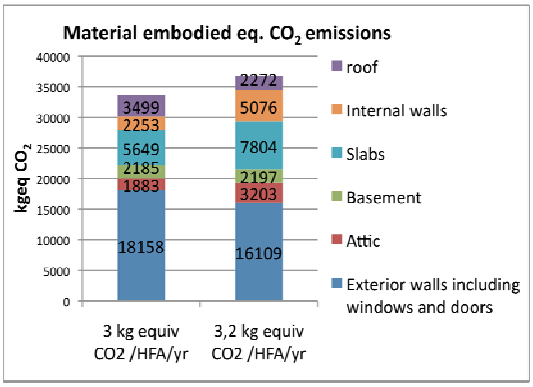

Figure 4. Results of the manual calculations – The masonry house VS the steel framed house.

7 CONCLUSIONS

In the present research, the life cycle environmental profile of two houses located in Belgium was studied with two different tools. The results of the study are the materials embodied CO_2 emissions and the yearly consumed energy and CO_2 emissions related to the Use Phase.

The main objective of this study was to identify whether or not the conclusions drawn in (Garcia de Campos Coelho 2010, Andrade 2010) could be extended to more traditional construction systems used in Belgium and to compare the environmental profile of two construction systems namely traditional masonry houses and steel framed house. It is possible to affirm that, as it is the case for Coimbra climate in the basis study, the Use Stage is the most harmful period during

the building life cycle in Belgium. In the same line of thoughts, the energy consumption is the major source of impacts.

Coming to the embodied CO_2 emissions, it is possible to reach the legislation requirements with less materials emissions for the steel house. It is important to note that, in order to respect Belgian regulations, it was assumed a greater insulation thickness for the steel framed house, and the corresponding embodied CO_2 emissions are consequently increased.

In addition, it is interesting to point out that both houses have reached the Belgian regulations quite easily. Globally, they consume the same amount of energy. The difference in embodied CO_2 emissions comes from the slabs and the internal walls of the masonry house. A nice alternative could thus be to consider a traditional masonry house with internal floors and walls made of steel acoustically isolated with wool just as it is considered for the steel house option.

Moreover, the sensitivity analysis showed that the quantity of steel can be increased to 30% of its value in order to reach the embodied CO_2 emissions of the masonry house and thus, this parameter doesn't affect the final conclusion.

Another point worth highlighting is that, due to the different materials and insulation thickness, both systems lead to a different thermal behavior of the houses. Thus, it could be interesting to perform the same kind of analysis to determine if the current ways of construction is still in line with the current requirement of a diminution of the environmental impacts.

In the second case study, the insulation thickness was increased in the steel house such that the materials embodied CO_2 emissions almost reach the masonry house ones. Therefore, using approximately the same amount of embodied CO_2 emissions, the heat loss in the steel framed house is lower than the masonry house. This can be explained thanks to the roof and exterior walls that can reach a lower U-value.

The next step will be to study similar houses for different climates in order to address the third conclusion that concerned the influence of the energy mix on the environmental profile.

Finally, the limitations from the tool used should not be forgotten. First, for the CO_2 emissions, only cradle-to-gate data are considered. Another important parameter that could be considered is the embodied material energy for sake of completeness especially seen the big amount of energy needed for the production of steel. Second, the scenario, although quite comprehensive for such a manual calculations, take into account an internal heat gain expressed in terms of a diminution of the required indoor temperature. It is thought that it could be useful to try to consider a realistic heat gain due to human heat production plus solar passive heating.

Last, the weight of the masonry house per heated floor area (HFA) is more than double of the steel house weight; the thicknesses of the walls are also different especially if the height of the profiles is optimized; the execution phase is not accounted for; all these parameters could be taken into account for a complete evaluation of the environmental profile of these two houses.

The authors do not claim to have fully covered the domain but this study nevertheless compared, to a certain extent, two realistic houses designed on the basis of common rules.

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Life-cycle assessment of thermal insulation materials for external walls of buildings

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ABSTRACT: This paper includes a review of the results of research studies regarding the life-cycle assessment (LCA) of insulation materials used in a building's external walls. The results concerning the environmental evaluation of the most common solutions are compared with the results of non-traditional solutions, namely in the issues related with production, transport and end-of-life phases.

This kind of benchmarking will evolve into a direct comparison of the environmental information of the insulation materials of each European producer when CEN TC350 - "Sustainability of construction works" - finishes its standardization work. Then, it will be possible to develop "Type III" Environmental Product Declarations (EPD) for each construction material or building assembly, which are based on LCA methodology. Nevertheless, the EPD's of insulation materials already available in international programs and listed in this paper are important to define a point of reference for the thermal performance of this group of materials.

1 INTRODUCTION

In the European Union, residential and commercial buildings represent an important part (about 40%) of the global energy consumption and CO_2 emissions, about half of the emissions not covered by the "Emission Trading Scheme", and approximately 40% of all man-made waste. All possible reduction in the impact of a building leads to significant economic, social and environmental benefits, and the reduction potential of this kind of construction is high (namely in CO_2 emissions) and has negative or low abatement costs (CIB, 1999; EC, 2008; UNEP, 2007).

The envelope is one of the main parts of a building. One of its parts, the external walls, directly influences its thermal and environmental performance through its considerable weight in the envelope's initial embodied energy, life cycle energy consumption, life cycle cost and the users comfort. Walls can represent up to 15% of the overall environmental impacts of a building over a 60-year life cycle (Bingel et al., 2006). The environmental impacts of each external wall solution result directly from the attributes of the materials used (namely the insulation materials), such as its initial embodied energy and thermal properties, and from the way the solution is designed and built.

The evaluation of the environmental impacts of buildings should be made from a life-cycle point of view. The life-cycle assessment (LCA) integrated approach is one of the most often used to achieve this goal and allows for the evaluation of the environmental impacts of insulation materials by considering their source and the resources used in their execution, the maintenance operations, the expected service life, and the end-of-life phase.

This methodology could be applied via a "cradle to grave" (including the extraction and processing of raw materials, the transport and distribution, the use, maintenance and final disposal) or "cradle to cradle" approach (also including the reuse and/or recycling) based on ISO 14040:2006 and ISO 14044:2006 international standards (ISO, 2006b, 2006c). The application

of the LCA methodology must be followed by the creation of extensive and reliable Life Cycle Inventory data, namely concerning the construction materials.

The purpose of this paper is to make a review of international LCA research studies of common and non-traditional insulation materials used in external walls of buildings. The final aim is to identify the most environmentally friendly solution and find lacunas and opportunities for research development.

2 SCOPE AND METHODOLOGY

The aim of this research work is to develop cradle to cradle LCA studies of the external wall solutions used in Portugal. Even though it is imperative to use national production data (because the production technology, energetic mix and most significant environmental impact categories differ from country to country), this work started by benchmarking LCA research results concerning the materials integrated in a building's external walls. For this reason, this paper includes a review of the results of research studies made in the last decade regarding the LCA of insulation materials from the main scientific databases.

3 INSULATION MATERIAL CLASSIFICATION

Insulation materials can be grouped in 3 families according to their chemical or physical structure: mineral/inorganic; oil derived ones; and so-called "organic natural" ones. Further, these materials can have a fibrous or cellular structure which will determine to a great extent both their mechanical and thermal properties (Table 1) (Kotaji & Loebel, 2010). Mineral/inorganic materials account for 60% of the market in Europe; oil-derived ones account for about 30% (namely Extruded Polystyrene (XPS), Expanded Polystyrene (EPS) and Polyurethane/Polyisocyanurate (PUR/PIR)); and "organic natural" and other materials account for about 10% (Ardente et al., 2008). In this last group, Agglomerate of Expanded Cork (ICB) can be highlighted as Portugal is the world's largest producer and exporter. This material can be used as insulation but also as an external covering (Figure 1).More exotic materials, like transparent and dynamic insulation, 'ecological' materials based on agricultural raw materials, and gas-filled and vacuum insulated panels have found limited acceptance in the market, mainly because of their high cost (various references cited by (Ardente, et al., 2008)).

Table 1. Classification of insulation materials by chemical and physical structure.

	Fibre	Cellular	Granular
Mineral "Inorganic"	Mineral wool - MW (Glass/ Stone wool - GW and SW)	Foam glass	Expanded perlite; expanded vermiculite; LECA (Light Expanded Clay Aggregate)
Oil-derived "Organic synthetic"	-	EPS; PUR/PIR; XPS	
Plant / animal derived "Organic natural"	Cellulose; Wood wool; Cotton/Sheep wool; Duck feathers; Flax; Hemp; Straw bale; Recycled paper or denim	ICB; Recycled paper	Cork granulate; Recycled paper

Figure 1. Images from the Portuguese Pavilion at the Xangai exhibition (from http://www.stylepark.com and http://corticeira-amorim.blogspot.com).

3.1 *Thermal performance of insulation materials*

The U-value or thermal transmittance is defined as the thermal conductivity of the insulation material divided by its thickness. To achieve the same U-value (0.4 W/(m^2.ºC), for example), different thicknesses are needed for each insulation material: 9.3 cm for EPS and XPS, 10 cm for PUR/PIR, GW and SW, 11.3 mm for ICB and 40 cm for LECA.

Along with the thermal performance, other characteristics have to be taken into account when an insulation material is chosen for a specific use in a building, namely for external walls, as very few are capable of performing all functions (CIB, 2010). The absorption of water, the durability, the mechanical and fire resistance, the sound absorption, and the release of hazardous substances, namely during a fire, are some of the characteristics that have to be evaluated along with the environmental performance to make a conscientious choice of the adequate solution possible (Al-Homoud, 2005). The environmental performance will be described in detail for some types of insulation materials in the next section of the paper.

4 LCA OF THERMAL INSULATION MATERIALS USED IN A BUILDING'S EXTERNAL WALLS

In order to benchmark the environmental performance of different insulation materials, this section of the paper presents a review of the results of different research works regarding the LCA of insulation materials used in a building's external walls. This review also includes some considerations about important environmental impacts of these materials, namely in the following life-cycle phases: production, transport and end-of-life.

4.1 *Benchmarking of LCA research results*

PU-Europe, the "European association of rigid polyurethane foam insulation manufacturers", ordered from the UK "Building Research Establishment", a LCA study of a building with different insulation materials in the envelope, including the production of construction materials and the energy use considering the same U-value in walls, roof and ground floor (Kotaji & Loebel, 2010). The main conclusions were that: there are not enough LCA data available to the public on "natural" plant or animal derived insulation materials to perform meaningful LCA comparisons; PUR and MW and GW have similar environmental performance and the building's energy use dominates the Global Warming Potential (GWP). In terms of the production of construction materials, Acidification, Photochemical ozone creation and Eutrophication dominate the potential impacts.

A LCA study in Greece collected information about raw materials and energy flows from material manufacturers, and emissions from production, transportation and installation from SimaPro (a LCA software). The results presented in Figure 2 are dimensionless and compare the scale of CO_2 emissions (GWP) between the materials (PUR, MW, XPS and EPS) considering the same U-value. The results for embodied energy are similar, but in this case the environmental performance of PUR and MW are significantly different (Anastaselos et al., 2009).

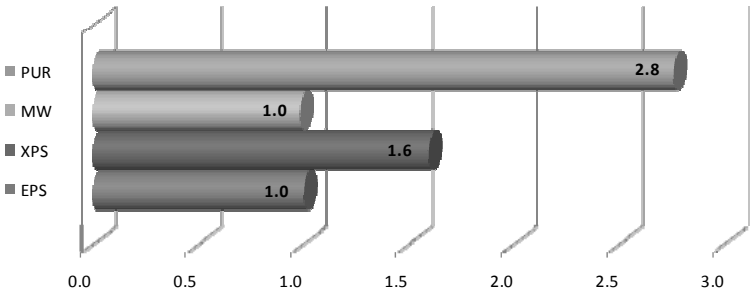


Figure 2. Dimensionless results for Global Warming Potential from production, transportation and installation of four insulation materials, considering the same U-value (Anastaselos, et al., 2009).

Also in Greece, a cradle-to-gate LCA included SW (mattress) and XPS production. XPS has 2.3 times more GWP than SW per functional unit (m^2 of insulated surface), greater than the 1.6 value of the previous study, where the thermal conductivity considered for the MW was just 6% lower than the one considered for the SW of this study (Papadopoulos & Giama, 2007).

In Canada, a study was devoted to the energy associated with the manufacture of four insulation materials. The production of EPS or PUR can consume more than 40 times the energy of the production of cellulose insulation (Figure 3) (Harvey, 2007).

Kenaf (*Hibiscus cannabinus*) is a plant cultivated in Italy and other Mediterranean countries and mainly used in the thermal insulation field and in pulp production. The life-cycle impacts of production and end-of-life of kenaf-fiber insulation boards have been compared to the performances of their competitors (SW - natural minerals and recycled post-production waste materials, mixed with binder and impregnation oil; paper wool; flax rolls; PUR; GW; MW derived from basalts and dolomites). The introduction of recycled materials into the manufacturing process or incineration with energy recovery and electricity production could decrease the energy requirements of the kenaf-fiber insulation. The results also show that the lowest energy consumption is ascribed to MW. Regarding the other environmental categories, paper wool has the best performance. PUR has the largest impact in terms of consumed energy and air releases due to the large use of fossil fuels during the production process. The environmental impacts of insulation boards are also largely due to the employment of oil derived resins and binders during the production, even in natural-fibre based products (Ardente, et al., 2008).

LCA from cradle-to-gate (Europe), including packaging and end-of-life, were applied to SW, flax and recycled cellulose. The results (Figure 4) show that a large consumption of non-renewable materials (e.g. binders and flame retardants) in the production of flax insulation adds a significant contribution to GWP and energy consumption (Schmidt et al., 2004a).

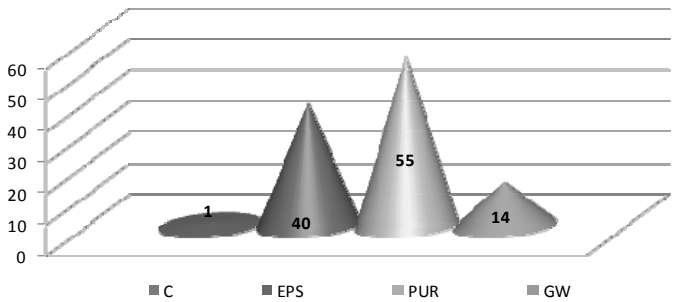


Figure 3. Dimensionless results for the energy associated with the manufacture of four insulation materials, considering the same U-value (Harvey, 2007).

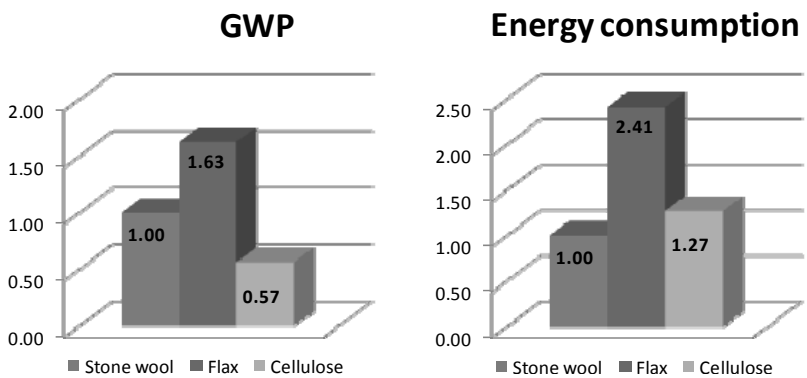


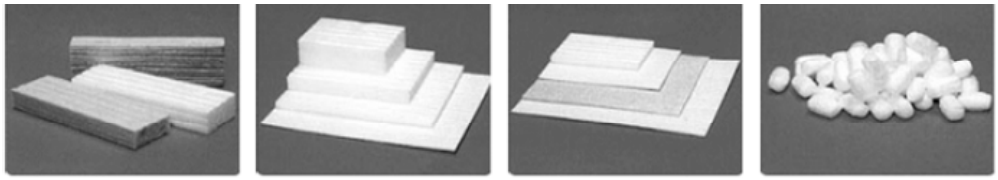
Figure 4. Dimensionless results of the Global Warming Potential and Energy Consumption from cradle-to-gate, including packaging, and end-of-life, considering the same U-value (Schmidt et al., 2004b).

4.2 *The production of insulation materials*

The influence of the production phase can be crucial to the energy and components embodied in each insulation material. To decrease the consumption of raw materials, a solution is to use a

significant quantity of recycled materials, e.g. insulation made of natural denim and cotton fibres (90% post-consumer) (Figure 5) and paper insulation made from cellulose from waste paper, which is available in the form of a board or filling type particles (Figure 6).

Figure 5. Insulation that consists almost entirely of natural denim and cotton fibers (90% post-consumer) that are 100% recyclable (from http://www.bondedlogic.com/ultratouch-cotton.htm).



a) Low density board b) Medium density c) High density d) Filling particles

Figure 6. In South Korea, paper insulation can be found in the form of a board or filling type particles: the cellulose from waste paper is mixed with starch and polypropylene resins; then undergoes a process of expansion using steam and a press moulding process (Kang et al., 2008).

The environmental characterization of the production phase of some insulation materials is already detailed in "Environmental product declarations" (EPD). EPD's are voluntarily developed documents that present quantified environmental information about the life-cycle of a product, thus allowing comparisons among functionally equivalent products. EPD's correspond to Type III environmental declarations which are defined in detail in the international standard "ISO 14025:2006 - Environmental labels and declarations - Type III environmental declarations - Principles and procedures" (ISO, 2006a). Table 2 includes the EPD's of insulation materials already available in international EPD programs.

Table 2. EPDs of insulation materials already available in international EPD programs.

EPD Program	Country (Organization; website)	Insulation materials with EPD
Programme de Déclaration Environnementale et Sanitaire pour les produits de construction	France (*Centre Scientifique et Technique du Bâtiment"; www.inies.fr)*	147 EPDs of insulation materials - cotton wool; duck feathers; EPS; expanded perlite; foam glass; hemp; MW; PUR; wood wool
Umwelt-Deklarationen (EPD)	Germany (*Institut Bauen und Umwelt; bau-umwelt.de/ hp421/Declarations.htm)*	Foam glass and MW
EcoLeaf	Japan (Japan Environmental Management Association For Industry - JEMAI; *www.jemai.or.jp/english/ecoleaf*)	EPS and XPS
International EPD System	(Non-profit international organization; *www.environdec.com/*)	PUR and XPS
Declaración Ambiental de Produto (DAPc)	Spain (*Col·legi d´Aparelladors, Arquitectes Tècnics i Enginyers d'Edificació de Barcelona* e *Generalitat de Catalunya; es.csostenible.net/dapc/ el-sistema-dapc/*)	MW

4.3 *The transport of insulation materials*

Despite being low-density materials, the transport phase of insulation products can be significant in a LCA study because of the volume they can reach.

Following the study (Harvey, 2007) already described, another one in Ireland analyzed the energy for transport of insulation materials from the producers (GW from Germany; others from the UK) and concluded that the delivery of cellulose insulation needs slightly more energy than its production (Collins et al., 2010).

In Thailand, insulation boards are produced from agricultural waste: bagasse (the waste from sugar production), coconut coir and rice hull. Ongoing research in this country aims at reducing the thermal conductivity between 80 % - bagasse - and 5 % - rice hale (coconut coir - 15%) to make these solutions almost as intensive in energy as Cellulose or GW imported from Los Angeles, USA (Panyakaew & Fotios, 2009).

4.4 *The end-of-life of insulation materials*

In the study made in Europe, LCA from cradle-to-gate, including packaging, and end-of-life with different scenarios were made of SW, flax (crop grown) and cellulose (recycled) (Schmidt, et al., 2004b). The reference case was "100% recycling" in low-grade applications; but the best end-of-life option may be unavailable due to technical or economic constraints.

The end-of-life of insulation materials continues to be a problem and not even the new European Laws contribute to ease its resolution. The targets for reduction of quantities, recycling or reuse of construction and demolitions wastes (CDW) are all defined in weight (EP, 2008) and, consequently, the insulations materials become dispensable or forgotten in the process of CDW, and the most probable destiny is landfill. If this criterion is changed in order to define the importance of CDW in volume when they have a density of less than 300 kg/m^3, reality would look different for the end-of-life of insulation materials.

There are other problems which prevent the best end-of-life option for insulation materials. One of them is the inclusion of brominated flame retardants in EPS and XPS production, components whose risk assessment results are already available but are not conclusive or contradictory. Alternative solutions for these compounds are being introduced, but there are still a lot of insulation materials in buildings with them (BuildingGreen, 2009; EPSMA, 2009; IARC, 1990; SFT, 2003). Selective demolition methods may allow collecting a significant quantity of plastic insulation products in old buildings. Nevertheless, these products contain fire retardants that are economically unfeasible to characterize in detail. The knowledge about the behaviour of these compounds during recycling is still low and does not advise this procedure. Therefore, these problems jeopardize any possible recycling process and the disposal of plastic insulation products normally takes the form of incineration with energy recovery (Brandrup et al., 1996). Regarding CFC's, these compounds where banned from PUR (CFC-11) and XPS (CFC-12) production. However, the recycling of these products, when recovered from an old building, has the same problems as foams with fire retardants, and also has the potential of releasing CFC's (Andersen & Sarma, 2002; Harvey, 2007).

MW is also a group of insulation materials that represents a concern for anyone that works in their production, installation or recovery in demolition processes, but the conclusions about its effects on health are still limited (IARC, 1998, 2002). The same observation applies for insulation materials made from flax or paper fibres due to the exposure to the corresponding production dust (Schmidt, et al., 2004a). These concerns related with the end-of-life of insulation materials limit a cradle to cradle approach.

5 CONCLUSION AND PERSPECTIVES

In conclusion, each country has their own common construction materials and solutions for thermal insulation of buildings, as stated in the works described in this paper. The production technology, energy mix and most significant environmental impact categories also differ from country to country. Despite these differences, all LCA research studies must have a definite scope and methodological approach to compare functionally equivalent products. Some of the studies included in this paper do not follow these principles which prevents comparing their results, namely due to differences in the thermal performance considered for each material in the studies that clearly influence the final results. These problems create limitations to the interpretation of the results of the studies. However, careful and detailed readings of all the studies col-

lected allow some partial and global conclusions that maintain the aim and justify the significance of this work. Nevertheless, a detailed study of the durability and end-of-life of all the insulation materials continues to be necessary. For these reasons, it is important to develop cradle to cradle LCA studies of the traditional external wall solutions of each region with production data from the same regional source and including the maintenance and reuse or recycling phases and the operation energy. This last feature is a powerful tool which allows the comparison of alternatives without the obligation of considering the functional equivalence of thermal performance, and enlarges the amount of solutions that the designer can consider. The LCA analysis could be complemented by a life-cycle cost calculation for each alternative, without forgetting that all these solutions must comply with the regulations and standards minimum requirements (Bingel, et al., 2006).

Regarding the production phase, the introduction of recycled materials into the composition of the products and the use of natural resins are good options to improve their environmental performance. The results related with the transport phase reveal that when choosing insulation material it is important to consider both the energy associated with manufacture and the location of the insulation production site.

From the insulation materials referred to in Table 1, only expanded vermiculite, LECA, ICB and other natural products (e.g. straw bale and recycled paper or denim) had not yet been studied in terms of environmental performance via the standard LCA methodology. This should be considered when assessing information provided by the manufacturer and not until all products have undergone LCA's will accurate comparisons be possible (CIB, 2010). Nevertheless, it must be stressed that the end-of-life phase may have a positive contribution to natural insulation materials, despite not being studied in detail in any of the works included in the review made. Health issues still prevent mineral and oil-derived insulation materials to be sent to the best end-of-life options.

This kind of benchmarking will evolve into a direct comparison of the environmental information of the insulation materials of each European producer when CEN TC350 - "Sustainability of construction works" finishes its standardization work, in 2012. Then, it will be possible to develop "Environmental Product Declarations" (EPD) of construction materials and building assemblies based on Rules for each construction Product Category. Namely, it will be possible to develop "Type III" EPD's which are based on an LCA with a definite scope and functional equivalent of each construction material or building assembly and, for this reason, are a complete, robust and scientifically validated source of information of the environmental impacts of the product being studied during their life-cycle. Nevertheless, the EPD's of insulation materials already available in international programs are important to define a point of reference for the Life-Cycle Assessment of a group of materials that is simultaneously so heterogeneous in their composition and production process and so important in their contribution to the thermal and environmental efficiency of buildings, and to promote a cradle to cradle approach.

6 ACKNOWLEDGEMENTS

The authors thankfully acknowledge the scholarship of FCT (Foundation for Science and Technology) to support the PhD study of the first author and the support of the ICIST Research Institute from IST, Technical University of Lisbon.

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Life Cycle Assessment of building structure

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ABSTRACT: Starting from the environmental assessment of a residential building, used as a case study, the research highlights some distinctive aspects of reinforced concrete, steel and wood, utilized for load-bearing structure of buildings.

1 THE ROLE OF THE LOAD-BEARING STRUCTURE

The load-bearing structure of the buildings seams to be one of the subsystems less investigated and less deepened in terms of environmental compatibility, particularly as regards the widespread construction sector. This sector is characterized by the absence of large structures or of complex engineering characteristics, but their large quantity in the territory makes appreciable the amount of environmental impacts attributed to them: most of buildings that constitute the residential fabric of the Italian cities, developed starting from the reconstruction post-war, are attributable to this category.

In addition, the duration characteristics are rarely the subject of a thorough study, although this aspect is essential from the perspective of the environmental compatibility verifiable over time. Likewise, the interferences between the various subsystems that make a building up are often neglected and particularly the fact that the subsystem structures both influences and is influenced by other sub-systems, such as the horizontal and vertical closures and the internal partitions, the connective and distributive elements, the equipments. Despite this close relationship with the elements not performing structural functions, the load bearing structure is the only part that can not be replaced or modified during the life of the building, or at least only in small percentage. In contrast, the global renovation of buildings under the age of 50 years often involve the complete removal of all non-structural components, keeping only the load bearing structure which will become, after that the process is completed, the structure of the new building. The daily practice, specifically in Italy, excludes the process of demolition and re-construction of buildings carried out from the second post-war as standardized activity in management processes of urban transformation. On the contrary we tend to modify the existing buildings by acting only on the distributive, technological or finishing components, in order to obtain an increase of the internal functional areas through the aggregation of new volumes, side by side or stacked to the existing.

Given this premise, it is clear that the structure should be designed to perform its function for a period equal to n cycles of the building use and reuse. Similarly, in assessing the environmental compatibility it should consider that the impacts generated during the construction phase will be "dilute" on a particularly long scenario of useful life.

With this in mind, during the research to which the present results refer, a Life Cycle Assessment was adopted as method to quantify energy consumptions and environmental impacts

spawned of the structure assumed as a case study. This approach allows in particular to relate the entire useful life of the building, with the assess of the processes of production and disposal.

2 ENVIROMENTAL ASSESSMENT OF A BUILDING'S CASE STUDY

2.1 *Architectural description*

The case study adopted during the research in order to conduct a Life Cycle Assessment of the bearing structure is the project of a new building for residential use. The main volume has a rectangular plan with overall dimensions of 32.30 x 8.70 m and is configured as a series of 8 residential modules, 4.00 m wide, put side by side to compose a building that develops on four levels above ground. Behind the residential part is placed a distribution volume, consisting on long balconies and stairwells, which has a size of 40.50 x 3.60 m. Along the northern front, behind the distribution body are located some overhanging volumes that can be used as study halls.

The building project was developed in the executive details in three different material variations: reinforced concrete frame structures and masonry; steel frame structures and cladding on light steel-framed construction, dry assembled; laminated wood frame structures and light closures dry assembled on wooden frame. Here below the drawings of the executive project show the technological characteristics of the three solutions.

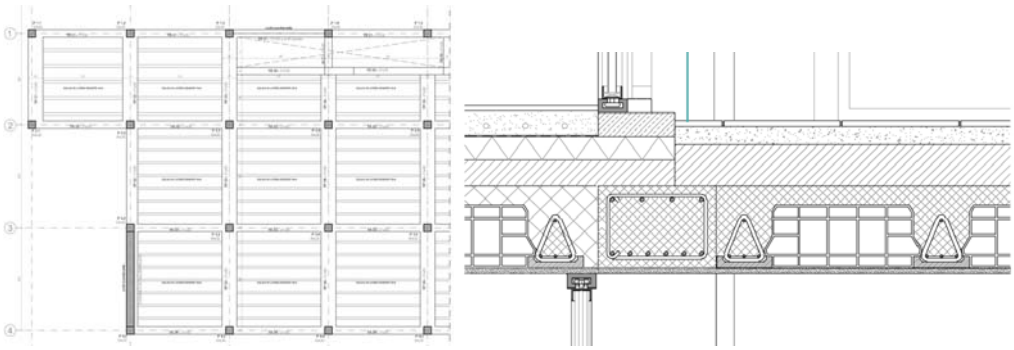

Figure 1. Drawings of the structure made by reinforced concrete.

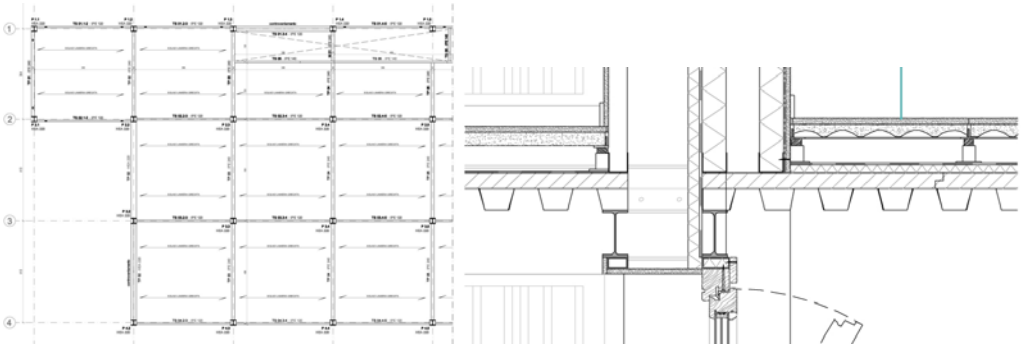

Figure 2. Drawings of the structure made by steel.

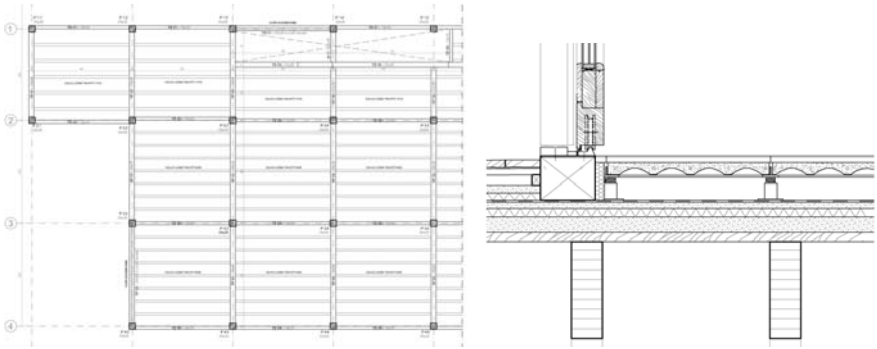

Figure 3. Drawings of the structure made by wood.

2.2 *Environmental assessment outcomes*

The building project has been developed till the level of constructive detail, through the selection of building products available on production catalogs in order to obtain the same thermal performances of the vertical and horizontal closure and internal partitions in the three technical solutions. Alongside were assessed building energy consumptions during operation and the values of the embodied energy and the carbon dioxide related to the production and construction phases. The comparative assessment of three technical solutions allowed to perform a comparison between the energy and environmental impacts related both to the pre-use phase (production and construction) and to the building use phase (energy consumption for heating, cooling and ventilation), highlighting also to the role of the various parts (bearing structures and other subsystems) in the overall environmental loads.

The building energy consumptions causes an annual consumption (per unit of floor space) double than the impact of the construction phase, considering a life of the building of 50 years. This condition allows to assimilate the solutions with concrete and steel structures, while the lower energy content of wood reduces the ratio to about 40% in the third alternative. In regard to the relationship between bearing structure and the other subsystems of the building, it is to be noted that the result related to steel solution is almost double compared to the other hypothesis; this result is also confirmed by the CO_2 produced.

The comparison between the three alternative materials shows that the embodied energy of the steel frame is of 136% higher than the embodied energy of the concrete frame and of 148% compared to wood. Turning to the quantity of CO_2 produced, the gap between steel and wood is +306%. The difference of the energy consumption in the use phase between the first and the third solution is small, while is high on the environmental impacts front.

EMBODIED ENERGY AND EMBODIED CARBON VALUES							
DESCRIPTION	UNIT	EMBODIED ENERGY			EMBODIED CARBON		
		CONCRETE	STEEL	WOOD	CONCRETE	STEEL	WOOD
All building	MJ	4'464'174	5'470'458	4'285'145	353'400	426'585	281'221
All building / m^2 useful surface	MJ/m^2	2'899	3'552	2'783	229	277	183
Structure	MJ	1'128'586	2'663'370	1'075'426	96'691	237'049	58'334
Structure / All building	%	25,28	48,69	25,09	27,36	55,57	20,74

Figure 4. Amount of the Embodied Energy and the Embodied Carbon in the three structural solutions.

2.3 *Critical aspects of the assessment process*

The evaluation process of the project highlights several issues, among which it should be stressed those related to structural elements.

The assessment of the environmental impacts and the energy content of the materials used for the construction of structures immediately raises a difficulty common to many building components, that is due to the difficulty in obtaining primary data. In fact, the number of construction products with an EPD certification, able to describe the component ecoprofile as close as possible to the real condition, is quite small. This deficit must be overcome by using the information contained in specific databases, which however describe a “media” condition, whose adherence to the specific case is dependent on the industry processes and on the geographical context analyzed to build the database itself.

With regard to concrete and masonry structures, it is necessary to highlight that the existence of certain EPD certifications for bricks and one about concrete does not help to refine the evaluations, because there are many uncertainties related to the high availability of different concretes in the Italian context. In addition, the wet process of assembling in the building site causes more uncertainties in the assessment of impacts related to the construction phase. Also for the steel and wood structures it is difficult to obtain primary data, but the dry assembly system usually involves a reduction of impacts caused during construction.

3 ENVIRONMENTAL CHARACTERISTICS OF CONSTRUCTION MATERIALS

3.1 *The reinforced concrete*

In Italy, the bearing structures made of reinforced concrete are commonly considered to be durable in a life scenario of one century. It should be noted that the project performance maintenance over a period so long is subject of quite a large number of variables, many of which were not regarded until a few decades ago. In particular, can be taken as examples the choice of an aggregate with the appropriate physical-chemical quality, the proper design of steel reinforcement rods and a correct measure of the thickness of the protective cover of reinforcement rods: aspects to which in the past little attention was addressed but which may affect the stability of a structure in a time span lower than expected. Progress in technological research has recently led to a comprehensive review of the Italian regulatory apparatus that deals with the sizing of the bearing structures in relation with performances in case of earthquake, that is the reason why structures built 20-30 years ago no longer guarantee adequate levels of security.

The issue related to the aggregates quality interacts also with the theme of material recycling. The reinforced concrete structures are commonly considered to be recyclable for the aggregates production of new blends, but the common practice in Italy sees generally the use of inert from demolition in the formation of massive layers and drained soils near to the buildings foundations. The environmental analysis of recycling process of concrete from demolition to produce aggregates reveals the existence of numerous impacts, that normally are not assessed, but that in many cases tend to undermine the positive effects from the use of secondary raw material. A good example is the need to increase the cement percentage if the aggregates are fully recycled, with a higher consumption of raw materials and an increase in weight of manufactured goods, which is an issue of great impact in the multi- storey structures as it causes the need to increase the foundational system.

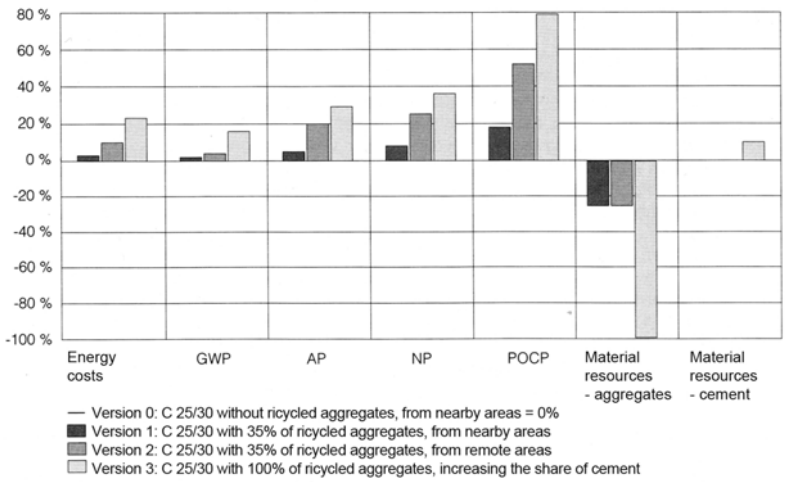

Figure 5. Environmental impacts of four different type of concrete.

3.2 *The steel*

The high energy and environmental impacts due to steel products depends in part by the surface treatment to protect the components from corrosion. Several years ago, in addition to the typical operations as galvanizing or painting was introduced triplex treatment that is the overlap of the powder coating on a traditional galvanizing process. It is important to highlight that a superficial analysis of environmental compatibility of the new solution leads to consider the innovation in a negative way because it involves the sum of the two alternative treatments. On the contrary, an objective and balanced analysis, which considers also the treatments durations and distributes the impacts on a plausible scenario of life, reverses the opinion: the triplex solution ensures indeed duration twice than the galvanizing process and more than five times higher than the painting.

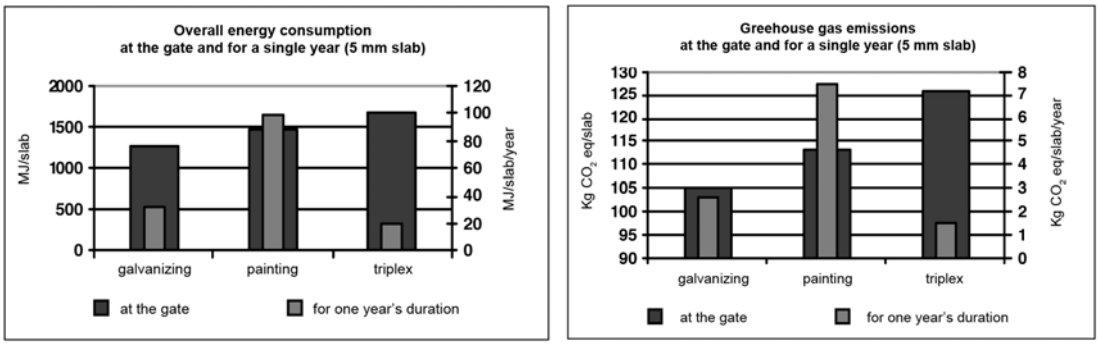

Figure 6. Energy consumption and greenhouse gas emission of three surface treatments for steel.

Steel is undoubtedly the material between those used for the structures construction which can best be recycled, but even so not all the dismantling material becomes new raw material and equally there is also a quantitative difference between the semifinished products of recycling process and those produced from primary steel. It should be noted the existence of some operational constraints affecting the Italian situation. In fact in Italy there are mainly steel mills with electric furnace, suitable for the recycling process to produce bars and profiles smaller than the HE200. In contrast, planar elements and larger profiles derive from primary steel, produced outside the national borders in blast furnace. The existence of plants able to produce concrete reinforcement elements matches the needs of the construction market that in recent decades and still nowadays mainly requires elements for concrete structures.

A second peculiarity of steel structures is directly related to the dry assembly typology of the profiles that guarantees the system reversibility and the following possibilities for reuse in other structure. In this case the theory clashes with the need for compliance with mandatory regulations that require the characterization of the structural elements, which is not possible on components taken from a dismantled structure. The ways of protection of the users' safety creates limits to the potential environmental compatibility inherent in the material.

3.3 *The wood*

In the case study project, the wooden frame was foreseen as organized in a bearing frame of columns and beams with the goal of making comparable the alternative solution realized in concrete and steel with the same spatial configuration. In daily practice and particularly in recent years, the use of two-dimensional structural panels has been developing, changing both the design approach and the environmental impacts due to the significant increase in use of the material. Regardless of the structural solution adopted, it is stressed as the replacement of components made of solid wood with similar elements produced by wood reconstructed, through the use of adhesives, increases the environmental impacts. Following there are the environmental profile data of certain products available in the catalog in order to illustrate how the progressive increase of resin content, from a solid element to others made with strips of progressively smaller size (X-LAM) up to the sawmill residues (LVL), greatly affects the compatibility of the product. Reducing the size of the wooden parts actually allows the use of waste materials of a top-level manufacturing, but involves an increase in energy consumption in the industrial cycle and in parallel an increase in impacts related to the higher use of resins.

The theme of the real durability of a wooden structure remains largely unexplored. The assessment of the maintenance of the structural performance over time is a prerequisite to understand if the major impacts attributable to the solutions in engineered wood (reconstituted with resins) can be balanced by the increase of the service life. The dualism between solid wood and reconstituted wood has a important role in relation to the end of the life cycle of building components because the wood, commonly referred to be a natural and recycled material, gradually loses its ability to become a secondary raw material with the increase of the resin adhesives percentage, non-recyclable and even not separable from the wood portion. If it is true that processing wood waste, like bark, shavings and sawdust, can give rise to new products through the use of resins and adhesives, it is also true that the elements reconstituted, as plywood, particle

board, OSB and MDF, hardly can be considered recycled. We note, however, that the disused panels are reusable as packaging.

SLIM WOODEN ELEMENTS								
IMPACT INDICATORS		MASSIVE WOOD						GLUE W. PLATE
DESCRIPTION	UNIT	TYPE 1	TYPE 2	TYPE 3	TYPE 4	TYPE 5	TYPE 6	
Natural resources	g Sb eq.	145	182	447	496	628	721	1660
Global warming potential (1)	Kg CO_2 eq.	-775	-922	-728	-944	-701	-911	-571
Global warming potential	Kg CO_2 eq.	20	26	68	74	95	107	202
Photosmog	g C_2H_2	60	57	71	142	120	211	210
Acidification potential	g SO_2 eq.	144	184	344	787	649	1221	1750
Eutrification potential	g PO_4 eq.	17	22	32	107	70	162	173
PEI non renewable	MJ	308	389	1012	1038	1381	1483	3335
PEI renewable	MJ	8740	12853	9293	16604	12125	20676	19640
NOTES								
Global warming potential (1): it also consider carbon storage in wood								
Type 1: spruce fir, crude from sawing machine, air-dried								
Type 2: larch, crude from sawing machine, air-dried								
Type 3: spruce fir, not planed, kiln dried								
Type 4: larch, not planed, kiln dried								
Type 5: spruce fir, planed, kiln dried								
Type 6: larch, planed, kiln dried								

WOODEN PANELS								
IMPACT INDICATORS		MASSIVE WOOD		XLAM		LVL	PLYWOOD	
DESCRIPTION	UNIT	UF GLUE	PF GLUE	UF GLUE	PF GLUE		UF GLUE	PF GLUE
Natural resources	g Sb eq.	1399	1589	2244	2538	4098	4542	5214
Global warming potential (1)	Kg CO_2 eq.	-648	-626	-810	-775	-554	-504	-424
Global warming potential	Kg CO_2 eq.	148	170	236	271	470	459	538
Photosmog	g C_2H_2	104	102	310	307	343	358	353
Acidification potential	g SO_2 eq.	923	1019	1674	1818	3210	3288	3612
Eutrification potential	g PO_4 eq.	81	81	148	148	269	298	297
PEI non renewable	MJ	2957	3433	4602	5339	8658	9392	11115
PEI renewable	MJ	10301	10299	21742	21740	27399	27406	27402
NOTES								
UF glue: urea and formaldehyde based glue								
PF glue: phenol and formaldehyde based glue								

Figure 7. Environmental indicators for some types of wooden construction elements.

4 CONCLUSIONS

The presented analysis want to illustrate how the choice of construction technology to create the bearing structures of a building involves numerous environmental implications that concern to a large number of different research fields. In the project it is necessary to consider not only the more strictly architectural and formal aspects, but also the technical choice associated with the methods of structures assembly, but also the energy and environmental impact assessment, the end of life scenarios and the critical issues arising from reuse of waste materials. A careful analysis of possible scenarios in relation to the life cycle of materials is an important basis for constructive choices, to not be deceived by flattering and simplistic opinions about environmental performance.

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Life cycle inventory (LCI) of cold-formed hollow structural steel sections for the sustainability assessment of metal structures

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ABSTRACT: One of the most established and accurate methodologies developed during recent years and currently being applied for the sustainability assessment of a variety of products, services or systems, including construction projects, is Life Cycle Assessment (LCA). Based on the concept of the life cycle, this method calculates results, the validity of which depends on the environmental data or Life Cycle Inventory (LCI) data used to quantify the environmental impacts associated with the delivery of a construction project. However, the more specific the type of project examined, the more difficult it is to find LCI data within existing databases which correspond to the materials and processes used for its construction. Metal structures constitute one of these areas for which LCI data is currently in scarcity. The current research presents the analysis of the production process for one of the most commonly used type of structural steel members in metal structures, cold-formed hollow sections. Each production stage has been documented in terms of environmental inputs and outputs based on data supplied by one of the largest structural steel members manufacturers in Greece and complemented by existing literature, where necessary. The results contain a substance list of the main environmental in-puts and outputs to air, water and soil and also impact assessment results obtained with some of the most widely used impact assessment methods available.

1 INTRODUCTION

Sustainable development has been introduced, on a global level, as one of the main goals that must be accomplished in order to ensure that the ability of future generations to fulfill their needs will not be compromised by current developments. Every aspect of human activity has been affected by this movement, as it is being strongly promoted by European and international legislation. The construction industry, one of the largest raw materials and energy consumers, is one of the business sectors whose response to this challenge can provide significant environmental benefits. As a result, all construction technologies are called to incorporate the principles of sustainable development into standard practice and ultimately achieve sustainable construction.

Metal structures constitute an important part of current construction activity which also has to adapt to this changing industry. As a first step towards achieving sustainable construction with metal structures, it is necessary to establish the ability to assess the environmental impact associated with specific design solutions. This will enable construction professionals and clients to compare the environmental impact caused by different design solutions and make decisions based on sustainability-related criteria.

1.1 *Life cycle assessment (LCA) of metal structures*

Life Cycle Assessment (LCA) has been introduced and established as the most appropriate methodology to assess the environmental impacts associated with a product, system or service. This method is also acknowledged and currently widely used within the construction sector for the purpose of assessing the environmental sustainability of all types of structures, including metal construction projects.

The LCA methodology is greatly affected by the quality of the environmental data -or Life Cycle Inventory (LCI) data- used for the quantification of environmental inputs and outputs associated with specific products or services. The highest level or accuracy concerning LCA can be achieved only with the collection of primary LCI data which reflect the particular characteristics of each specific study. However, the collection of accurate LCI data usually requires a very long time and significant amounts of work, an overall effort of often disproportional size compared to the desired LCA. It is therefore usually impossible to avoid the use of already existing LCI databases which contain environmental data prepared for use within other LCA studies.

As the validity of LCA results is very closely linked to the quality, accuracy and appropriateness of the data used, the selection of data from existing databases becomes an issue of critical importance. For metal structures, very few databases contain the necessary data and even they do not often provide the exact dataset required.

Structural steel members are one of the most environmentally damaging points within a metal structure, mainly due to the increased volume of members required (Zygomalas et al., 2009). The current research presents a detailed analysis of the production processes carried out to manufacture one of the most commonly used structural steel member type in metal structures, namely cold-formed hollow sections such as SHS, RHS etc. (square, rectangular hollow sections).

1.2 *Methodology*

Initially, a market research was conducted to determine the situation surrounding the manufacturing of structural steel members in Greece. The majority of steel member suppliers were found to operate mostly as trade firms, importing finished or semi-finished products from abroad and using them to answer local demand. A second category consists of firms involved in the manufacturing of semi-finished steel products, such as billets, slabs etc., which are then supplied to other firms to carry out further processing. Among the few Greek firms that actually manufacture structural steel members from start to finish, the one with the largest market share was selected as representative of the production process of structural steel members in Greece. The data provided was used for the current analysis and the documentation of environmental inputs and outputs.

Regarding the steel making route used to manufacture structural steel members, it has been documented (World Steel Association, 2009) that the total amount of steel manufactured in Greece is produced with the electric arc furnace (EAF) method which is based on the recycling of iron and steel scrap rather than the extraction of raw materials.

1.3 *Life Cycle Inventory (LCI) analysis parameters*

The goal of the current research is the creation of a new LCI dataset, which will contain all environmental inputs (raw materials, energy, etc.) and outputs (emissions to air, water and soil) associated with the production of 1 kg of cold-formed hollow structural steel members, of steel quality Fe360 (equivalent to S235JR or RSt 37-2), via the EAF route. Based on this dataset, raw material requirements and environmental emissions for all similar type structural steel members are calculated according to their weight, within steel structure-related LCA.

The manufacturing processes documented range from raw material extraction to storage of the finished product at the production factory before shipment for use (cradle-to-gate). Processes are examined in terms of inputs and outputs, including possible sub-processes, while the production and maintenance of the production machinery is not included in the calculations.

The geographic coverage of the dataset is primarily the Greek region, but it can also be used within the wider European region. Minor modifications could enable its utilization within global or even more localized LCA studies.

2 MANUFACTURING PROCESSES

2.1 *Production of steel billets*

The production of the steel billets used to manufacture the cold-formed hollow sections is the same for all long structural steel members manufactured in the steel facility. It consists of several stages, namely the transport of scrap to the steel manufacturer's facilities, its inspection at the factory gate, processing and storage, the loading of the EAF, the ladle furnace operation, continuous casting and also the reheating furnace before the processing of the steel billets (Figure 1).

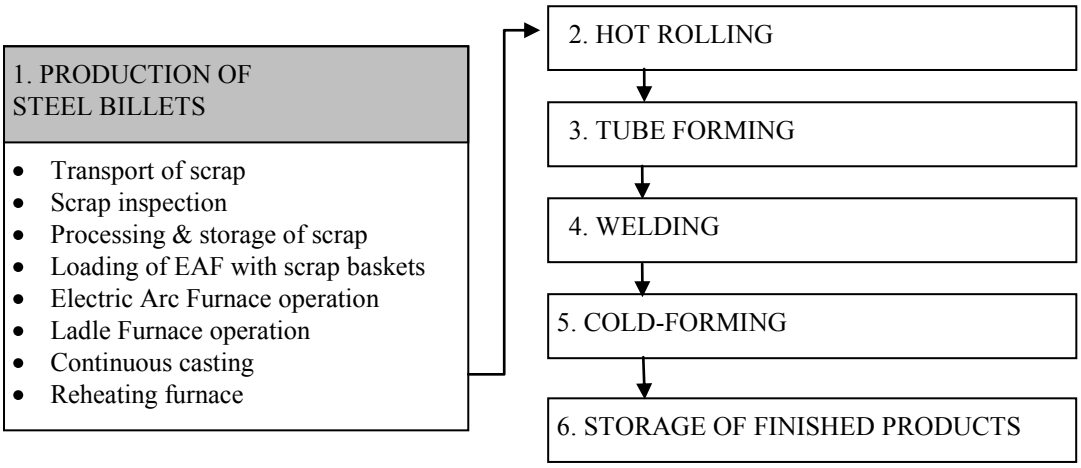

Figure 1 Production processes for the manufacturing of cold-formed hollow structural steel sections via the EAF steelmaking route.

2.2 *Remaining production processes*

After the reheating of the steel billets, they are hot-rolled into flat steel strips which are then formed into circular-section tubes, welded and finally cold-formed into the required hollow structural steel section. These stages are briefly described below.

2.2.1 *Tube forming*

During this stage, steel strip of the appropriate width is formed into circular-section tube up to the point at which the two outer edges of the strip are joined together.

2.2.2 *Welding*

The next stage is the welding along the length of the steel strip edges. The welding is achieved as the two edges are heated to the temperature required for the optimum steel welding conditions, with the use of high frequency electric power. This welding method is called High Frequency Electric Resistance Welding (HF-ERW) and is an autogenous welding technology, as the connection is achieved with compression only, without the use of additional welding materials or an electrode.

2.2.3 *Cold-forming*

The final stage of the production process is the cold-forming of the circular steel tube into square or rectangular hollow sections, through a series of properly shaped rolling mill components.

2.3 *Life cycle inventory (LCI) of manufacturing processes*

The first stages required for the manufacturing of cold-formed hollow structural steel sections – from scrap collection to reheating of the steel billets- have been documented in terms of LCI in previous research concerning the prerequisites for the creation of an LCI database focusing on structural steel components. (Zygomalas et al., 2010). The remaining manufacturing processes are analyzed in terms of environmental inputs and outputs and complemented by literature research, where necessary. As an example, the LCI data referring to the cold-forming of the circular steel tubes into square or rectangular hollow sections (Athena Sustainable Materials Institute, 2002) is listed in Table 1.

Table 1 Life Cycle Inventory (LCI) data for the cold-forming of the circular steel tube

Manufacturing stage	Process	Required data	LCI data	Comments
Cold-forming of steel hollow sections	The circular steel tube is formed into square or rectangular hollow sections.	- Electric power consumption (kWh). - Emission of substances to the air (kg).	- 0,34 GJ electricity or 0,34*277,78= 94,4 kWh / t of product. - 0,73 g particulates (air) / t of product.	Cold-forming does not affect the quantity (weight) of the finished product.

3 INVENTORY RESULTS

The first set of results derived by the analysis is the inventory substance list. This list contains over 700 entries in total, referring to the environmental inputs (raw material requirements) and outputs (emissions to air, water and soil) associated with the manufacture of 1 kg of cold-formed structural steel hollow members according to the Greek conditions. Table 2 contains the most important substances according to input and output category.

Table 2 Most influential substance inputs and outputs for the production of 1 kg of cold-formed structural steel (EAF) hollow members

	Substance	Category	Unit	Amount
Inputs:	Coal (brown, in ground)	Raw material	kg	0,9525
	Dolomite ($CaCO_3$, in ground)	Raw material	kg	2,1713 E-04
	Iron (46% in ore, 25% in crude ore, in ground)	Raw material	kg	0,0883
	Manganese (Mn, in ground)	Raw material	kg	4,5360 E-08
	Natural gas (in ground)	Raw material	m^3	0,1052
	Natural gas (35 MJ per m3, in ground)	Raw material	m^3	0,0643
	Oil (crude, in ground)	Raw material	kg	0,0651
	Steel scrap	Raw material	kg	1,1463
	Water (unspecified natural origin)	Raw material	lt	7,1362
	Zinc (Zn, in ground)	Raw material	kg	2,2092 E-09
Outputs:	Carbon dioxide (CO_2)	Air emission	kg	0,2332
	Carbon dioxide, fossil (CO_2)	Air emission	kg	1,2119
	Carbon monoxide (CO)	Air emission	kg	3,1886 E-03
	Dinitrogen monoxide (N_2O)	Air emission	kg	2,4275 E-05
	Hydrogen Chloride (HCl)	Air emission	kg	2,3080 E-04
	Hydrogen Sulphide (H_2S)	Air emission	kg	5,6199 E-06
	Lead (Pb)	Air emission	kg	5,9065 E-07
	Mercury (Hg)	Air emission	kg	6,2227 E-08
	Methane (CH_4, fossil)	Air emission	kg	3,5709 E-04
	Nitrogen oxides (NO_x)	Air emission	kg	1,8419 E-03
	Non-methane volatile organic compounds (NMVOC)	Air emission	kg	5,8618 E-04
	Particulates, < 2.5 um ($PM_{2,5}$)	Air emission	kg	5,7295 E-04
	Particulates, < 10 um, mobile & stationery (PM_{10})	Air emission	kg	3,6410 E-06
	Sulfur dioxide (SO_2)	Air emission	kg	4,2865 E-03
	Sulfur oxides (SO_x)	Air emission	kg	8,5671 E-05

Zinc (Zn)	Air emission	kg	6,7608 E-07
Ammonia, as N (N)	Water emission	kg	1,2400 E-07
Cadmium, ion	Water emission	kg	7,6784 E-07
Chemical Oxygen Demand (COD)	Water emission	kg	0,0022
Chromium, ion	Water emission	kg	8,8790 E-07
Iron	Water emission	kg	4,1017 E-06
Lead (Pb)	Water emission	kg	3,6451 E-06
Nickel, ion	Water emission	kg	7,5162 E-05
Suspended solids	Water emission	kg	3,7676 E-04
Zinc, ion	Water emission	kg	2,3714 E-05
Calcium	Soil emission	kg	1,5761 E-05
Heat, waste	Soil emission	MJ	0,0110
Iron	Soil emission	kg	1,5574 E-05
Oils, unspecified	Soil emission	kg	2,5169 E-04
Steel waste	Waste	kg	0,0542
Waste, unspecified	Waste	kg	0,1432

4 ENVIRONMENTAL IMPACT ASSESSMENT

Based on the inventory documentation of the manufacturing processes for cold-formed structural steel hollow members, environmental impact assessment is conducted according to two of the most widely used impact assessment methodologies, namely Eco-Indicator 99 and Global Warming Potential (GWP). The results are calculated on the basis of 1 kg of manufactured product, so that they can be easily compared to similar studies' findings and also used within the scope of future studies.

4.1 *Eco-Indicator 99 impact assessment*

In order to assess the environmental impact, the Eco-Indicator method was used (Eco-Indicator 99 (E), Europe EI 99 E/E). According to this method the total impact is calculated in Pt, where 1 Pt is representative of one thousandth of the yearly environmental load of one average European inhabitant (The Netherlands Ministry of Housing, Spatial Planning and the Environment 2000). It was therefore calculated that the total environmental impact for 1 kg of cold-formed structural steel hollow members is equal to 0,0839 Pt. The impact breakdown, as caused by each production stage is presented in Figure 2.

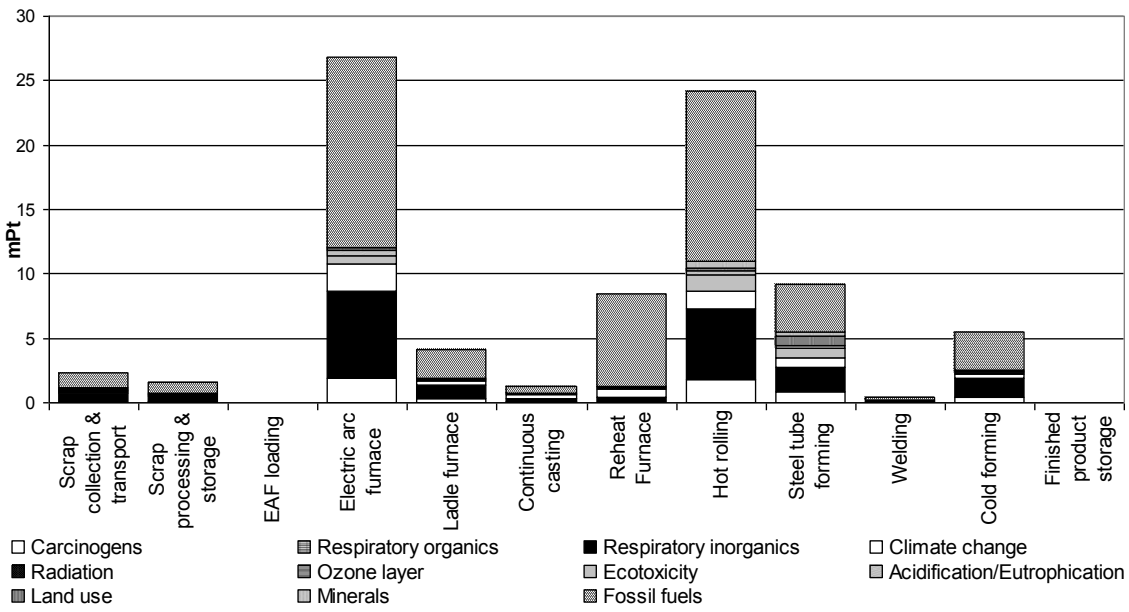

Figure 2 Environmental impact caused by main production stages for 1 kg of cold-formed structural steel hollow members (EAF)

As shown in Figure 2, the most environmentally damaging processes are the operation of the electric arc furnace and hot-rolling. The steel tube forming, reheating furnace, ladle furnace and cold forming processes also result in noticeable environmental impacts, while the rest of the processes affect the overall impact at a lower degree. In terms of environmental impact categories (Figure 3), the categories "fossil fuels" that refers to natural resources and "respiratory-inorganics"-associated with negative effects on human health- are mainly burdened. The manufacturing stages primarily responsible for these negative effects are again identified as the operation of the electric arc furnace and hot-rolling.

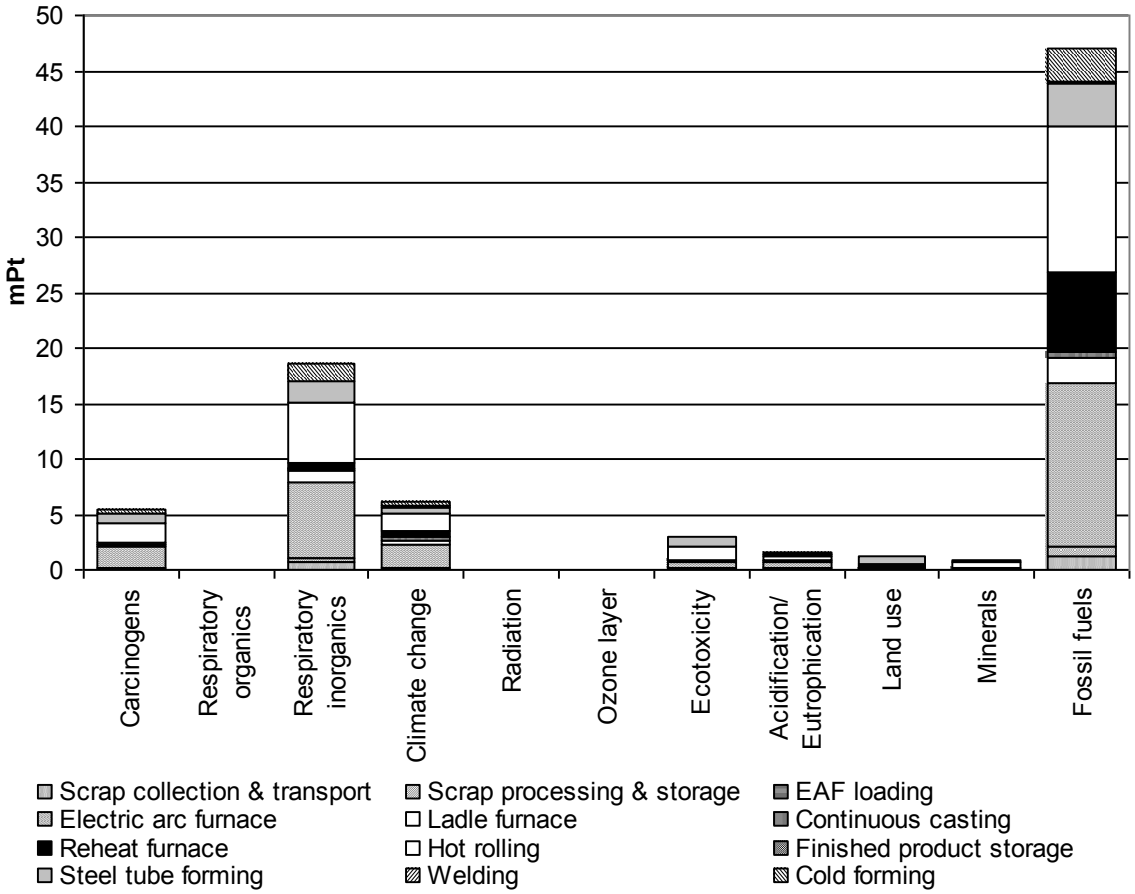

Figure 3 Environmental impact associated with the production of 1 kg of cold-formed structural steel hollow members (EAF) according to each impact indicator

In order to identify the sources of environmental burden within each manufacturing stage, it is also necessary to examine the network of environmental burden flow for the production of 1 kg of cold-formed structural steel hollow members, presented in Figure 4. For presentation purposes, the diagram contains only the most influential processes. As the thickness of the arrows indicates the environmental loads, it is evident that electricity requirements are responsible for more than half (52,7%) of the total environmental impact.

Further down the diagram, the lignite burned at the power plant for the production of the electric energy is revealed as the main source of environmental burden. This also explains why the "fossil fuels" impact category is so heavily affected by the operation of the electric arc furnace and the hot-rolling process, both of which require significant amounts of electricity. On the other hand, natural gas is also used as an energy source, yet its environmental impact is quite lower. Electricity and natural gas requirements account for 59,8% of the total environ-

mental load, a figure which leaves little room for doubt that in order for structural steel member manufacturers to improve their products' sustainability, they will have to reconsider their current energy sources.

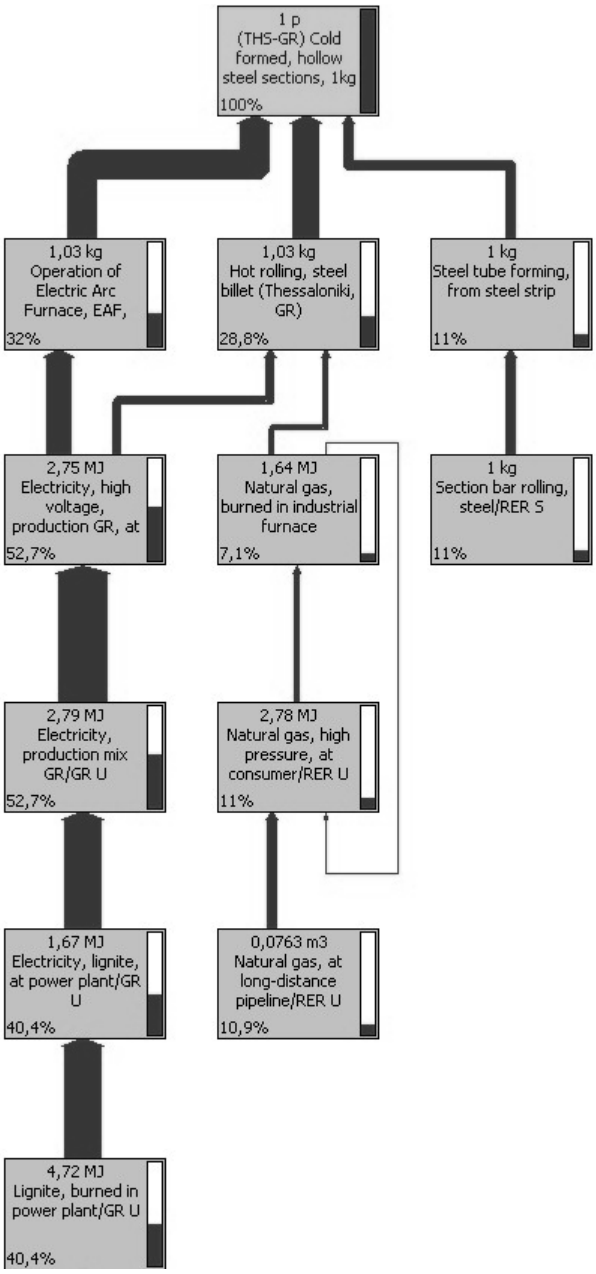

Figure 4 Environmental impact flow for the production of 1 kg of cold-formed structural steel hollow members (EAF)

4.2 *Global Warming Potential (GWP) impact assessment*

It is also possible to assess the environmental impact with the calculation of the Global Warming Potential (GWP) index (IPCC, 2007). This methodology is based on specific factors with which every substance emission is multiplied and thus translated into equivalent gr of carbon dioxide, which are finally added to a total. In this manner, a single index becomes an immediate depiction of the environmental impact of a product or system, for a time horizon of 20, 100 or

500 years. For 1 kg of cold-formed structural steel hollow members, the GWP results are presented in Table 3.

Table 3. GWP index for the production of 1 kg of cold-formed structural steel hollow members based on the IPCC GWP 2007 methodology.

GWP methodology	Unit	Total
IPCC GWP 20a (20 years)	kg CO_2 eq	1,579
IPCC GWP 100a (100 years)	kg CO_2 eq	1,495
IPCC GWP 500a (500 years)	kg CO_2 eq	1,461

5 CONCLUSIONS

The current research provides a useful dataset for the development of a new LCI database for structural steel elements in Greece. The impact of the manufacturing of cold-formed structural steel hollow members was estimated, based on data provided by a Greek steel manufacturing company and secondary data found in literature and existing LCI databases as well. The results can be used as a reliable basis for future decision-making, strategy planning or in the case of steel structures, optimization of the design processes.

With regard to environmental impact, the main source of burden associated with the manufacturing of cold-formed structural steel hollow members was identified as the energy requirements. Energy has been an issue within the scope of sustainable development for quite some time now and as was shown by the research undertaken, it must also be integrated into the manufacturing process for steel members in order to ensure a sustainable manufacturing procedure.

The analysis can also be used as a framework which can be applied to other geographic regions for the assessment of the environmental impact of cold-formed structural steel hollow members. The main manufacturing stages will require minor modifications to fit the specific conditions which apply for each country, with the most significant part of data required being energy requirements.

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The use of cold formed steel systems for sustainable emergency housing: application of LCA methodology to a modular construction

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ABSTRACT: The emergency management after an earthquake is a complex present-day topic, as demonstrated by the recent earthquake in L'Aquila (Italy).
Starting from a critical analysis of the state-of-the art about the emergency housing, this paper presents the design of a modular unit that account environmental issues together with technological and structural problems. The developed system is a dry construction made of cold formed steel profiles that aims to present a valid solution in terms of high structural performance and eco-efficiency for provisional housing.
The structural design has been carried out in accordance with the Special Regulation developed by the National Civil Defense Department, within the triennial research RELUIS project.
Special emphasis has been given to the sustainability performance of cold formed steel structures, and in particular, a comparison between the same system with two different *end of life* scenarios has been developed.
The latter study has been implemented with a LCA analysis according to the international standards UNI EN ISO 14040 (2006) and UNI EN ISO 14044 (2006). This analysis allows to evaluate the difference in terms of environmental sustainability between the recycling of the steel components and the final dismantling in dump. The LCA highlights the importance of reusing the components and demonstrate that to foresee the recycling of all the steel components instead of dismantling in dump can reduce the life cycle environmental impacts of about the 13%. This study underlines the importance of LCA as supporting tool for an integrated design approach in the structure sector.

1 INTRODUCTION

After every hazard (earthquake, flood, eruption), available and affordable new houses becomes a urgent need. Usually, the large requirements for a big number of construction in a reduced time brought to the adoption of prefabricated temporary buildings, that even if provisional, they have to satisfy high performance in terms of safety, comfort and sustainability. Since these constructions have to recover the population for few years up to the complete reconstruction, each unit has to be safe and has to provide the space for all the essential facilities that people expect in their homes. Moreover, the introduction of these units in a destroyed area can have important social, economic and environmental impacts. Therefore, the Evaluation of the Environmental

Impact considering the whole life cycle of the products, as defined by the ISO 14040-44 (2006), is a must.

Nowadays, reliable procedures that take into account resources consumption and emissions output are necessary in order to extend the concept of Life Cycle Engineering towards the environmental issue. To this end, the well-known Life Cycle Assessment (LCA) represents the most valid tool to define the environmental impacts in terms of quantitative results. This procedure, based on the life cycle thinking, can be consider as an important supporting tool in the structural design to choice the best sustainable solution. In fact, in the last years, the traditional engineering approaches that have been usually focused on the single elements of productive processes, are moving towards a global vision of productive system, that takes into account the entire cycle from the raw material processes to the end of life (Badino et al. 1998), as defined by the recognized formula from cradle to grave. In this background, the following work aims to present the results of an integrated methodology applied to an emergency building. The case study is a prefabricated dry construction building realized by assembling on site 3D-modules made by cold formed steel components, in which all the dimensional and structural requirements respects the requirements defined by the Special Regulations for Emergency Housing developed within the research project RELUIS (AA.VV. 2008).

2 STATE OF THE ART ABOUT EMERGENCY HOUSING

The adjective temporary is usually adopted for all the housing settlements realized to satisfy the housing requirements after exceptional events and natural hazards and it is intended only as an interim step until a permanent solution is achieved.

The idea of provisional housing has a relatively short story compared with permanent housing. In fact, while the permanent housing was born around 10000 years ago, the emergency housing in terms of temporary housing was born about 100 years ago, during the Second World War, when easy to be built constructions needed to replace the destroyed structures. In the last years, the increasing requirements of products and systems by Civil Protection Department, Military Service and Italian Red Cross encouraged the development of construction systems that could be easy to build and to transport and that allow the system itself or the components to be reused. Analyzing the historical development of emergency housing, four main phases can be identified, that correspond to specific period of the twentieth century (Figure 1).

The first experiments were carried out at the beginning of 20th century (between 1910 and 1940), when some important architects of the Modern Movement like Le Corbusier or Oud, designed small wood structures, that could be transported on road. In the same years, in Italy, after the Messina earthquake in 1908, the first emergency housing were provided by Russian and English military divisions to shelter the victims. The systems developed during these first period were characterized by standardization of components and industrialization of construction processes that are still current.

After the Second World War, between 1940 and 1970, the need for provisional housing able to offer an adequate recovery grow, opening the street to a new design research strand. In particular, this period saw the introduction of the container in the emergency field with the first realization by Jean Prouvè and Pierre Jenneret who designed, in 1945, the first transportable living module. The developed container was innovative for that time, since it was able to modify on site the shape and to triple the volume by adopting moving panels.

The idea of modifiability and flexibility was developed in the third phase (between 1970 and 1990), when the integrated construction systems, realized by adding prefabricated living units were created. Above all, the flexible house designed by W. Lubitz in Germany is emblematic for the adoption of a three-dimensional module that overturning the external walls allow different configurations to be created. Symbolic examples of these systems were, also, the Ca.Pro designed by Donato, Guazzo, Platania, Vittoria (Donato et al. 1983) and the S.A.P.I. by Pierluigi Spadolini in 1982 (Figure 2).

In the last period, from 1990 up to now, “do it yourself” systems appeared. They are made of a small number of prefabricated elements that can be easy assembled on site without big machines or specialist labours. These systems aim to involve the people affected by the emergency

in the building erection, so that they can participate in the reconstruction phase of the destroyed cities.

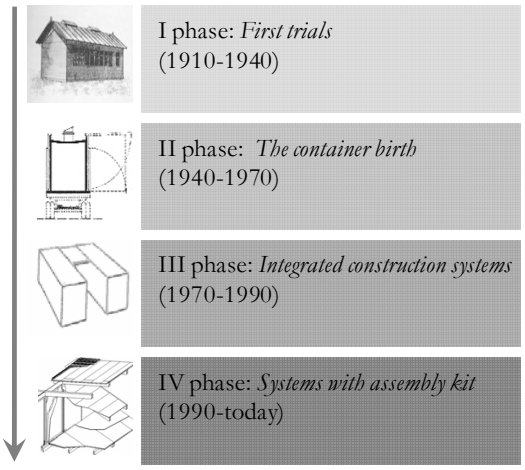

Figure 1 Four main phases for temporary housing

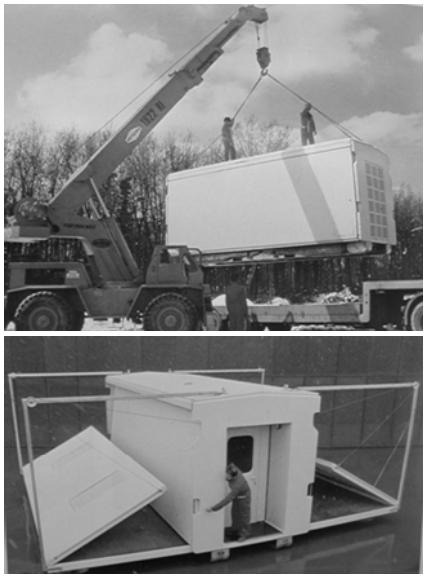

Figure 2 S.A.P.I. (www.ispro.it/site/content/dagli-alloggi-monoblocco-ai-mapi.)

3 LIFE CYCLE ASSESSMENT IN THE CONSTRUCTION SECTOR

In the era of globalization, the important conflict between "human economy" and "nature economy" determinate the born of the so-called *Sustainable* Development (Rees 2002). The Sustainable Development is a concept that includes the dynamic balance between three main dimensions (Figure 3): *Environment* (Ecosystems integrity; Reproducibility of natural resources, Biodiversity), *Economy* (Growth of employment and income; Eco – efficiency; Economic development; Productivity) and *Society* (Safety; Health; Education; Cultural identity; Empowerment; Accessibility; Stability; Equality).
Nowadays, the development of the Life Cycle Assessment (LCA) in the construction sector (Figure 4) is related to a more environmental awareness, which represents an important aspect to be considered for the definition of an integrated design approach, based on the *life cycle* concept (Neri 2008). The aim of LCA is to compare the environmental performance of products in order to choose the least cumbersome by assessing the raw material production, manufacture, distribution, use and disposal of the product itself (*from cradle to grave*) (Lavagna 2008).

Figure 3 The three main pillars of Sustainable Development

Figure 4 Sustainability in the construction sector

The LCA methodology is normalized by the standards UNI EN ISO 14040 (2006) and UNI EN ISO 14044 (2006), which describes the principles and the framework for life cycle assessment (UNI 2006a, b). The LCA, includes four major stages:

1. *Goal and Scope Definition*. This phase describes the overall objectives, the boundaries of the studied system, the sources of data and the functional unit to which the achieved results refer.
2. *Life Cycle Inventory (LCI).* It consists of a detailed compilation of all the environmental inputs (material and energy) and outputs (air, water and solid emissions) at each stage of the life cycle.
3. *Life Cycle Impact Assessment (LCIA).*This phase aims to quantify the relative importance of all environmental burdens obtained in the LCI by analysing the relative influence on the selected environmental effects. The general framework of a LCIA method is composed of mandatory elements (*classification* and *characterisation*) that convert LCI results into an indicator for each impact category, and optional elements (*normalisation* and *weighting*) that lead to a indicator across impact categories using numerical factors based on value-choices.
4. *Life Cycle Interpretation (LCIN).* In the last step, the results from the LCI and LCIA stages must be interpreted in order to find hot spots and compare alternative scenarios.

Taken into account the large amount of data to be processed, several software have been developed to support and implement the environmental analysis. In particular, in this work, the SimaPro v. 7.1.8 software application has been used as supporting tool in order to implement the LCA model and carry out the environmental impact assessment presented hereafter (Pre Consults 2008).

4 CASE STUDY: UNIKA

4.1 *Description of structural design*

As underlined in the state of the art about provisional housing, the need for housing able to assure a fast erection and an easy transportation require the adoption of light structures, in which the term light refers not only to the weight of the elements, but also to the production process (construction process, installation time, etc.). For this reason, Cold Formed Steel Structures can provide a valid solution for provisional housing, in terms of high structural performance and eco-efficiency. Taking into account that, according to the prefabricated level, three main structural typologies are available: *stick-built* (lowest prefabrication degree); *panelised* (intermediate prefabrication degree); and *modular* (highest prefabrication degree) constructions (Landolfo et al. 2001 and 2002, Iuorio et al. 2009). In this paper, a modular unit for emergency housing (UNIKA) is described as case study. The structural design of UNIKA has been carried out according to the Special Regulation developed by the National Civil Defense Department, within the triennial research RELUIS project (AA.VV. 2008). The Special Regulation defines the minimum standards for the temporary units in terms of functional/architectural (Table 1) and structural requirements (Table 2), regardless of the construction technology (steel, wood, concrete, etc.).

Table 1 Minimum functional/architectural requirements (AA. VV.2008)

Unit house	Minimum Useful Area	Net Useful Area				Height
		Living/Dining/ kitchen	Bathroom	Bedroom	External area	
Type A	$A_{u,\,min}$ [m²]	A_{min1} [m²]	A_{min2} [m²]	A_{min3} [m²]	$A_{u,ext}$ [m²]	H [m]
1 or 2 person	24	n.1 ≥ 9,50	n.1 ≥ 3,50	n.1 ≥ 11,00	≥20% $A_{u,\,tot}$	≥ 2,40

The temporary house has been designed for two persons, placing back-to-back two basic modular constructions (Figure 5), in order to guarantee the minimum usable area ($A_{u,\,min}$) equal to 24 square meters (Table 1), two rooms (living /dining / kitchen area and bedroom) and one bathroom are settled.

Table 2 Minimum structural requirements and design actions (AA. VV.2008)

Earthquake	Wind	Snow	Temperature variation		Live loads		
PGA	Altitude A.S.L	Altitude A.S.L	Exposed structure	Unexposed structure	Intended use		
a_g [m/s²]	a_s [m]	A [m].	ΔT_u [°C]	ΔT_u [°C]	q_k [kN/m²]	Q_k [kN]	H_k [kN/m]
0,35	750	750	± 25	± 15	2,00	2,00	1,00
Soil category	q_p [kN/m²]	s_k [kN/m²]					
D	3,00	1,15					

In order to adapt the structure to every type of ground configuration and to allow the passage of pipes, the modules are supplied with height adjustable support devices. It is a punctual support, which is connected to the modular structure by a bolted flanged connection system.

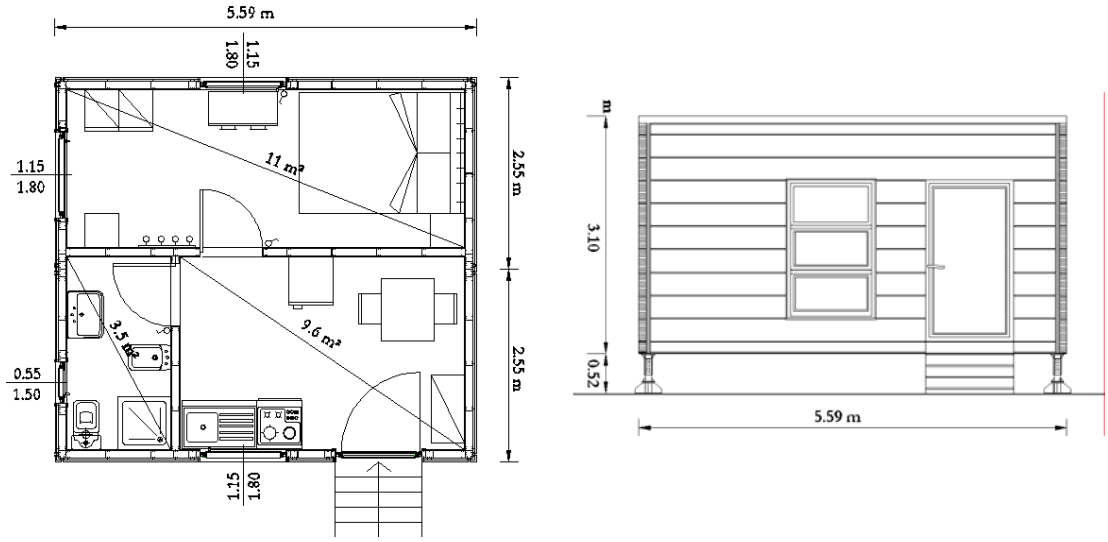

Figure 5 UNIKA: configuration plan and elevation

4.2 *Stage1: Goal and Scope definition*

The goal of the LCA analysis is to evaluate and compare the environmental impacts produced by the presented structure, considering two different *end of life scenarios*:

Scenario 1. Recycling of CFS elements (S1);

Scenario 2. Disposal to landfill of CFS profiles (S2).

In order to contextualize this study to the recent seismic event, it was supposed that UNIKA is located in L'Aquila city.

The *functional unit* consists in all the technological elements by which the structure is composed. The unit processes that are taken into account for the environmental assessment are described in the *system boundary* (CEN TC 350 2009). It includes the whole life cycle for the modular unit, considering three different stages and in particular, the *pre-use* phase, *construction/use* phase and *end-of-life* phase (Figure 6).

UNIKA is a temporary house, therefore, the maintenance processes have not been considered in this analysis. In order to reduce environmental impacts produced by transport operations, the following assumptions have been carried out: a. the use of local products (*pre use phase*), this means that the products production and construction site are quite close; b. the waste treatment (*end of life phase*) occurs in plant site are located as close as possible to the construction site.

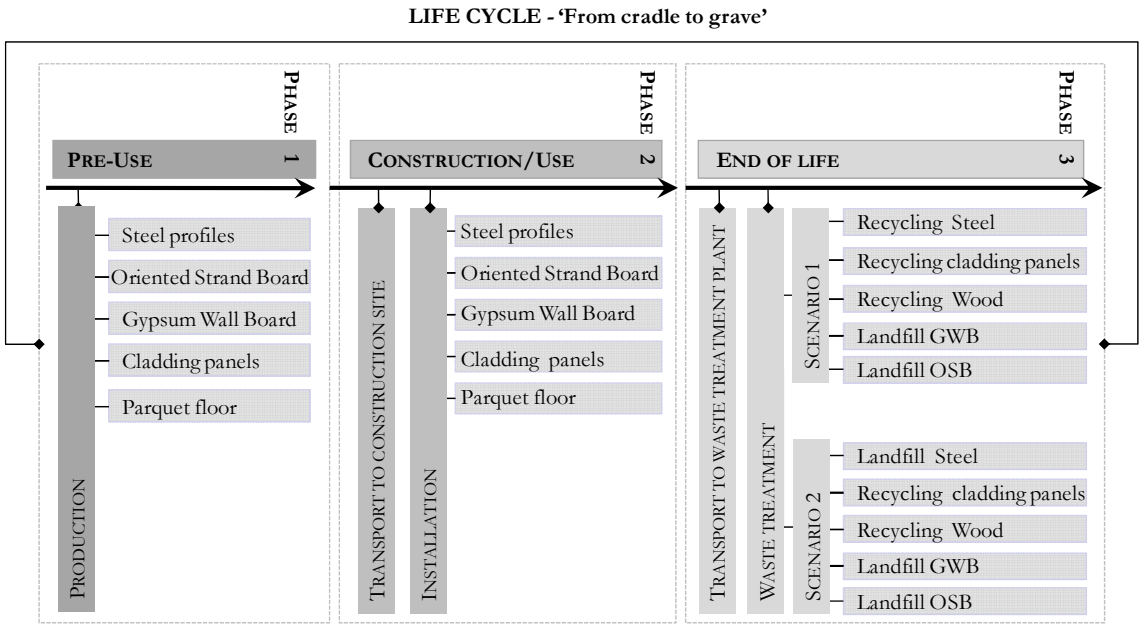

Figure 6 System boundary: life cycle stages of UNIKA

4.3 *Stage 2: Life Cycle Inventory (LCI)*

The inventory analysis has been carried out taking into account all the processes and activities included into system boundary, previously described.
All the unit processes have been modeled starting from databases included in the SimaPro v 7.1.8 software, with special regards to the Idemat 2001, the ETH-ESU and Ecoinvent databases for product materials (*pre-use phase*) and steel recycling processes (*end-of-life phase*), the BUWAL 250 database for transport operations.
The following figures illustrate the network diagram of Scenario 1 'recycling of steel' (Figure 7) and Scenario 2 'disposal to landfill of steel' related to the *phase III* of UNIKA.

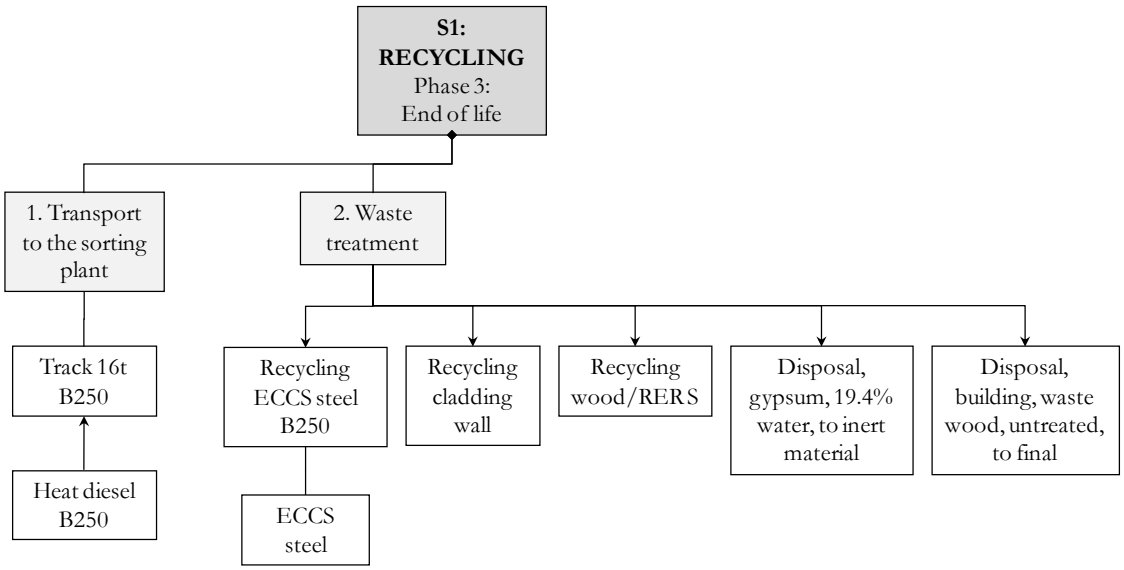

Figure 7 Output SimaPro: network diagram of Phase 3'End of life' – Scenario 1: recycling steel

4.4 *Step 3: Life Cycle Impact Assessment (LCIA)*

In the present study, the impacts assessment has been carried out using Environmental Product Declaration (EPD) v.1.02 method, included in SimaPro v.7.1.8 software, which considers the *impact categories* reported in the Table 3.

Table 3 Impact categories reported in the EPD

Impact category	Symbol	Formula	Unit
Global Warming Potential	GWP	CO_2 eq	kg
Ozone Layer Depletion	ODP	CFC_{11} eq	kg
Photochemical oxidation	POCP	C_2H_4	kg
Acidification	AP	SO_2 eq	kg
Eutrophication	EP	PO_4 eq	kg
Non renewable, fossil	PEInr		MJ

4.5 *Stage 4: Life Cycle Interpretation*

According to the main aim of this analysis, the *waste treatment process* of CFS profiles is the parameter by which is possible to compare the two different end of life scenarios. The following Figure 8 shows the LCA results for each impact categories considered in EPD method (in percentage values).

The bar chart proves how the Scenario 1 is more sustainable than Scenario 2.

In particular, it illustrates that, among all impact categories, the *Global Warming Potential* (GWP) produces the most significant difference between the two *end life scenarios*: the amount of CO_2 released into the atmosphere by the recycling steel is less for about the 19,70% than its disposal to landfill.

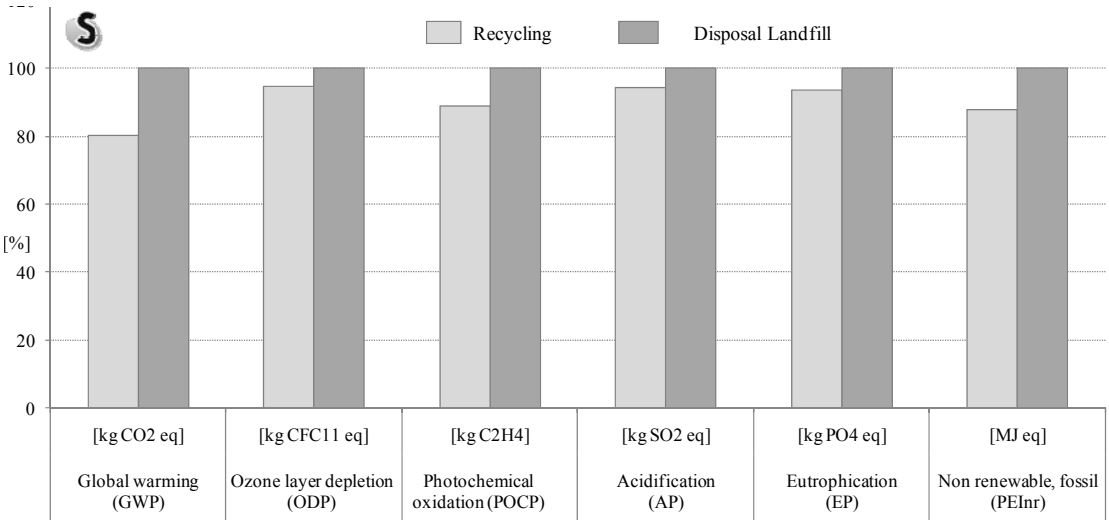

Figure 8 SimaPro output: LCA results of UNIKA

5 CONCLUSIONS

In this study, starting from a critical analysis of the state-of-the art about the emergency housing, the environmental impact assessment of a modular construction considered as study-case (UNIKA) has been evaluated. The temporary house has been designed in accordance with the Special Regulation developed by the National Civil Defense Department, within the triennial research RELUIS project.

The analysis reflects a grater environmental awareness in construction sector, expressed by the use of Life Cycle Assessment (LCA) methodology, as a supporting design tool.

LCA method allowed to evaluate and compare two different end of life scenario (recycling of steel components and the disposal to dump), in term of environmental sustainability. The results have been carried out using the Environmental Product Declaration (EPD) method, included in SimaPro v.7.1.8 software, which supports and implement LCA model.
The analysis highlights the importance of reusing the components and demonstrate that when for all the steel components the recycling is foresaw instead of the dismantling in dump, the life cycle environmental impacts can be reduced of about the 13%.

This study underlines the importance of LCA as supporting tool for an integrated design approach in the structures sector, in order to consider not only structural and technical performance but also environmental issues.

ACKNOWLEDGMENT

This work was carried out within the triennial research RELUIS DPC-Line 10 "*Establishment and development of data archives for risk assessment and emergency definition*", Task 8: Emergency planning and management - Task 8.4: Emergency housing management.

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Environmental impact assessment of steel residential buildings

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ABSTRACT: The aim of this paper is to investigate the environmental credentials of steel housing and note the necessity on the environmental impact assessment study of this activity, regarding the extent of the steel housing activities within a city or country. Steel is becoming a distinctive choice of construction material and also a system in housing in Greece, as in many other countries that are in highly risked seismic zones and has stratified historic landscapes where the site is vitally important to build on. Regarding steel's features as high strength-to-weight ratio, good ductility, ease of fabrication and erection, as well as aesthetic appearance and provision of significant solutions contributing to sustainability and life-time engineering requirements, its role in construction activities and eventually on environment can easily be verdict. Henceforth, the intrinsic aim of this paper is to present the environmental impact categories and values in a steel housing activity through a case study in Crete, which would form the basis for an environmental impact assessment study that takes environmental friendliness of a construction activity as a valuation criterion. In this framework, an inductive study via utilization of the life cycle assessment (LCA) methodology which provides a thorough understanding of the environmental performance of steel in housing construction is conducted. A life cycle assessment tool is being utilized for the analysis of building materials and activities whilst achieving the life-time long environmental performance values of a steel residential application through its production, transportation, execution and the treatment after use of components. The results of the LCA are being evaluated to put out the necessary values to be used in further studies.

1 INTRODUCTION

In the latest years the need for adopting environmentally friendly policies in all fields of economy and society is widely acknowledged. In the construction field in particular, where the building sector is the biggest consumer of raw materials and energy, all factors like national organizations, technical companies, engineers face the additional demand of sustainability complementing safety, strength and functionality and the necessity to assess the impact of building activities on the environment is deeply felt. The new challenge is to achieve environmentally friendlier treatment of construction activities, namely to reduce the environmental impacts and to improve the overall energy efficiency of the structures. Minimizing building costs, materials and waste, as well as low operating and maintenance costs are becoming nowadays some additional goals of the design process.

Furthermore, the choice of construction materials and their performance throughout their lifetime possess a significant role in the sustainable design of buildings. When choosing a material for any application it is important to look at the whole of the product's life cycle. Life cycle analysis in fact goes far beyond the production processes alone. It also covers the impacts and benefits of the material throughout the lifespan of the different products, including its reuse and recycling. In the field of residential buildings, steel represents an attractive structural

material as steel-based structural systems and technology applications exhibit high mechanical performance and at the same time provide great flexibility regarding the design and construction processes in dwellings.

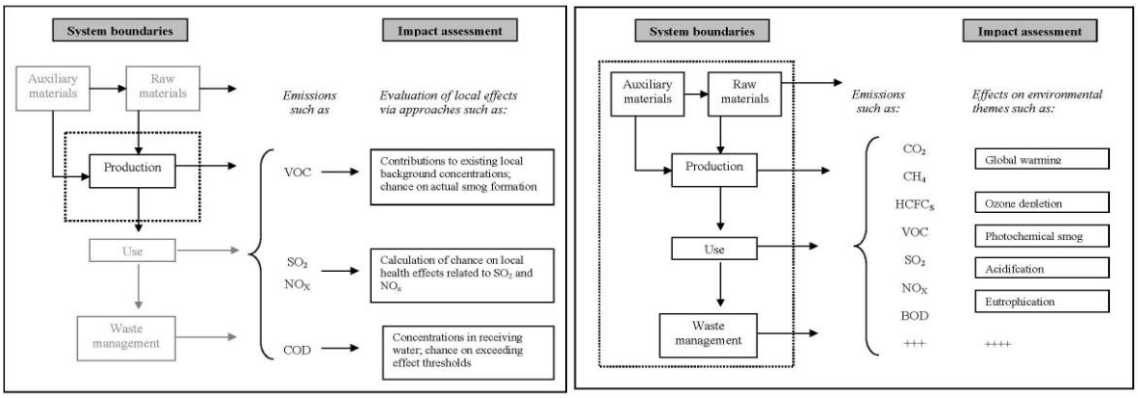
The herein presented activity focuses on the life cycle performance of steel members in a residential application by applying an LCA study and carrying out an environmental impact assessment. The investigation of a steel housing project in terms of sustainability is analysed and the importance of an integrated approach in the design is highlighted. In addition and since initially, environmental calculations were not incorporated in the design and construction of the project, the paper describes the input of each parameter of the project in terms of sustainability and contributes to the broadening of knowledge on the integrated design of such structures.

2 SUSTAINABILITY ASPECTS AND STEEL RESIDENTIAL APPLIACTIONS

2.1 *Environmental impact assessment and LCA study*

Towards the goal of sustainability, new aspects and parameters have been introduced regarding the design and alternative methods and practices have been implemented in the construction activities. Sustainable design involves life cycle assessment studies which cover the entire life cycle of the buildings whereas inventory data is used in order to proceed to calculation of the environmental effects (Edwards 2007). Environmental impact assessment (EIA) is an evaluation process of the building projects and refers to a decision making procedure on the application of one project as well as on the choice of a project among the alternatives, based on the least harmful impact on the environment while sustaining the comprise of other inventories and related societies. EIA aims to provide a high level of protection of the environment and to contribute to the integration of environmental considerations into the preparation of projects, plans and programs with a view to reduce their environmental impact (European Commission 2010).

Yet, mainly EIAs depend on the environmental effects' assessment of the proposed project that result from the existence of the project, the use of natural resources, the emission of pollutants, the creation of nuisances and the elimination of waste are documented and evaluated for which life cycle assessment (LCA) is mostly adapted (European Commission 2010). The LCA is utilized as the specification and comparative data supply tool for EIA via which all environmental impacts of a product along its life-cycle is being listed and classified. In Figure 1 the impact categories that are classified in a LCA study are and can be inputs of an environmental impact assessment are presented (Tukker 2000). Thus, referencing LCA is not one and only assessment tool that EIA can be based on, while the role of LCA varies according to the preset structure of the impact assessment and system definition.



i) ii)

Figure 1. i) EIA focus ii) Extend of an LCA.

2.2 *Characteristics of steel and environmental approach*

In terms of sustainability, steelworks can generate many environmental credits. The majority of steel organizations have acknowledged the need for commitment to sustainable steel construc-

tion and have already ventured into efforts of establishing movement towards this direction. The major requirements are to reduce the primary energy use and CO_2 emissions, as well to minimise materials use and waste. In addition, the accomplishment of recyclability and improvement of thermal performance are among the major challenges in the sustainability design framework. The steel sector is capable of achieving a very high level of sustainability due to the particular characteristics of steel as a structural material and its construction systems. Steel's high strength-to-weight ratio make it a preferable choice for multi-storey dwellings, while its long-span capabilities allow for the design of flexible, column-free spaces that can adapt to changes during the life of the structure (SCSSC 2002).

Furthermore, the fact that all steel elements are manufactured off-site maximises the reliability of steel construction and minimizes defects. One of the most effective ways of reducing these impacts is by maximizing offsite prefabrication, which not only minimizes site activity, but can also provide efficient, safe, high quality and fast construction. Of course all steel products are manufactured offsite, with the degree of prefabrication increasing from linear elements, to infill panels to complete modules which are fully finished and fitted out in the factory, ready for assembly on site.

As far as waste is concerned, steel construction generates the smallest quantities and any waste that may be generated during the manufacture of steel elements can be recycled and reused. The amount of waste from steel products on-site is virtually zero. Prefabrication and factory based work also enable waste to be minimized, not just on site, but throughout the design and manufacturing processes, which are optimized through computer aided design and manufacturing and fully or semi-automated production lines. For steel construction, whilst wastage rates will vary depending on the complexity of the manufacturing process and the product, they are typically between 1% and 4%. Lately, it has become preferable to apply coatings for corrosion and fire protection in the factory rather than on-site, resulting in improved quality control, reduced waste and reduced on-site work.

3 ENVIRONMENTAL IMPACT ASSESSMENT

3.1 *On the building under investigation*

As the object of this study, the steel house in Crete is a single storey house with a basement. The area of the steel house is 119m² with a concrete basement that covers 60m² (Figure 2). The cross sections for the steel members are hollow sections RHS 100x50x3 and SHS 100x4. As far as the structural materials is concerned, Fe360 was used for the steel structure, whereas C16 and S500s for the reinforced concrete. Regarding the steel structure it was analyzed according to the relevant codes (CEN 2002).The basic advantages of the structural steel as the easy configuration and construction using prefabrication, adding a relatively small dead weight to the building, the flexibility it enables in architectural design and above all, the reversibility opportunity it gives for future interventions were regarded in the choice of the steel (Gallerakis 2010).

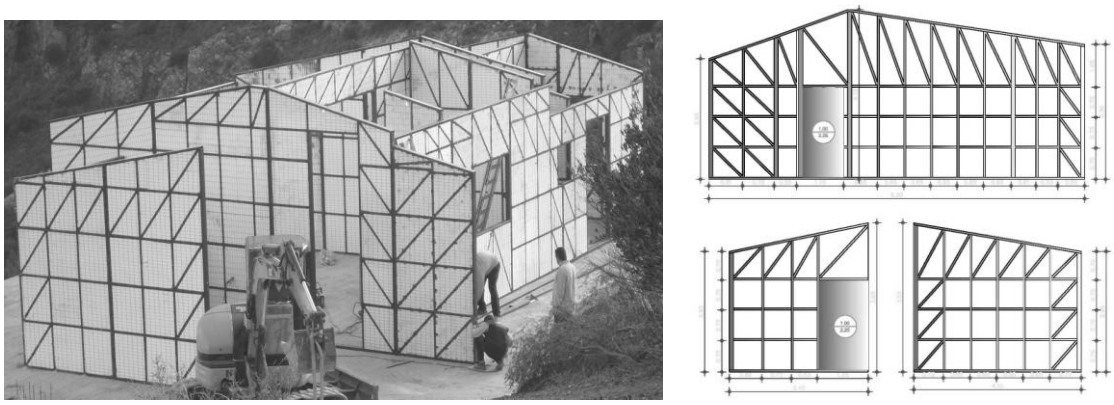


Figure 2. Steel residential building in Crete, Greece.

3.2 *LCA methodology*

The life cycle assessment (LCA) is a comprehensive system in evaluating and assessing environmental impacts and their cross comparison of a product which in this study is a steel house construction activity. The examination of the series of activities carried out for the restoration in terms of sustainability, can be achieved with the application of one the most acknowledged and widely used methodologies; life cycle assessment (Blok & Gervásio 2008). This method is based on a detailed documentation of the materials and processes used to achieve all possible works together with the complete life cycle of the project, from raw material acquisition and initial construction to maintenance and end scenarios (Zygomalas et al. 2009).

LCA bases on a holistic approach where the construction activity as a product is analysed to five phases namely the design (development), the constructional material production (resource extraction), the construction (production), the use (consumption) and finally the demolishment-rehabilitation (end of life activities) (Braganca et al. 2007). It achieves an assessment through 4 steps; goal and scope definition, inventory analysis, impact assessment and interpretation. The herein presented LCA study on the steel house construction is conducted by Simapro 7.2, the life cycle assessment tool that utilizes Eco-indicator 99 (E) V2.07 / Europe EI 99 E/E to define the environmental impacts (Pre Consultants 2008).

3.3 *Goal and definition*

The first stage of the LCA study is to define the theoretical background, namely the goal of the study, its scope and its subject (or system). The goal of the current LCA study is to identify the key areas responsible for the primary environmental impacts associated with the construction activity (Morris & Therivel 1998). The system to be studied is the construction activity and the functional unit used is the sum of construction phases carried out for the steel house construction. In regard to the scope of the study, only few system boundaries were set, namely the exclusion of works related to the infrastructure and landscaping.

3.4 *Life cycle inventory*

Following the definition of the goal and scope of the study, it is now necessary to document the life cycle inventory that lists all necessary materials and processes for the completion or delivery of the functional unit – the steel house construction. LCI contains all required resource quantities and relevant substance emissions to the environment (emissions to water, air and soil, such as CO_2, CH_4, SO_2 etc.) therefore is a vital data supplier for an environmental impact assessment of a project. For the current study, Table 1 shows the main construction materials with the respective quantities and processes used for the steel house construction.

Table 1. Materials and processes for the steel house construction.

Components	Products / processes	Quantity
Steel members	RHS and SHS type (Fe360) steel members	7,45t
Covering boards	Interior and exterior board covering were applied	580m²
Concrete	C16/20 type concrete for the composite slabs and foundation of the building	70m³
Reinforcing bars	10, 12 and 16mm diameter reinforcing steel bars	8t
Roof covering	Classic roman tiles were used	123,8m²
Floor covering	Ceramic tiles were laid on all of the building floors	166m²
Mortar	Cement-based fine mortar was used	11,4kg
Excavation	Excavation for basement and foundation	180m³

In addition to these materials, the necessary transport processes were taken into account, for the transport of the materials to the site. For the association of the materials and processes with the respective environmental loads, data contained in existing LCI databases was used. Primarily, the Ecoinvent database was used, as it contains data mostly from the geographical region of Europe.

In some cases, a complete match of the available datasets and the required processes was not possible. When it could not be avoided, logical assumptions were made in order to include all the environmental inputs and outputs as accurately as possible.

3.5 *End scenario*

In terms of end scenarios for the project life cycle, one scenario is adapted following the decision to demolish the structure. For the scenario, environmental benefit is concerned; complying with the main goal of steel house construction activity. A priority is given for reuse and recycling of the materials. Accordingly, the structural steel members and the covering boards of the main structure are collected separated in order to be recycled or reused. Tiles and reinforcing steel are sent for recycling, assuming varying percentages for the amounts collected, mostly 80% of the actual material quantity. The remaining materials are assumed to be sent for the use in landfills.

3.6 *Life cycle impact assessment*

Impact assessment of the construction activity, following the inventory listing, of an LCA study is an important step that constitutes the impact categories with values to assist an environmental impact assessment study of a project. Figure 3 contains a chart which presents the single score results of environmental impact categories for the construction of the steel house together with the end scenario. Accordingly, the construction processes with a harmful environmental effect are shown as positive, whereas processes which actually have a positive effect on the environment are shown as negative in the chart. Therefore, it is obvious that the recycling and reuse of construction materials have a positive effect on the environment.

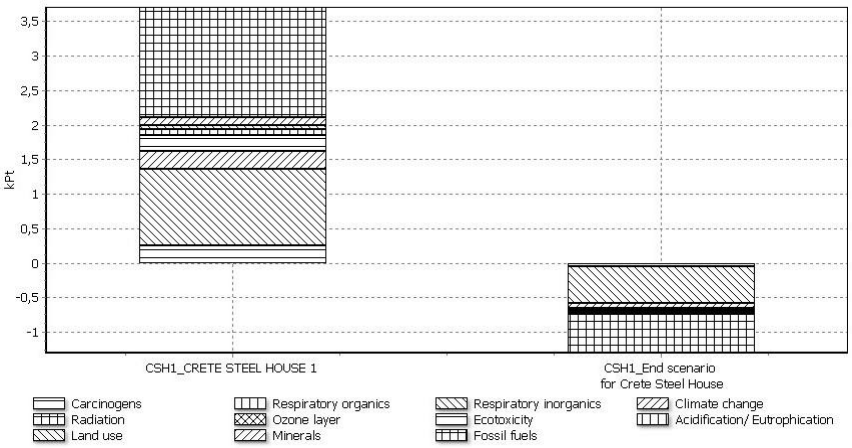


Figure 3. Single score results of environmental impact categories.

As also can be interpreted from the chart, the category ‘fossil fuels’ which refers to the increase in the amount of energy required to extract the raw material, due to the degrading of their quality (high quality raw material is extracted first, leaving lower quality material for future use) is primarily affected. The second most negatively affected impact category is ‘respiratory inorganics’ which refers to the negative impact of inorganic substances to the human respiratory system, which means that the processes and materials necessary for the construction activity mainly affect human health.

It is also necessary to gain a more detailed perspective of the processes responsible for the caused environmental impact especially for decision making on the type and methodology of the construction activity. Figure 4 presents the single scores and the impact categories involved by each construction phase of the whole steel house activity.

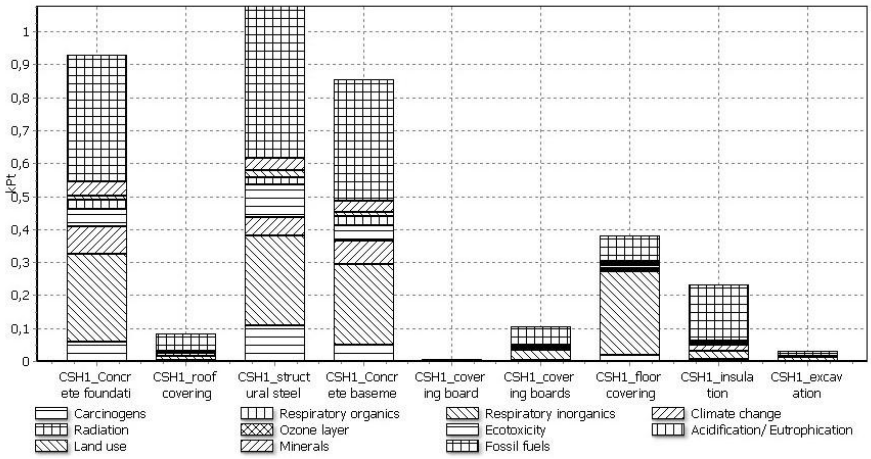


Figure 4. Single scores and the impact categories for each construction phase activity.

As it is shown in the Figure 3 steel and concrete, as materials and construction phases are responsible of the negative environmental impacts of the construction activity as they consume more primary energy and resources while exposing more as CO_2, CH_4, SO_2 and others to deteriorate the environmental values. However, as can be interpreted through the Table 2, steel construction is also a highly environmentally conscious construction activity as mostly its recycle and reuse ability has decreased the negative impacts on environmental burdens: respiratory inorganics by 47.6%, fossil fuels by 36.2%, acidification by 27% and on climate change by 26.4%.

Table 2. Effect of steel construction.

Impact Category	Unit	Total	Steel construction	End scenario
Carcinogens	Pt	198,0292	248,3207	-50,2915
Respiratory organics	Pt	0,736319	0,864094	-0,12777
Respiratory inorganics	Pt	585,6391	1116,536	-530,897
Climate change	Pt	187,2171	254,4073	-67,1902
Radiation	Pt	2,960804	3,347751	-0,38695
Ozone layer	Pt	0,080356	0,086781	-0,00643
Ecotoxicity	Pt	189,3728	220,1828	-30,8101
Acidification / Eutrophication	Pt	62,60199	85,7518	-23,1498
Land use	Pt	47,15967	62,80805	-15,6484
Minerals	Pt	99,99589	122,7069	-22,711
Fossil fuels	Pt	1031,717	1588,55	-556,834

3.7 *Interpretation of the LCA study*

As it is the general concern of LCA studies, the environmental impacts of the studied steel house construction activity are also influential on human health, eco system and natural resources. The Figure 5 clearly shows the environmental impact of each individual construction activity that are mostly on human health and resources due to steel and/but mostly by concrete based activities.

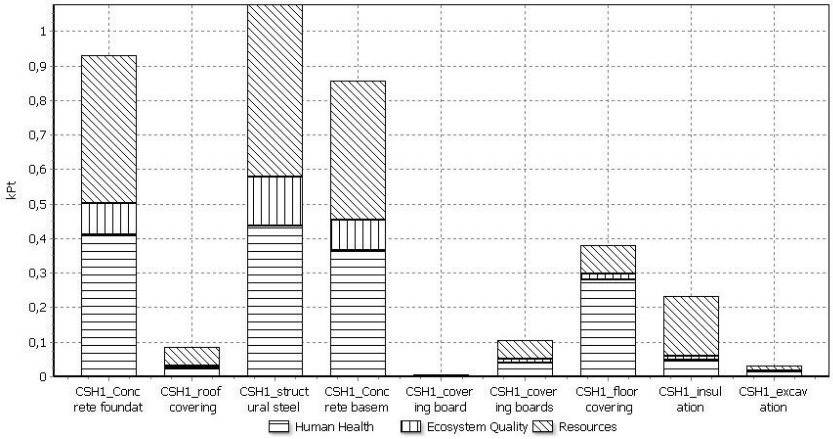


Figure 5. Environmental impact of each activity.

Regardless of the environmental impacts associated with the construction works required for the steel house construction activity, the waste scenario at the end of its operational life can greatly affect the total environmental impact.

It is also important to be able to separate the steel members and components from other materials at the demolition stage. To enable this separation to a satisfactory level, the project designer must take it into account and design for easily separated components. The composite slabs, for example, which were constructed for the project studied, present an issue at this area. It is very difficult to separate the steel members from the inside of the slabs and as a result a good quantity of recyclable steel is discarded along with the rest of the construction waste. An alternate technology for this part of the project could offer additional steel recycling potential and increased environmental benefits.

Although the house construction was steel-based, the concrete used for the slabs and foundation was found to have the most negative impact –mainly on human health- among all the required materials and processes. Its high weight-to-volume ratio makes it quite "expensive" in environmental terms. With recycling not a viable option, the use of concrete increases the environmental impact of the whole project, with no way to make up for the damage caused. It is therefore necessary to try to reduce the amount of concrete necessary or use prefabricated components that can be reused at the end of the life cycle.

Tiles, including roof and floor, were also found to have a noticeable environmental impact, compared to the rest of the materials used. Of course, it is not possible to dismiss all types of roof and ceramic tiles, yet the traditional roman and ceramic tiles used for this project can be replaced with an alternative material that would be more environmentally friendly.

4 CONCLUSIVE REMARKS

This study was conducted to present the environmental impact categories and values in a steel housing activity through a case study in Crete, which would form the basis for an environmental impact assessment study that takes environmental friendliness of a construction activity as a valuation criterion. In this framework, a life cycle assessment (LCA) methodology was applicated, which provides an understanding of the overall environmental performance of a housing construction.

The aim of this research activity was to point out the need for an integrated approach in the design process, combining environmental performance assessment with structural calculations. Environmental impact assessment of the construction activity was carried out, following the inventory listing, in order to reach to useful conclusion on the environmental study of the project.

Although steel and concrete proved to be responsible of the negative environmental impacts as they consume more primary energy and resources while exposing more as CO_2, CH_4, SO_2 and others to deteriorate the environmental values, the ability of reuse and recyclability of steel has decreased the negative impacts of steel construction on environmental burdens.

As the analysis showed, recycling of construction waste becomes a critical issue, which can ensure a number of environmental benefits. In order to implement this principle in a construction activity, it is necessary to integrate it into the design stage of the project and chose materials and systems which have a high potential for recycling at the end of the project's life cycle. Steel is a material which can be recycled almost completely, a property that should make it preferable to other materials and technologies in terms of environmental impact. Construction waste that is to be buried in landfills offers absolutely no environmental benefits and should be avoided as much as possible.

5 ACKNOWLEDGEMENTS

The authors would like to thank "Galerakis Construction", a building company with head offices in Crete in Greece, for the useful collaboration and essential contribution to this research by means of provision of the project details.

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Life cycle analysis of a steel framed building in Romania

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ABSTRACT: An example of a sustainable building is presented. The structure is a block of flats built in 2007 in Timisoara, Romania. The keys for this kind of structure are built-in flexibility and energetic efficiency. The main structure is made of steel profiles with light floors. Column-free and free floor slabs are the optimum answer to allow users to optimally reconfigure internal areas and this generally means long-span solutions. Some innovative design solutions have been used in this project, i.e. thermo-energetic cladding system, gas-electric energy supply system etc. An intensive study has been carried out in order to choose the correct cladding solution. Several types of cladding systems have been analysed, i.e. walls with or without cavity. Based on the chosen solution, interesting data related to the performance cladding system have been collected during the 2008/2009 autumn / winter season. The paper presents aspects related to design and detailing, as well as solutions for cladding and roofing, including structural features and thermo-energetic performance. One of the issues raised in case of this structure concerns the environmental impact. In the second part the paper presents an evaluation of the environmental impact for the building, for the construction stage.

1 INTRODUCTION

Construction sector plays an important role to sustainable development of the world and national economies. Sustainable construction has different approaches and different priorities in various countries. Some of them identify economic, social and cultural aspects as part of their sustainable construction, but it is raised as a major issue only in a few countries. Sustainable construction can be regarded as a subset of sustainable development and contain a wide range of issue, i.e.: re-use of existing built assets, design for minimum waste, minimizing resource and energy use and reducing pollution.

Steel as material for construction play an important role as component of buildings and engineering structures, and it is used in a wide range of applications. On the other hand, steel is the most recycled material and from the total production in the world, almost half is obtained from waste material. The steel construction sector has a great deal to offer sustainable development. Like other industrial activities, steel construction works for continuously improvement in terms of sustainability. The following guiding principles for sustainable constructions can be emphasized (Plank & Dowling 2003):

- Understand what sustainable development means for clients and customers;
- Use whole-life thinking, best value considerations and high quality information to inform your decision making;
- Design for flexibility to extend building lifetimes and, where possible, further extend the life of buildings by renovation and refurbishment;
- Design and construct with maximum speed and minimum disruption around the site;

- Design to minimize operational impacts (e.g. energy use);
- Design for demountability, to encourage future re-use and recycling of products and materials;
- Engage organizations within your supply chain about sustainability development;
- Select responsible contractors who have embraced sustainable development principles.

2 SOME CONSIDERATIONS ON THE BUILDING ENVELOPE

In the *Building Envelope Technology Roadmap* guide, the vision for 2020 is that building envelopes will be energy-positive, adaptable, affordable, environmental, healthy, intelligent and durable. This roadmap focuses on residential buildings, including new and existing low-rise multi-family dwellings as well as townhouses and single family detached homes. To achieve the vision a strategic approach containing five strategies were developed by the industry:

- Promote education/outreach along the construction value chain;
- Build a platform for collaboration in R&D leading to systems approach and improved envelope construction;
- Expand skilled workforce trained in labour reducing technology;
- Develop a building envelope performance rating system;
- Support the acceptance of emerging technologies by Codes and Standards.

The envelope is essential in ensuring the comfort and energy savings of the system taken as a whole. All envelopes have to address some of the following problems:

- To provide an exterior layer which has to balance the needs of protection from the elements, visual value and economics;
- The thermal insulation has to be compatible with the exterior layer and mechanically fastened to the structure;
- Optionally there could be a cavity space for ventilation;
- The interior component of the envelope containing the finishing surfaces can be permeable or not. The consistency of this last layer has a great influence on the indoor air quality. The trend today is to use gypsum board and vapour barrier on studs. Currently, some directions of the research focus on finding alternatives, i.e. new or traditional materials which allow for vapour migration to the wall cavity and could provide thermal inertia.

Regardless of the system / wall assembly, the envelope has to provide as much as possible a uniform “wrapping” of the steel structure in order to avoid and/or control thermal bridging. This aspect is most important, as all condensation problems start from here.

In Romania, the current trend, based on tradition, is to use as exterior layer stucco applied on a fibre glass mesh. This system which is generalized now has about a 10 years history. Before, the stucco used on the traditional brick houses was applied in a layer of 2-3cm thick and with a right composition, lasted for more than 50 years. Even though the Romanian climate is not very suitable for stucco because of the high temperature and humidity variations, the stucco is set to be used for some time in residential applications.

Because of its position on the south-eastern part of the European continent, Romania has a climate that is transitional between temperate and continental. Climatic conditions are somewhat modified by the country's varied relief. The Carpathians serve as a barrier to Atlantic air masses, restricting their oceanic influences to the west and centre of the country, where they make for milder winters and heavier rainfall. The mountains also block the continental influences of the vast plain to the north in Russia, which bring frosty winters and less rain to the south and southeast. In the extreme southeast, Mediterranean influences offer a milder, maritime climate. The average annual temperature is 11°C in the south and 8°C in the north. In Table 1 are presented the Romanian average temperature. Precipitation is generally modest, averaging over 750mm only on the highest western mountains – much of it falling as snow. In the delta of the Danube, rainfall is very low, averaging only around 370mm per year, whilst in the more westerly lowland like Bucharest it is around 530mm.

Table 1. Romanian average temperature/month.

	Bucharest	The Coast	The Mountains
January	-3°C	-1°C	-5°C
February	-1°C	1°C	-10°C
March	4°C	3°C	-3°C
April	11°C	13°C	5°C
June	21°C	24°C	9°C
July	23°C	26°C	13°C
August	22°C	26°C	11°C
September	18°C	22°C	8°C
October	13°C	17°C	5°C
November	5°C	11°C	0°C
December	1°C	6°C	-3°C

3 GENERAL DATA OF THE BUILDING

The structure is a block of flats built in 2007 in Timisoara, Romania (Dubina et al. 2007a,b). Architectural views, structure during erection and final view of the erected building are presented in Figure 1. The keys for this kind of structure are built-in flexibility and energetic efficiency. The main structure is made of steel profiles with light floors. Column-free, free floor slabs are the optimum answer to allowing users to optimally reconfigure internal areas and this generally means long-span solutions.

Figure 1. Architecture; structure during erection and final view of the erected building.

3.1 *Envelope Design*

In building this high-end three story residential building, the builder/developer aimed at providing superior levels of comfort at a reasonable cost. With this in mind, the design was directed to fulfil three main objectives: (1) to minimize heat loss through the envelope; (2) to ensure high levels of physical well-being; (3) to equip the building with an energy saving heating system.

Timisoara is located in a moderate seismic risk region. In what concerns the climate, Timisoara city is located in the temperate continental moderate climate region which characterizes the Southern-Eastern part of The Panonic Depression. General climatic features consist of various and irregular weather conditions. The average annual temperature is of 10.6°C while the hottest month of the year is July (21.1°C). Figure 2 presents the average temperature for Timisoara. Being predominantly under the influence of North-western maritime air masses, the precipitations that occur in Timisoara are far more numerous than those from the Romanian Plain. The average 592 mm annual amount (see Figure 3) is reached due to the rich May, June and July precipitations (34.4% of the total yearly amount).

Given the wide variations of seasonal temperature levels, as described above, and the cumulated effects of:

a. overheating of the south and west facades in summer;
b. heat loss due to the windchill effect on the north / north-west sides of the facade in winter,

special attention was paid first of all to the passive energy saving measures.

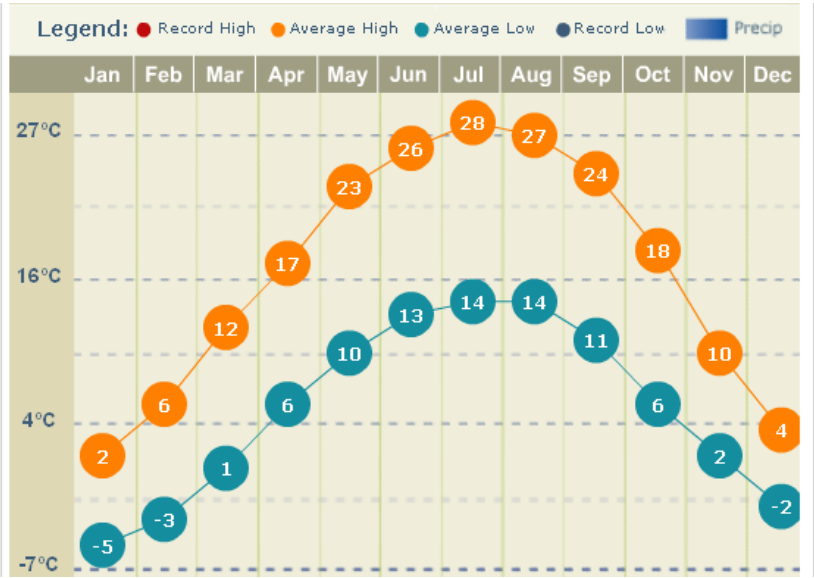


Figure 2. Timisoara average temperature.

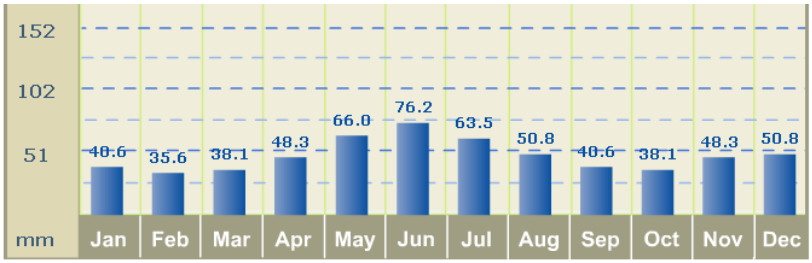


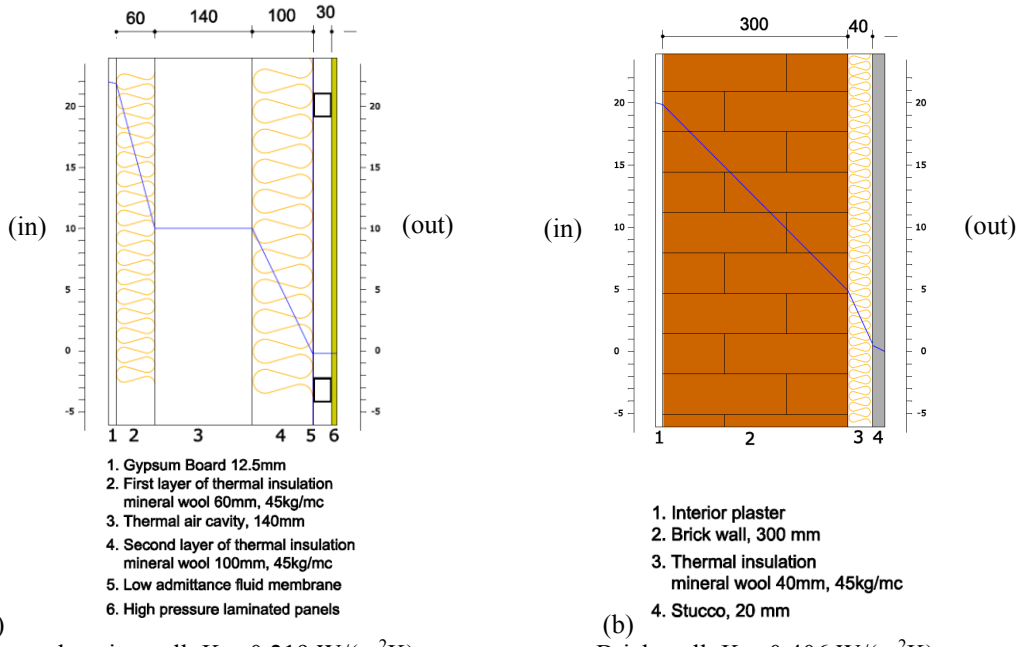
Figure 3. Timisoara average precipitation.

The envelope design was rationalised, as permitted by site conditions and functional parameters (Arghirescu et al., 2009):

a. glazing was essentially restricted to the short facades [east and west], protected from the afternoon sun by deep loggias. Windows and exterior doors are thermpane with stratified wood frames;

b. the long facades, facing North and South are mostly solid envelope, conceived as a thermal cavity system wall.

In Figure 4a are presented the actual layers for the cladding (in/out). Figure 4 illustrates the importance of adequate insulation both as thickness and position in the wall assembly; the comparison is made with a brick wall. The combined effect of insulation thickness 60+100mm and the thermal buffer produced by the 140 mm air layer, provides a high level of insulation for this climatic zone, both in summer and winter (K= 0.22 W/m^{2}K). By comparison, a brick wall with 60 mm insulation, has K=0.406 W/m^{2}K.



(a) Thermal cavity wall: K = 0.219 W/(m^{2}K)

(b) Brick wall: K = 0.406 W/(m^{2}K)

Figure 4. Importance of adequate insulation.

Figure 5 presents some pictures with the envelope during erection. The materials used in the building store moisture for a very limited period of time. The thermal insulation, mineral wool (basaltic), with the density of 45kg/m^3, allows for constant vapour migration. In order not to trap the moisture in the rooms, the vapour barrier layer under the gypsum board was eliminated, allowing for the free vapour migration through the wall to the exterior. Given the gradual migration of vapour through the thermal cavity wall, conditions for condensation are practically eliminated.

Figure 5. Envelope during erection.

In order to ensure a high level of physical well-being for the occupants, the following set of conditions has to be kept under control:

- Control of average surface temperature of enclosing elements and room temperature;
- Control of relative humidity and room air temperature;
- Control of floor temperature and room temperature;
- Control of air movement around occupants and room temperature;
- Control of acoustical influences.

The high level of thermal insulation combined with the moisture control benefits of the thermal cavity wall, address in a satisfactory manner the set of control measures enumerated above.

3.2 *Ambiental measurements*

Measurements were taken at the beginning of 2009 over a period of about two months (January and February), the coldest for this location, considered as indicative for the whole period in which the building is heated (see Table 2).

Table 2. Northern facade measurements.

Reading Hour	Date	Temperatures			Δ	Exterior Humidity (%)	Interior Humidity (%)	Interior Adjusted Humidity (%)
		T_{ext} (ºC)	T_{tc} (ºC)	T_{int} (ºC)				
08:00	15.01.2009	-0,6	+10,1	+22,5	23.1	93	12	45-55
07:30	16.01.2009	-1,2	+8,7	+21,5	22.7	93	23	45-55
07:50	17.01.2009	-6,0	+7,9	+21,5	27.5	93	18	45-55
08:22	19.01.2009	+2,8	+10,5	+21,1	18.3	66	24	45-55
07:50	20.01.2009	+3,1	+12,0	+21,3	18.2	51	26	45-55
08:00	22.01.2009	+10,0	+16,0	+21,9	11.9	77	33	45-55
24:00	27.01.2009	+6,8	+16,3	+21,3	14.5	76	34	45-55
08:00	29.01.2009	+2,3	+13,0	+20,2	17.9	72	34	45-55
07:50	30.01.2009	+0,3	+9,5	+19,5	19.2	68	26	45-55
07:30	09.02.2009	+3,0	+12,7	+19,8	16.8	71	33	45-55
08:00	16.02.2009	-3,1	+7,1	+19,6	22.7	88	22	45-55
07:30	18.02.2009	-1,6	+7,8	+19,7	21.3	81	22	45-55
08:00	20.02.2009	-6,7	+3,1	+21,1	27.8	90	22	45-55
07:50	21.02.2009	-6,4	+5,8	+21,4	27.8	92	2	45-55
07:30	22.02.2009	-4,0	+7,5	+22,4	26.4	93	2	45-55

Two sets of temperature reading sensors were placed on the North and South facades of the building, in order to measure the interior, the wall cavity and the exterior temperatures. The positions of the sensors correspond to the living room area of the apartments, with a volume of approximate 120m^3. It has to be added that at the time the measurements were taken, the apartments were not occupied and as a result, the contribution of human produced humidity in the room was not present.

As Table 2 shows, moisture content in the building, during the heating season tends to be low, as long as no fresh air supply is provided. During the heating period, humidity levels in the building rise to 30-34% after short natural ventilation periods. When occupied, the humidity level is adjusted to reach 45-55% at 20°C, through natural ventilation, human produced humidity and/or with the help of humidifiers if required. It becomes evident that by removing the vapour barrier under the gypsum board, vapour migration through the envelope is accelerated. This factor combined with the mineral wool characteristics (of not storing moisture) are the key elements for moisture control.

3.3 *The Heating System*

From technical point of view, the chosen solution is trying to make use of the energetic performances of the building, not only by means of production and distribution, but also by another parameter, i.e. the heating time, because it is very important to heat up only what we need and when we need.

The technical solution consists in the production of the thermal agent in a gas heated boiler and, in the same time in a CHP (combined heat and power unit). The distribution is made exclusively through the interior of the building, and the dispersion of the heat is done by convectors placed in the ceiling, which ensure a massive heat exchange (heating or cooling), in a short amount of time.

The usage of the CHP unit, which simultaneously produces hot water at 90°C and electricity, leads to a substantial reduction of costs, as the in-house produced electricity is cheaper than the electricity available from the distribution network. The hot water is stored in a tank, that can use thermal agent from the boiler/ CHP/ boiler + CHP/ solar panels/ heat pump/ electrical.

Some areas in the vicinity of the windows or the floors in the bathrooms are fitted with an intelligent electrical heating system, integrated in the floor. This has the advantage of being cost efficient, safe in exploitation, flexible in configuration, and can be controlled via the internet.

4 EVALUATION OF ENVIRONMENTAL IMPACT

On the following the environmental impact for the block of flats is presented, performed at the level of construction stage only. The analysis was performed using the *SimaPro* software, a general and comprehensive tool, widely used in environmental design and LCA, which uses the *Ecoinvent* database. As mentioned before, in the analysis were included the material production and construction stage.

The inventory analysis has been done according to the system boundary conditions. According to this, several aspects were considered:

- no finishing were taken into account (for example wall painting, the floor finishing, doors, windows and electrical or heating system);
- the transportation was not taken into account;
- the domestic use (water/gas/electricity use) of the building was not accounted for;
- the energy used for construction purposes (such as cranes and other technological machinery) were not integrated in comparison.

It is to be noticed that due to the lack of information for the Romanian processes and materials, the mean European values were used for the inventory instead.

For the environmental impact calculation of the building, the input materials have been considered according to the constructive elements: (1) exterior walls; (2) interior walls; (3) flooring system; (4) terrace; (5) foundation-infrastructure.

In order to have an easier input of construction materials in LCA tool used (*SimaPro*), there have been computed average values for the weight of materials. These have been estimated for each type of constructive element as follows: the total weight of materials (resulted from the material lists) was divided to the total area of constructive element (in sqm). In this way, the final result represents an aggregate average per square meter of constructive element. This represents in fact the inventory used for SimaPro tool.

The following figures present the environmental impact by considering the above input data for construction phase but disregarding the materials and processes according to the boundaries described previously. All the results are given in “Eco-indicator points” (Pt) (Eco-indicator 99, 2000), which express the total environmental load of a product or process, based on data from a life cycle assessment, in order to have unitary and comparable outcomes. The method used for impact analysis is Eco-indicator‘99.

Figure 6 presents the impact for the block of flats for the construction process ranked per constructive elements. The major impact corresponds to exterior walls and infrastructure. These constructive elements are high consumers of resources, but also have a great impact on human health.

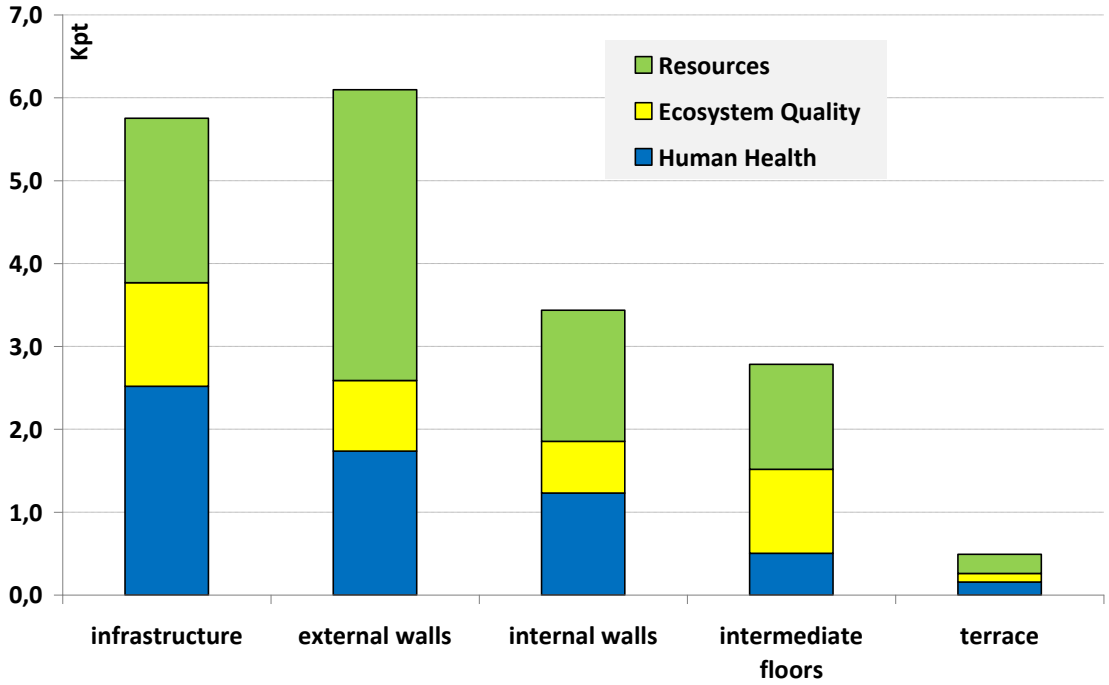


Figure 6. Environmental impact per constructive element.

Figure 7 presents the impact deduced only for construction stage. One could realise that for the structure the major impact comes from fossil fuels, as these resources are used for the fabrication of building materials at all levels. Also, important values of impact are recorded for inorganic respiratory emissions and ecotoxicity.

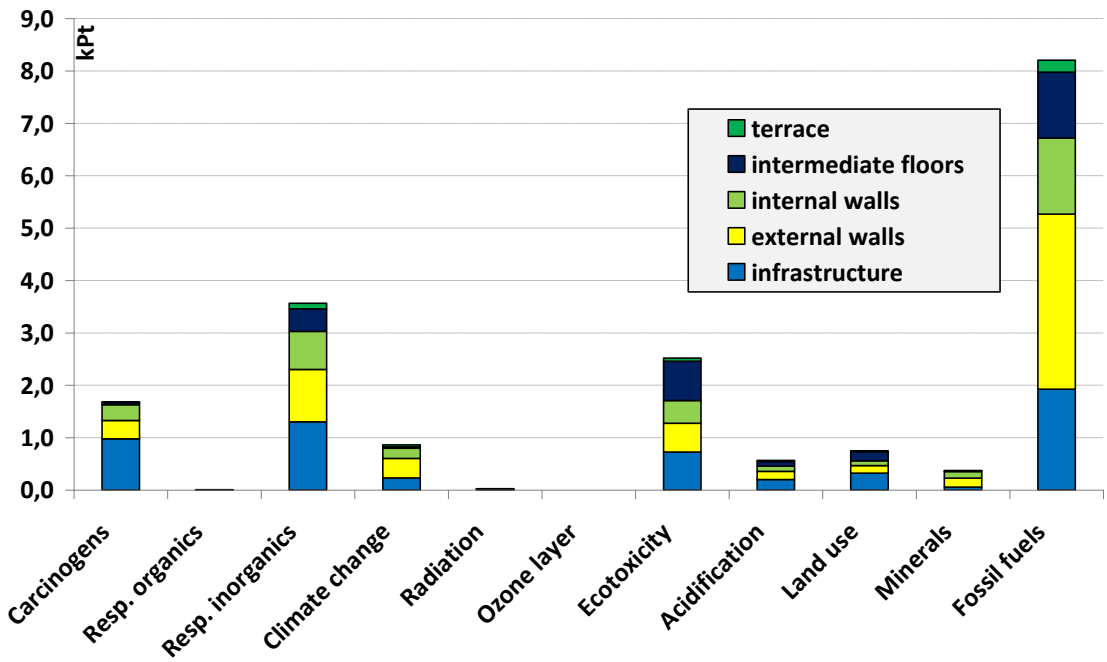


Figure 7. The environmental impact for the block of flats (weighting).

The results presented above on impact (or damage) categories are aggregated into a single score (see Figure 8), leading to an overall score of 18560 points.

Finally it can be observed that the major impact corresponds to exterior walls, followed by the infrastructure and interior walls. These constructive elements are high consumers of resources but also have a great impact on human health.

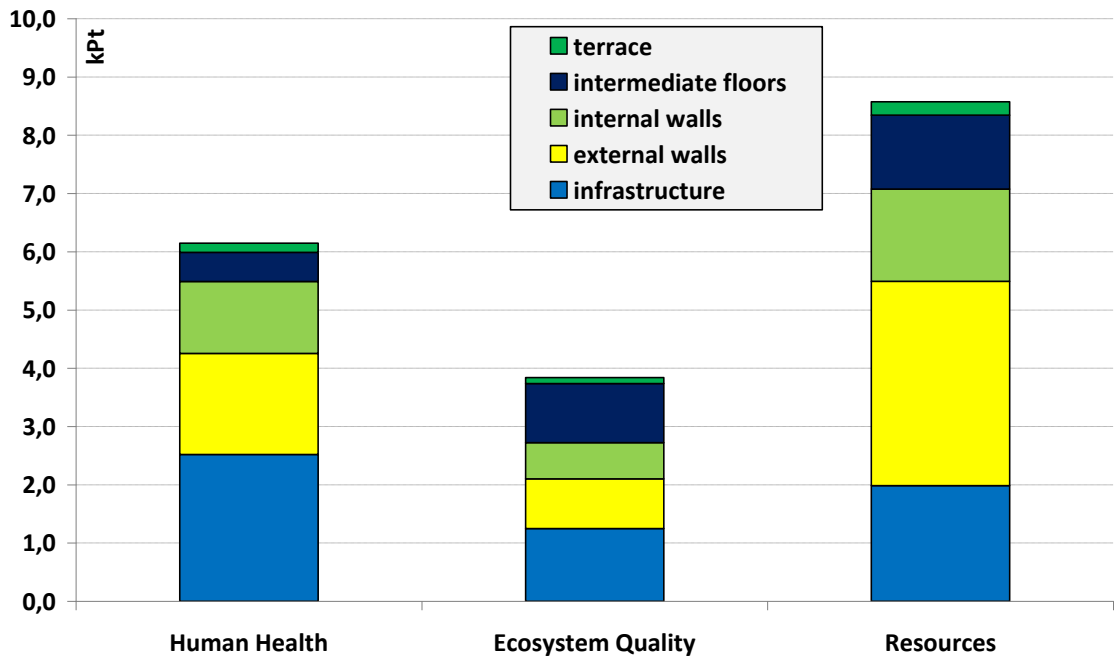


Figure 8. The environmental impact for the block of flats – single score.

5 CONCLUSION

The building represents a complete sustainable technology of high performance thermo-energetic materials used for cladding and finishing. It enables to obtain flexible partitions and allows for further up-grade, easy modifications and/or development.

The steel main frame allows for: (1) high design and construction safety standards; (2) larger spans; (3) layout flexibility; (4) faster fabrication and erection times; (5) high solution diversity for flooring and envelope.

In what concerns the physical well-being for the occupants, a set of parameters can be kept under control: (1) inside average temperature; (2) relative humidity and room air temperature; (3) air movement; (4) acoustic insulation.

In the second part, the authors perform an environmental impact analysis for the block of flats, for the construction stage only. The analysis shows that the major impact corresponds to exterior walls, followed by the infrastructure and interior walls. These constructive elements are high consumers of resources but also have a great impact on human health

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Environmental Product Declaration for structural steel as basis for sustainability assessment of constructions

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ABSTRACT: The sustainability assessment of constructions requires LCA-data of the employed construction products. To make assessment and comparison meaningful mandatory system boundaries, data quality and parameters are required. Since October 2010 an Environmental Product Declaration (EPD) "Structural Steel", obtained by bauforumstahl and valid for sections and plates of some European producers, is available. With this EPD the environmental assessment of steel or composite buildings and structures gets a reliable basis. This contribution describes the normative context and boundary conditions of life cycle assessment according to ISO 14025 and prEN 15804, the product definition of the EPD Structural Steel and LCA results with particular view on the end-of-life scenario. Furthermore the application to sustainability assessment of constructions in the framework of the upcoming European standard prEN 15978 is discussed with a comparative example.

1 INTRODUCTION

Various labeling systems for the assessment of the ecological or even sustainable quality of buildings have been developed in the recent years. The German DGNB-label (Deutsche Gesellschaft für Nachhaltiges Bauen) or the American LEED label (Leadership in Energy and Environmental Designs) are examples. These labeling systems are based on a life-cycle assessment. However they ask for different requirements concerning the environmental performance of the buildings. To assure a comparable buildings life-cycle and quality assessment, the building materials and products need to be included in this assessment.

Due to the variety of production processes behind each product (raw material extraction, transport to production site, fabrication, etc.) the designer is however not able to collect and assess a complete set of product data for each building. This task has to be taken over by the producers on the basis of their technical know-how and required internal company information on raw material sources, production and fabrication processes as well as energy consumption and/or emissions. The relevant information is provided in terms of an Environmental Product Declaration (EPD).

Every single producer or association of producers is able to develop an EPD on a liberal basis. For this EPD, relevant information for the eco-balancing has to be collected, e.g. data for quantity and kind of raw materials consumed during production. Producer specific eco-balancing is performed based on these collected values and the results are listed. In addition, many of these EPDs include further product specific information, e.g. building-physical parameters.

To assure the quality of Environmental Product Declarations the content is reviewed by an independent third-party-body to verify its accordance with ISO 14025, which standardizes eco-balancing relevant for EPDs.
In the following life-cycle assessment (LCA) is introduced. Further the EPD for structural steel is presented and the relevance of taking end-of-life into account is outlined. Finally the life-cycle inventories of structural steel are listed, discussed and summarized in reference to their environmental product declaration by bauforumstahl.

2 NORMATIVE CONTEXT AND BOUNDARY CONDITIONS OF LCA

2.1 *Normative context*

In 2005 the European Committee for Standardization (CEN) created the Technical Committee "Sustainability of construction works" (CEN/TC 350). This committee has developed several drafts for the sustainability assessment of buildings and construction products. As yet, the work of CEN/TC 350 has mainly focused on the development of standards for life cycle assessment of construction works. Other standards regarding the social and economic performance of buildings will be finished by 2012.

The standard prEN 15978 deals with the environmental performance of buildings and defines system boundaries that have to be considered in an LCA. The assessment includes all building-related construction products, processes and services used over the life cycle of the building. The information about products and services is obtained from Environmental Product Declarations. Principles for the preparation of these EPDs are given in prEN 15804.

2.2 *System boundaries*

As information from product level is directly used for building assessment, both life cycles have to be structured identically. Therefore CEN/TC 350 has created a module-based life cycle description, see Figure 1.

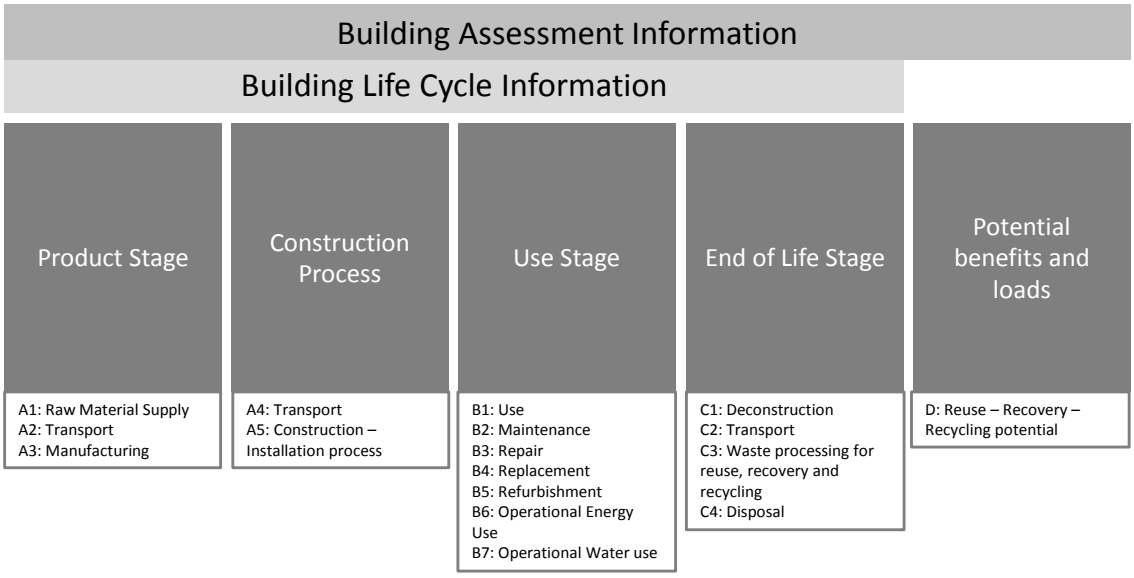

Figure 1. Life cycle stages of buildings and construction products according to the suite of CEN-standards for sustainable construction works.

This CEN/TC 350 description for the life cycle of buildings is composed of four information modules. It starts with the extraction of raw material and ends after demolition and waste processing. In order to determine the whole environmental impact caused by a construction work it is also necessary to take the fifth module, Module D, into account. This module con-

tains the net value of benefits and loads that arise from reuse and recycling of the recovered construction products (see chapter 4).

2.3 *Types of Environmental Product Declarations of construction products*

There are four types of Environmental Product Declarations:

1. Cradle to gate: The EPD only covers the product stage (Modules A1 to A3).
2. Cradle to gate with options: Such an EPD covers the product stage plus other selected Modules based on specified scenarios, e.g. maintenance or refurbishment.
3. Cradle to grave: EPD with Building Life Cycle Information: This EPD provides all information needed to describe the life cycle of a building based on specified scenarios for Modules A4 to C4.
4. Cradle to cradle: EPD with Building Assessment Information: This type of EPD provides all information to assess the environmental impact of a construction product.

3 THE PRODUCT DEFINITION OF THE EPD "STRUCTURAL STEEL"

The environmental product declaration for structural steel covers steel products rolled out to structural sections, merchant bars and heavy plates in steel grades S235 up to S960. The products can be used as structural steels intended for bolted, welded or otherwise connected constructions as:

- single storey buildings (industrial and storage halls, etc.),
- multistorey buildings (offices, residential, shops, car parks, high rise, etc.), see Figure 2,
- bridges (railway bridge, road bridge, pedestrian bridge),
- other structures (power plants, stadiums, airports, stations, etc.), see Figure 3 and Figure 4.

They are covered by the product standards EN 10025, ASTM A36, A572, A992, A913, A/SA283, A514, A573, A588, A633 and A709.

Figure 2. Multistorey buildnigs: Time Warner Towers, NY, USA.

Figure 3. Wind mill tower. [©Mickléy]

Figure 4. Guggenheim museum, Bilbao, Spain.

These steels are produced by the two following routes:

- Blast Furnace with Basic Oxygen Furnace (BF + BOF)
  In the integrated steel production route iron ore (Ferro-oxides) is mixed with coal and sintered as preparation for being fed into the blast furnace together with coking coal, the reducing agent. Pellets may also be used. The pig iron produced in the blast furnace is transferred into the basic oxygen furnace. In this vessel, the iron is converted into steel by lowering the carbon content of the iron through an exothermic reaction, by blowing oxygen into the melt. For temperature control, used steel (scrap, up to 35%) is added to the melt.
- Electric Arc Furnace (EAF)
  In the electric steel production route used steel (100% scrap) is molten in an electric arc furnace to obtain liquid steel.

Refining (lowering of sulphur and phosphorous) and alloying (e.g. about 1 % Mn, 0.2% Si) and/or micro-alloying (e.g. about 0.01% V) is applied to give the requested characteristics to the steel.

At the end of the steelmaking process, the liquid steel is transformed into a semi-finished product in a continuous casting machine or ingot casting is practiced.

For the hot rolling process the semi-product (slab, beam-blank, bloom or billet) is rolled into the final product dimensions (heavy plate, wide flats, H-shape, I-shape, U-shape, L-shape and other merchant bars). In Figure 5 to Figure 7 selected steps of the steel making process are shown.

Figure 5. Steel melting in the electric arc furnace.

Figure 6. Semi-product (beam-blank) exits the continues caster.

Figure 7. Hot rolling of a H-shape profile.

In table 1 the base materials' primary products and additives are listed for both routes. It should be noted, that the rates of the additives are depending on the steel grade.

Table 1. Base materials' primary products and additives for both routes, blast furnace and electric arc furnace.

Routes	Blast furnace (BF + BOF)	Electric Arc Furnace (EAF)
Base materials primary products	- At least 65% iron ore and up to 35% scrap (pre-consumer, post-consumer)	- 100% scrap (pre-consumer, post-consumer and internal)
Auxiliary substances / additives	- Coking coal - Coal - Lime - Ferroalloys* - Aluminum	- Lime - Ferroalloys* - Aluminum

* Ferroalloyes are :Ferro-silicium, Ferro-manganese, Ferro-nickel, Ferro-niobium, Ferro-vanadium, Ferro-titanium.

Iron ore and coal are natural raw materials which are available in a large number of qualities depending on their natural composition and structure. Lime and alloys are also from natural sources, partly pre-processed for their use in the steelmaking process, alloys may also be from recycled material. Iron ore, coal, alloys and lime as natural raw materials are extracted from the soil usually in surface and underground mines. World's iron ore reserves are infinite as iron (chemical element: Fe) is one of the most frequent elements on earth. Further the world has large reserves of coal.

Steel scrap however is a secondary raw material traded in several well defined qualities depending on composition (Fe-content) and origin-related characteristics (e.g. plates and sections, galvanized sheets, shreddings and turnings). Scrap and alloys to some extent are collected from demolition and shredder sites and other end of use origins (post-consumer), from steel processing and manufacturing of steel products (pre-consumer), and internal recovery during steel making. Steel scrap (=used steel) is very abundant. Europe is a net exporter of scrap.

4 END-OF-LIFE SCENARIOS FOR MATERIALS - BENEFITS AND LOADS

4.1 *Basic Scenarios and their relevance for structural steel*

The consideration of the material production process (product stage A1-A3, Figure 1) only is regarded obligate according to prEN15804 for the environmental evaluation of construction material. Whereas further phases such as construction (A4-A5, Figure 1), use ((B1-B7, Figure 1) and decommissioning (C1-C4, Figure 1) form the so called life-cycle of the building, the actual building assessment must, according to prEN15804, also include the end-of-life scenario of the construction materials (benefits and loads, D, Figure 1). After the building has been decommissioned and dismantled the construction products and materials will be separated into the different material fractions and, as possible, are designated for new applications. Different scenarios can be assumed. According to the new EU Waste Framework Directive reuse of materials has to be preferred. Otherwise recycling as a material, without loss of quality, is the next choice before reclamation (e.g. energy) and disposal. Those scenarios are associated with additional benefits or loads which shall be considered when assessing the environmental impact of a building.

Reuse means that construction products are used again with the same shape and the same purpose for new buildings as in the old. Only minor efforts and emissions are required. Recycling involves processing used materials into new products. In a strict sense, recycling of a material would produce a fresh supply of the same material – for example, used office paper is converted into new office paper. However, this is for many construction products difficult or too expensive, so “recycling” involves often also producing different materials (e.g. paperboard) with often lower quality instead. This is then also called downcycling. When materials cannot be recycled as just explained reclaiming at least certain values of the material can be a strategy to reduce waste. Most common is the reclamation of energy by burning construction products thus producing energy but also CO_2.

For structural steel a truly functioning cycle has been established for many decades in Europe. Here the collection rate of structural steel is 99% - with other words: from 100 tons structural steel used in a building 99 tons will be recovered after dismantling. Then, in average, 11% of structural steel products – sections and plates – are reused again directly for structural purpose and 88 % are used for closed loop material recycling. For structural steel recycling means the remelting of used steel (scrap) and subsequent rolling of new sections or plates. Because of steel recycling the production of new steel from ore in the blast furnace (BF+BOF) is reduced leading also to less energy consumption or emissions and preserving the material without any degradation of material properties. In fact, because of the modern thermo-mechanical rolling processes even improvements of material properties (upcycling, e.g. steel grad S235 becomes S460) are possible. Reclamation and disposal are no options for structural steel because its inherent value.

4.2 *The benefit of the recycling potential*

When a material can be recycled as described above the use of new raw materials, the consumption of energy or the emission of CO_2 can be reduced. From the 88% of steel scrap which is actually recycled the fraction of the scrap which was necessary for the production must be subtracted (here about 460 kg used steel /scrap per ton). The remaining net scrap (here about 420 kg used steel /scrap per ton) is available to avoid additional steel production from ore and is called recycling potential, see also Figure 8.

The basic idea of this concept is that environmental loads are allocated to each material cycle as they are in a net balance of a cradle-to-cradle frame. As for steel, in the first necessary step of producing in the BF+BOF route total amount of energy consumption or emissions are relatively high. This steel is then for example used in a building. Let us now assume the collection rate was 100%. Then, compared to the original material iron ore, which can be found in nature, the valuable product used steel for reuse or recycling is fully available. Hence only the difference between iron ore and used steel (cradle-to cradle) must be allocated in this first material cycle. On the other hand, if the collection rate was zero the full effort of producing steel from

ore had to be allocated. If the used steel (scrap) is in the second step fully remelted in the electric arc furnace the total amount of energy consumption or emissions are lower than for the BF+BOF process. The steel is used again, this time perhaps for a bridge. Again the collection rate is assumed 100%. Now used steel is available in the same way as before. Or in other words: not using the material but loosing it is penalized. Thus the concept of a recycling potential encourages a careful planning and design as well as handling of construction products.

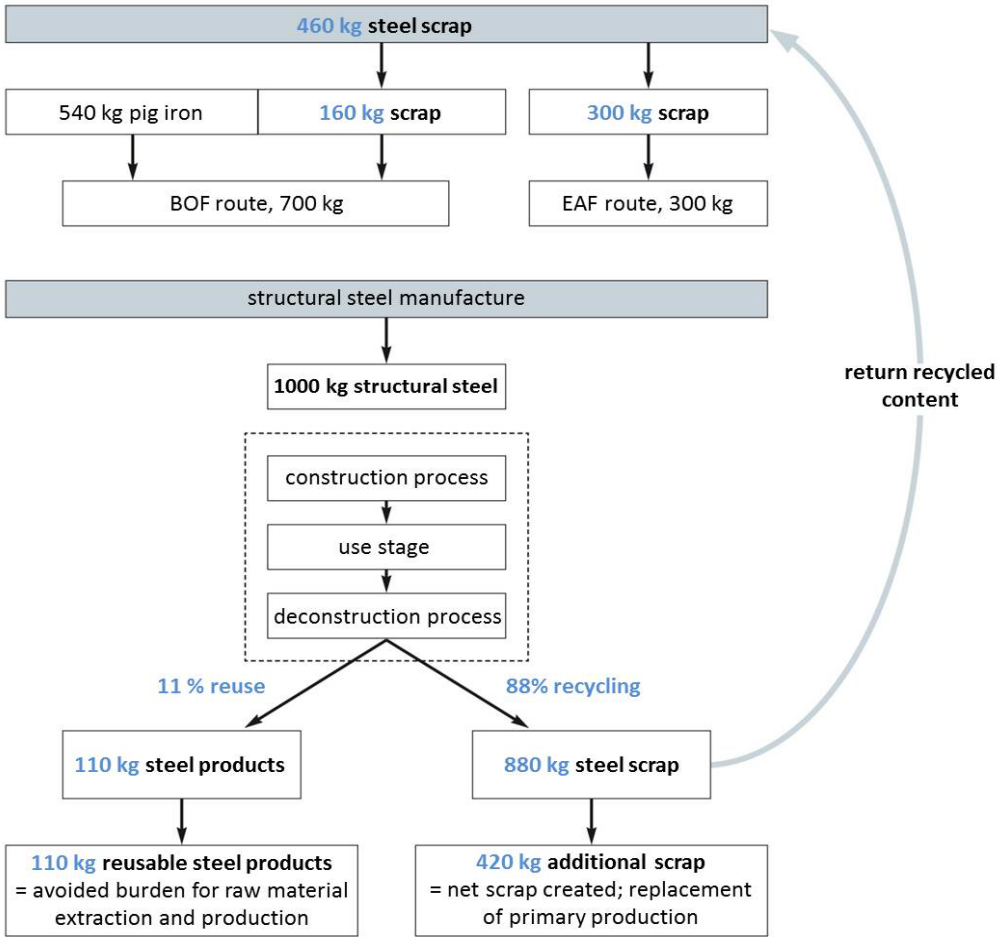

Figure 8. Schematic determination of the recycling potential
(net scrap replacing new production from iron ore, primary production).

5 DESCRIPTION OF THE ASSESSMENT RESULTS AND ANALYSIS

5.1 *Life Cycle Inventory*

Life cycle inventories are the determined material and energy flows along the manufacture and the End-of-Life of the considered products. Herefore the primary energy consumption, water utilization, wastes environmental impact are analyzed. In the following the life-cycle inventories as presented in the EPD “Structural Steel” are introduced.

5.2 *Primary energy consumption*

The average primary energy consumption of the production and recycling of 1 kg structural steel is shown in Table 2. The recycling benefit results from the avoided production of steel in the BF+BOF route due to the recycling potential. Therefore the primary energy demand in the production phase can be reduced to the actually consumed amount, see chapter 4.

There is no net-credit for the end-of-life of the energy carriers uranium and lignite. This is due to the power consumption (and the correspondent consumption of energetic resources) throughout the recycling process in the electric furnace.

Considering the different primary energy carriers during the production phase the hard coal has the highest influence (52 %) due to the coke resp. coal usage during the coke making process and in the blast furnace process. It follows with 25 % the energy carrier natural gas and the remaining ones are below 10 %. Uranium is only used in the extraction of power in nuclear power plants.

Table 2. EPD: average primary energy consumption of 1 kg structural steel (production and EoL).

Average volume production	Unit	Production	End-of-Life	**Total**
Primary Energy from Resources	MJ	19.48	- 7.70	**11.78**
Primary Energy from Crude oil	MJ	1.55	- 0.94	**0.61**
Primary Energy from Hard coal	MJ	10.54	- 7.11	**3.43**
Primary Energy from Lignite	MJ	1.10	+ 0.06	**1.16**
Primary Energy from Natural Gas	MJ	5.03	- 0.10	**4.93**
Primary Energy from Uranium	MJ	1.26	+ 0.40	**1.66**
Primary Energy from Renewables	MJ	0.65	- 0.08	**0.57**

5.3 *Water utilisation*

Table 3 shows the water consumption of one kg structural steel for production and EoL (= post utilization phase; reuse and recycling). It shows that the water consumption is divided in different categories. In the End-of-Life phase credit for water consumption is reached. Therefore the total amount of water consumption of one kg structural steel is 1.88 kg (6.750 from production – 4.870 credit from EoL). Mills operate mainly with a closed-loop water system.

Table 3. EPD: water consumption of 1 kg structural steel (production and EoL).

Average volume production	Unit	Production	End-of-Life	**Total**
Water Consumption (Total)	kg	6.750	- 4.870	**1.880**
Fresh Water	kg	3.011	- 2.966	**0.045**
Ground Water	kg	1.363	- 0.429	**0.934**
Origin not Specified	kg	6.560	- 2.671	**3.889**
River Water	kg	- 4.209	1. 226	**-2.983**
Sea Water	kg	0.020	- 0.028	**-0.008**

5.4 *Wastes*

The aggregated values of the life cycle inventory analysis, referring to waste production, listed in Table 4 represent one kg structural steel for production and EoL (=recycling).

Stockpile goods are dominated by overburden (> 96% contribution). Overburden is mainly generated by coal extraction (coal for power generation and iron making).

The gained credit of the End-of-Life phase is also depending on the overburden (stockpile goods). The recycling potential (avoiding of primary steel slab production) gives credit for the stockpile goods and dangerous waste and therefore the total amount of waste can be reduced.

Table 4. EPD: waste of 1 kg structural steel (production and EoL).

Average volume production	Unit	Production	End-of-Life	**Total**
Waste (Total)	kg	4.52	- 2.35	**2.17**
Stockpile Goods	kg	4.51	- 2.36	**2.15**
Consumer Waste	kg	4.25E-04	0.01	**1.04E-2**
Dangerous Waste	kg	0.003	- 1.79E-03	**1.21E-03**
Radioactive Waste	kg	4.3E-04	9.90E-05	**5.29E-04**
Hazardous Waste	kg	0.003	- 1.89E-03	**1.11E-03**

5.5 *Environmental impact*

For the evaluation of the potential environmental impact of the structural steel the CML-methodology (CML = Center voor Milieukunde at Leiden) with the characterization factors of 2007 (December) is applied. The impact assessment indicators and impacts of 1 kg structural steel for production and EoL (= recycling) phase are listed in Table 5.

Table 5. EPD: impact assessment indicators of 1 kg structural steel (production and EoL).

Average volume production	Unit	Production	End-of-Life	**Total**
Abiotic Resource Depletion (ADP)	kg Sb-Equiv.	8.77E-03	- 3.89E-03	**4.88E-03**
Global Warming Potential (GWP)	kg CO_2-Equiv.	1.68	- 0.88	**0.80**
Ozone Layer Depletion Potential (ODP)	kg R11-Equiv.	3.19E-08	1.04E-08	**4.23E-08**
Acidification Potential (AP)	kg SO_2-Equiv.	3.47E-03	- 1.68E-03	**1.79E-03**
Eutrophication Potential (EP)	kg PO_4-Equiv.	2.89E-04	- 1.31E-04	**1.58E-04**
Photochem. Ozone Creation P. (POCP)	kg C_2H_4-Equiv.	7.55E-04	- 4.57E-04	**2.98E-04**

Considering the influence of the two phases it can be seen that the share of the production phase is nearly for all categories the same. It ranges from 62 % to 75 %. For all considered impact categories, besides ODP, a credit can be given for the End-of-Life phase. There is no credit for ODP due to the fact that EAF process in the End-of-Life phase is based on power consumption.

Depending on the type of product (section or plate) and the type of production process (BF+BOF or EAF making) the influence of the process steps differs per considered impact category. While BOF route is dominated through the coke and coal input through the coke production process and in the blast furnace, the EAF route is mainly dominated through the power consumption in its environmental profile.

Global Warming Potential is dominated by the carbon dioxide emissions. The savings in the end-of-life phase are confronting the contribution of the production and remelting within the recycling to the GWP. In total, the GWP for the complete life-cycle is 0.8 kg CO_2-Equivalent.

6 APPLICATION TO SUSTAINABILITY ASSESSMENT OF CONSTRUCTIONS

Due to the growing importance of sustainability of constructions it is necessary to provide significant comparative studies to evaluate the environmental assessment of construction products in the framework of a functional unit, e.g. a building. The following research refers to an LCA study by Kuhnhenne et al. (2010).

Comparisons between assessment results of construction products shall only be made on the basis of their functional equivalence and have to include all influencing factors. For the study discussed here the complete structural system of a typical single storey building was chosen as functional unit. It comprises foundations, columns and girders. For more details see also Kuhnhenne et al. (2010). The study examined two life cycle approaches:

- product stage only (A1-A3, Figure 1),
- product stage plus disposal/ recycling potential (A1-A3 & D, Figure 1)

and five different structural systems for the single storey building:

- reinforced concrete column and beams,
- reinforced concrete columns with laminated timber girders,
- steel frame in S235,
- steel frame S355,
- steel frame S460.

The LCA data for timber, concrete and reinforcement refer to the ökobau.dat 2009 database (www.nachhaltigesbauen.de/baustoff-und-gebaeudedaten/oekobaudat), see also Table 6. Data for structural steel originate from the Environmental Product Declaration “Structural Steel: Sections and Plates”.

In Figure 9 the results for the product stage only (A1-A3, Figure 1) are depicted. Focusing on the product stage the steel structures are evaluated incomplete and hence disadvantageous because of the relatively high total energy consumption in the production process, see chapter 4.

Table 6. Life-cycle inventories for 1kg of further construction products (database: ökobau.dat)

Product	Average volume production	Unit	Production	EoL	**Total**
Concrete C25/30 (foundation)	Global Warming Potential	kg CO_2-Equiv.	0.09	0.03	**0.12**
	Primary Energy Consumption	MJ	0.47	0.06	**0.53**
	renewable	MJ	0.00	0.01	**0.01**
	non-renewable	MJ	0.47	0.05	**0.52**
Concrete C30/37 (column/beam)	Global Warming Potential	kg CO_2-Equiv.	0.10	0.03	**0.13**
	Primary Energy Consumption	MJ	0.51	0.06	**0.57**
	renewable	MJ	0.00	0.01	**0.01**
	non-renewable	MJ	0.51	0.05	**0.56**
Reinforcement (foundation, Column, beam)	Global Warming Potential	kg CO_2-Equiv.	0.87	0.00	**0.87**
	Primary Energy Consumption	MJ	13.41	0.00	**13.41**
	renewable	MJ	0.99	0.00	**0.99**
	non-renewable	MJ	12.42	0.00	**12.42**
Timber (girder)	Global Warming Potential	kg CO_2-Equiv.	-1.46	1.18	**-0.28**
	Primary Energy Consumption	MJ	32.13	-10.36	**21.77**
	renewable	MJ	20.57	-0.11	**20.46**
	non-renewable	MJ	11.56	-10.25	**1.31**

Here, availability of used steel (scrap) after the dismantling of the structure is not considered; same as effects of incineration of timber or disposal of concrete. Concrete/timber construction causes hardly any greenhouse gases and has a high percentage of regenerative energy due to the fact that timber stores CO_2 and solar energy when growing.

Subsequently the analysis is performed in the framework of the building assessment information (Figure 1) considering product stage, disposal and recycling potential; results see Figure 10. Including the benefits (recycling potential) and loads in the analysis shows that the factually reuse and recycling of steel implicates remarkable benefits for further life cycles. In contrast timber releases the stored CO_2 when energy is reclaimed in the incineration plant and gains less credit for thermal and downcycling. A high percentage of reinforced concrete goes for disposal and therefore gets additional loads. The utilization of high strength steel is somehow advantageous. Overall the different structural systems perform comparable.

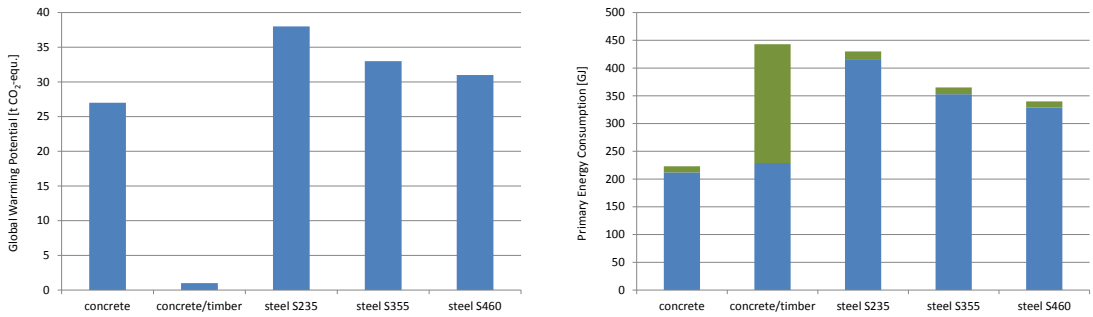

Figure 9. Results for product stage only (A1-A3, cradle to gate):
global warming potential (t CO_2 equ.), primary energy consumption (GJ).

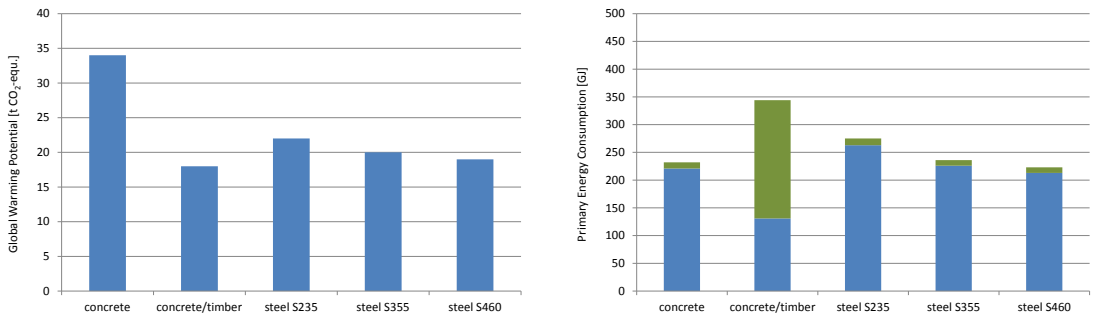

Figure 10. Results for product stage, disposal / recycling potential (A1-A3 & D, cradle to cradle):
global warming potential (t CO_2 equ.), primary energy consumption (GJ).

7 CONCLUSIONS AND OUTLOOK

The producers of construction materials are aware of the public interest in sustainability assessment of buildings and the sustainability of materials used in those constructions. Especially the necessity of comparing building constructions made of different products in an integral and holistic approach has been realized – which means a building assessment over the complete life-cycle – including the end-of-life of the construction materials. The Environmental Product Declaration (EPD) "Structural Steel" provides all relevant information for assessment; see Table 7 for a summary.

Table 7. EPD: summary of the life-cycle inventory for 1 kg structural steel (sections and plates).

Average volume production	Unit	Production	EoL*	**Total**
Primary Energy, non-renewable	MJ	19.48	- 7.70	**11.78**
Primary Energy, renewable	MJ	0.65	- 0.08	**0.57**
Global Warming Potential (GWP 100)	kg CO_2-Equiv.	1.68	- 0.88	**0.80**
Ozone Layer Depletion Potential (ODP)	kg R11-Equiv.	3.19E-08	1.04E-08	**4.23E-08**
Acidification Potential (AP)	kg SO_2-Equiv	3.47E-03	- 1.68E-03	**1.79E-03**
Eutrophication Potential (EP)	kg C_2H_4-Equiv.	2.89E-04	- 1.31E-04	**1.58E-04**
Photochem. Ozone Creation P. (POCP)	kg C_2H_4-Equiv.	7.55E-04	- 4.57E-04	**2.98E-04**

* The EPD is based on 99% recovery of used steel (with 11% reuse & 88% recycling)

It has been discussed in this paper that the end-of-life scenario for materials plays an important role in evaluating the environmental performance of a building. Whether a material is available again for the same construction purpose, only some energy can be reclaimed or the material must be disposed does make a difference if the associated benefits and loads are taken into account. The authors claim here that a full-fledged sustainability assessment of constructions must pay attention to those benefits and loads. This may be substantiated by the fact that availability of resources as well as reduction of waste etc. are hot topics of the present political agendas and will be part of the European normative framework for the construction sector.

Design for deconstruction is an upcoming key topic for engineers and architects to achieve high reuse and recycling rates of construction products. This will be our responsibility to reduce energy consumption and emission of green house gases in the construction sector. In the near future missing steps in the environmental assessment such as construction processes, use stage or the end-of-life of the building (not EoL of the material, which has been discussed here) must also be added to the assessment. In particular for steel construction with its typical high degree of prefabrication and other advantages (e.g. short construction times, light-weight elements, less influence of weather condition on site, safety on site, low sound and dust emission on site, easy to demount connections etc.) further benefits are expected.

The upcoming European suit of standards for the sustainability assessment (CEN/TC 350) looks at first at environmental aspects of constructions, which are addressed in this paper. But also work on the assessment of social and economical performance of constructions progresses.

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Life Cycle Assessment of Composite Bridges

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ABSTRACT: Life Cycle Assessment is a powerful tool for the environmental evaluation of built environment. The strength of this methodology lies in its holistic approach, considering the whole life of a product, from the extraction of raw materials through the manufacture, usage and destiny at its end of life. Life Cycle thinking is particularly of interest for the environmental evaluation of steel products, especially when the benefits of steel recycling at end of life of the structure are taken into account.
This paper introduces life cycle assessment for composite bridges, provides the life cycle inventories for the materials used (including sources), and finally illustrates the benefit of steel recycling properties in the assessment on the basis of a case study. With a recycling rate for steel girders of 99% the case study demonstrates the strong interest of using steel in bridge structures, not only to avoid emissions of CO_2-eq but also achieve sustainable structures.

1 SUSTAINABLE BRIDGES

1.1 *Introduction*

The preservation of natural resources in our industrialized societies has become priority in creation of built environment. As a result, construction concepts have to comply with changing economical parameters like the incorporation of life cycle analyses in the design of structures as well as with technological changes in considering sustainability goals in respect to the environment and society. These sustainability goals are in nature: ecological, economical, socio-cultural, technical oriented and process oriented.

They are interdependent as well as ambivalent, providing a coherent response to complex questions and ensuring future generations a pleasant environment.

Bridges are of vital importance to the transport infrastructure of societies. Growth in traffic density during recent decades has been tremendous. As a consequence, numerous new roads and railway lines were built or are planned to be realized in the near future. Meanwhile, existing bridges must carry the increased traffic; considering all bridges, short span bridges are the most frequent category. Therein, the use of composite bridges can play a significant role.

Sustainable composite bridges with the use of rolled steel sections provide the opportunity to give an answer to the infrastructural demand while being fully consistent with the various aspects of sustainability goals (AMCS 2009).

1.1.1 Ecological aspects of sustainability

The main ecological goals aim at using construction materials that are safe from health and environmental points of view, reducing waste when dismantling the structure at the end of their service life, and at preserving as best possible the energy content in the construction materials, thus maintaining their ideal efficiency. Here, structural steels offer high material efficiency and

constitute the most recycled construction material in the world. In the modern electric arc furnace (EAF) route; rolled sections are e.g. produced using 100% scrap as a raw material. In addition, EAF technology allows for significant reductions of noise, particle and CO_2-emissions as well as water and primary energy consumption in the production mills (AMCS 2003).

Bridges using these rolled sections are maintenance-friendly structures, easy in deconstruction and excellent to preserve the resources for recycling at the end-of-life (Hechler 2009). The recovery rate of rolled sections in bridges is 99% (Sansom 2002). Also, steel elements may be re-used after dismantling. Due to their low weight, the possibility to use detachable connections and fast erection schemes e.g. mobile bridge designs have been developed.

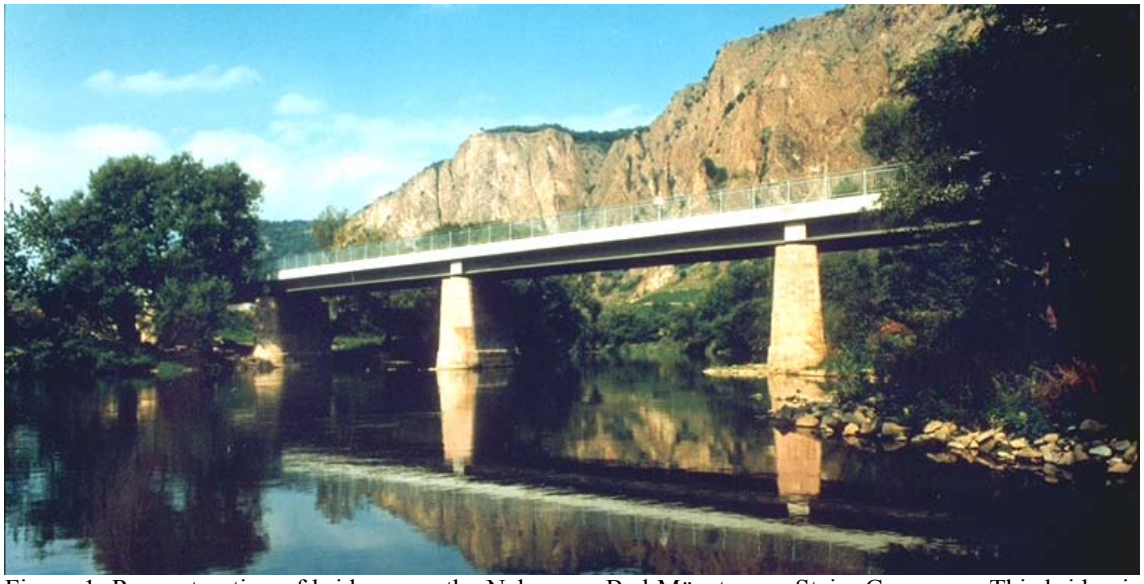

Figure 1. Reconstruction of bridge over the Nahe near Bad Münster am Stein, Germany - This bridge is located in a nature reserve. The light composite deck was constructed on the existing piers.

1.1.2 Economical aspects of sustainability

Besides being interested in the reduction of investment costs, investors are also concerned about the optimization of operational costs and the achievement of the longest possible service life in combination with high flexibility in use of the structure. Steel in bridge construction allow architects and designers to easily fulfill the requirements of investors by combining high quality, functionality, aesthetics, low weight and short construction times. Slender superstructures can be designed which decrease construction height and earthworks leading to a further decrease of material, fabrication, transport and construction costs.

Short construction times and therefore reduced traffic disturbance save user costs during construction, enabling public savings to be achieved. Tenders including the life cycle costs prove the competitiveness and sustainability of composite construction for bridges with short and medium spans. In addition to economic constructional costs, steel and composite bridges are also operationally economical. They are easy to maintain, because the structural components are readily accessible for inspection and maintenance work. Inspecting composite bridges is simple and reliable. Bridges using steel sections can be repaired. Composite bridges are a flexible and low cost method in adapting to changes in requirements e.g. the widening of traffic lanes or the strengthening of the structure.

1.1.3 Socio-cultural aspects of sustainability

Bridge design has also to take into account aesthetic demands with the social expectations of its surrounding environment, either by design of an architecturally uniform work or structures which do not over-dominate visually. Bridges with steel sections lead to transparent and lean structures combined with robustness and safety. Local inhabitants and their social environment remain clean in uncontaminated surroundings as steel in structures does not release any harmful substances into the environment.

1.1.4 Technical aspects of sustainability

Composite bridges have the advantage of being able to resist high level utilization and are adaptable to changes in use. These robust construction solutions are capable of coping well with variations in use during service life without damage or loss of functionality. Especially for the refurbishment of bridges, intelligent solutions are required. On the one hand the public economy has to be satisfied to a certain extent; on the other hand technical, economic and political boundaries have to be respected. In this regard, composite construction is providing the potential with the possibility to use cost-effective construction techniques and advanced construction procedures providing adaptability of the available bridge systems (Hechler 2007).

1.1.5 Process aspects of sustainability

Steel construction offers many advantages through its flexibility, lightness and cost effectiveness. In composite construction for short and medium span bridges, rolled beams are used as primary bearing elements. They are industrially produced to a high quality, offer good availability in a full range of sizes and steel grades, including the high strength grades (e.g Histar) (AMCS 2003). With long lengths possible the end product is accordingly delivered to site ready for erection. Quality control has already been carried out at the producing rolling mill. Smaller construction sites and plant equipment are therefore needed whilst minimal noise and dust disturbance on site are characteristics for steel construction.

The bridge solutions using hot rolled sections can reduce erection times. Hence, cost for traffic control measures are saved as well as accident potential is reduced. These bridges are designed to be constructed without essential interference to the traffic under the bridge as well as to incorporate minimized traffic disturbance throughout their maintenance.

2 LIFE CYCLE ASSESSMENT OF COMPOSITE BRIDGES

2.1 *Introduction*

Today the understanding of sustainability is however mainly associated with ecological aspects of sustainability. To evaluate ecological aspects of built environment Life Cycle Assessment (LCA) is applied as a powerful tool. The strength of this methodology lies in its holistic approach, considering the whole life of a product, from extraction of raw materials through the manufacture, usage and destiny at its end of life (EOL). In the following the traditional steps of an LCA (Goal and scope definition, Inventory analysis, Impact assessment and interpretation) as defined by the ISO 14040-44, are carried out for a composite bridge.

Life Cycle thinking is particularly of interest for environmental evaluations of steel products, especially when benefits of steel recycling at end-of-life of the structure are taken into account. End-of-life aspects can be integrated in LCA through various methodologies. The method proposed by WorldSteel Association (WorldSteel 2010) (used in this paper) has been reviewed and approved as being compliant with the ISO 14040-44 standard governing LCA methodology. The basis of the approach of WorldSteel is to consider steel in all its lives, starting from its production from iron ore, and continuing indefinitely through secondary cycles, avoiding the need for virgin material.

2.2 *Scope of this LCA*

2.2.1 Objectives

The purpose of this LCA is to evaluate the ecological aspects of composite bridges, made of concrete and steel. Bridges are designed specifically for each individual construction site, influenced by a large number of parameters, mainly however by the type of bridge (road, railway, pedestrian) to be designed, the span, the number of spans and the width. For this case study a typical bridge layout is chosen for environmental evaluation.

Focus of the assessment will be on the Global Warming Potential (GWP) as this indicator is the most significant for politics today (compared to others e.g. acidification). The GWP is a value for the specification of the increased warming of the troposphere due to anthropogenic greenhouse gases e.g. from the burning of fossil fuels. The model defining the Global Warming Potential of different greenhouse gases (GHGs) is developed by the Intergovernmental Panel on

Climate Change (IPCC 2007): "Greenhouse Gases differ in their warming influence (radiative forcing) on the global climate system due to their different radiative properties and lifetimes in the atmosphere.

These warming influences may be expressed through a common metric based on the radiative forcing of CO_2. CO_2-equivalent emission is the amount of CO_2 emission that would cause the same time-integrated radiative forcing, over a given time horizon, as an emitted amount of a long-lived GHG or a mixture of GHGs. The equivalent CO_2 emission is obtained by multiplying the emission of a GHG by its Global Warming Potential (GWP) for the given time horizon.". The reference substance is therefore carbon dioxide (CO_2) – the reference unit is [kg CO_2-equivalent]. The CO_2-equivalent is calculated from the green house gases according to (1) (IPCC 2007):

$$\text{GWP} = \text{Quantity of GHG x Conversion factor} \qquad (1)$$

for which the conversion factor is given in Table 1.

Table 1. GWP100 of different GHG (IPCC 2007).

GHG	Potential
CO_2	1
CH_4	25
N_2O	298
FCKW	<14.400
FKW/HFKW	<14.800
R-134a, HFC-134a	1.430
SF_6	22.800
NF_3	17.200

2.2.2 Functional unit

The functional unit is the primary function(s) fulfilled by the product under study (Guinee 2001). LCAs have always to be carried out for a functional unit – LCA-comparisons of masses or volumes of certain materials are not appropriate. For bridges, the functional unit is characterized by the number of spans and lanes, for a specific lifespan. The functional unit chosen here is a two-span composite bridge, as described in the following section. The lifespan (use phase) has not been considered in the following assessment as there are no effects on the results.

2.2.3 Products and case studies description

The functional unit defined is a two-span road bridge with spans of 2 x 29,27m. The width of the bridge has been specified to be 16,55m with a high truck flow rate. The solution elaborated and assessed is a composite bridge with partially pre-fabricated bridge girders and reinforced concrete cross girders. The cross section is shown in Figure 2. The bill of quantities is given on Figure 3.

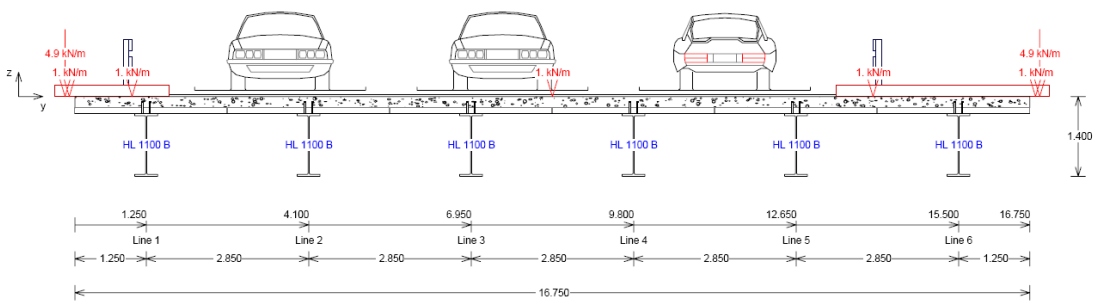

Figure 2. Cross section of the two-span composite road bridge with the use of partially prefabricated bridge elements.

Material	Tonnage [to]
Rolled sections	139
End plates	4
Shear studs	1,56
Concrete	~860
Steel reinforcement	47

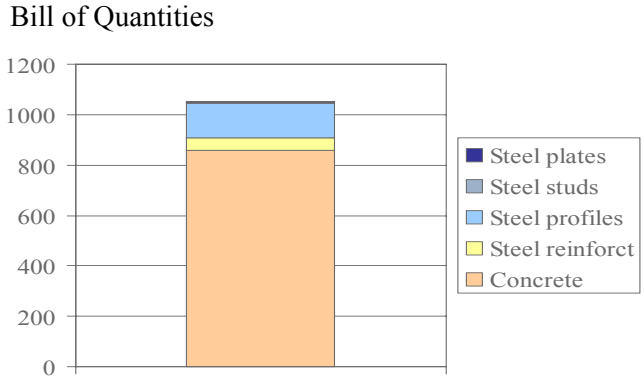

Figure 3. Bill of quantities of the composite bridge solution assessed.

2.2.4 System boundaries

The life cycle tree of the bridge considered is described in Figure 4, with especially focus on detailing the steps of their production and end of life. The boundaries of the system scrutinized include all stages of the life cycle of the bridges. However, as indicated in Figure 4, two stages are neglected: the finishing steps of steel elements and the use phase of bridges.

Finishing of steel elements was proven to be a negligible step in LCAs for steel products (Hettinger 2010) and is consequently not included in this evaluation. The use phase of bridges is not to be differentiated between alternative bridge solutions and is therefore considered to be neutral – having in mind that the traffic benefits from the new bridge and emissions are reduced. Further, as presented in Figure 4, after demolition, the constituting elements of the bridges are recycled, valorized or landfilled.

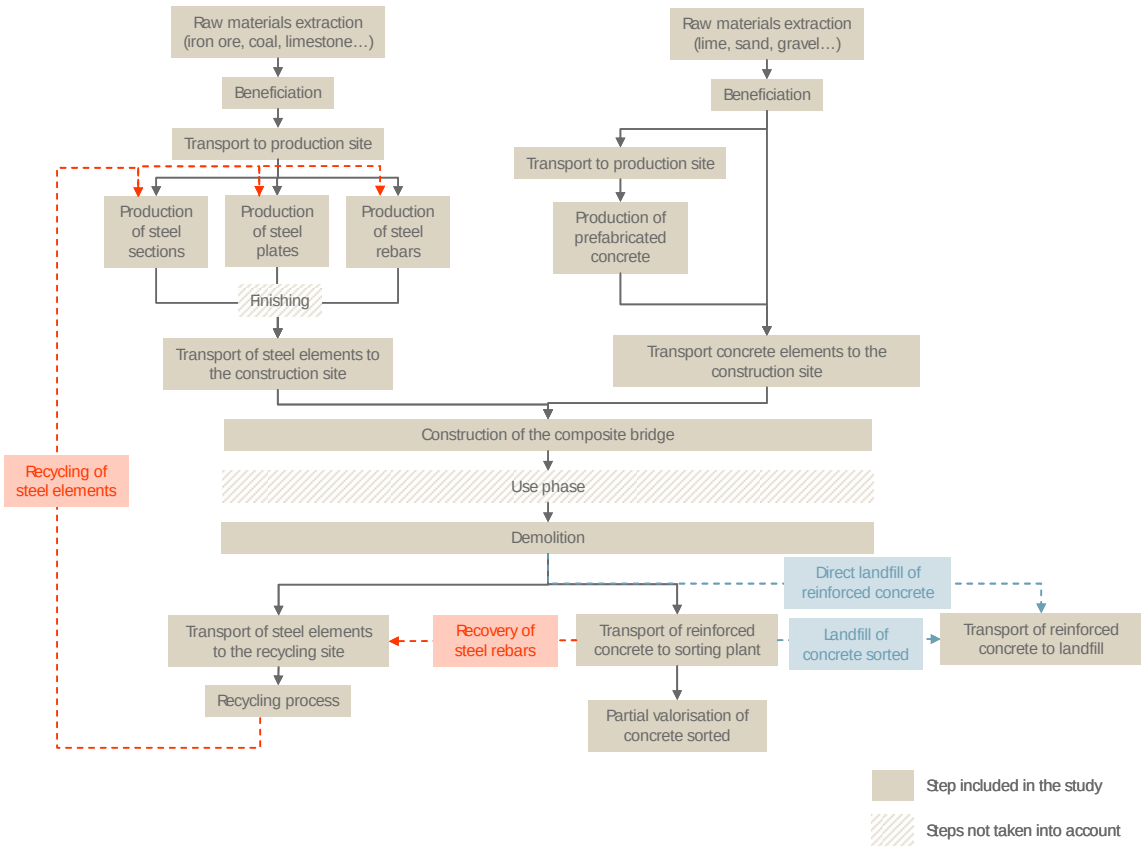

Figure 4. Life cycle tree of composite bridges.

2.3 *Life cycle inventories*

2.3.1 General

In the Life Cycle Inventory (LCI) analysis, the material and energy flows are grasped and listed during their entire life. In a first step, process structures are modeled in order to have a basis for assembling data. The material and energy flows are determined as input-/output-sizes for every partial process with regard to the system boundary. By connecting all partial processes, the relations between the modules and the environment are represented, and the mass/energy balance is drawn up as the inventory of the total system. All material and energy streams which pass the system borders are listed as quantities in physical units. The data refer to the functional unit. The Life Cycle Inventories used within this study are detailed in Table 3 and Table 4. In the following the basis for the determination of the LCIs are described.

2.3.2 Environmental profile of steel elements

Steel production is a mix of primary and secondary steel, produced through blast furnace (BF/BOF) and electric arc furnace (EAF), as illustrated in Figure 5.

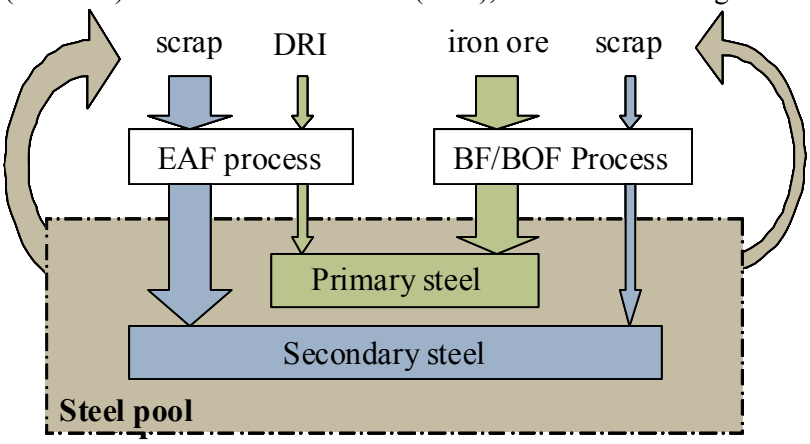

Figure 5. Description of primary and secondary production of steel (DRI = directly reduced iron ore) (WorldSteel 2010).

Recycling of scrap after steel usage is very efficient, due to several phenomena: its magnetic properties, facilitating scrap collection and separation, the economic value of steel scrap, the strict quality criteria (control of tramp elements) and the possibility to produce all steel grades from scrap (Thomas 2010). Thanks to these characteristics steel is the most recycled material in the world, with a global recycling rate of 83% (SRI 2008), and in particular in European construction field, structural steel sections reach 99% recycling rate (Sansom 2002). In addition, it is important to notice, that scrap is recycled an infinite number of times. If 1 tonne of steel produced is for instance considered with a mean recycling rate of around 90%, scrap for the production of, in total, 10 tonnes of steel is obtained.

The environmental benefits of this characteristic have to be integrated when performing an LCA. Two main methods are available to do so: the cut-off method and the system expansion (or credit) method.

The cut-off method is define as follows (Baumann 2004): “In the cut-off method, only loads directly caused by a product are assigned to that product, i.e. virgin production is allocated to the first product, the first recycling process to the second product and the second recycling process and the waste treatment process are allocated to the last product”. This method is adapted to materials that want to improve their recycled content, without predicting their end-of-life (concrete, plastics, rock or glass wool…). Steel products have already multiple cycles of recycling; the cut-off method is therefore not to be adapted to metals that benefit from high recycling rates at end-of-life.

A definition of the system expansion method is based on the statement of the ISO standard: “The use of secondary material displaces the use of virgin materials” and that “1 kg of recycled steel replaces primary steel”. In the case of scrap, any scrap leaving the system displaces the use of iron ore. In terms of calculation it means, that any scrap leaving the system bears a “credit”. This environmental value depends on the difference of impacts between primary manufacture

and recycling process, as well as the recycling rate (RR) of the product considered.

The system expansion method is the methodology applied by WorldSteel Association, which provides official LCI data for steel products. The data collection carried out by WorldSteel has been reviewed and approved by independent experts as complying with ISO 14040 standards.

The following example for a steel section demonstrates how WorldSteel has applied the methodology to LCI data, to account for end of life recycling. Figure 6 shows a life-cycle system for a steel section, which is used in a building. In this instance the steel section is manufactured via both BF (primary) and EAF (secondary) routes and the process uses a mean value of scrap of 0,85kg. At the end of the buildings useful life it is demolished and the scrap that is recovered (99%) is sent for recycling.

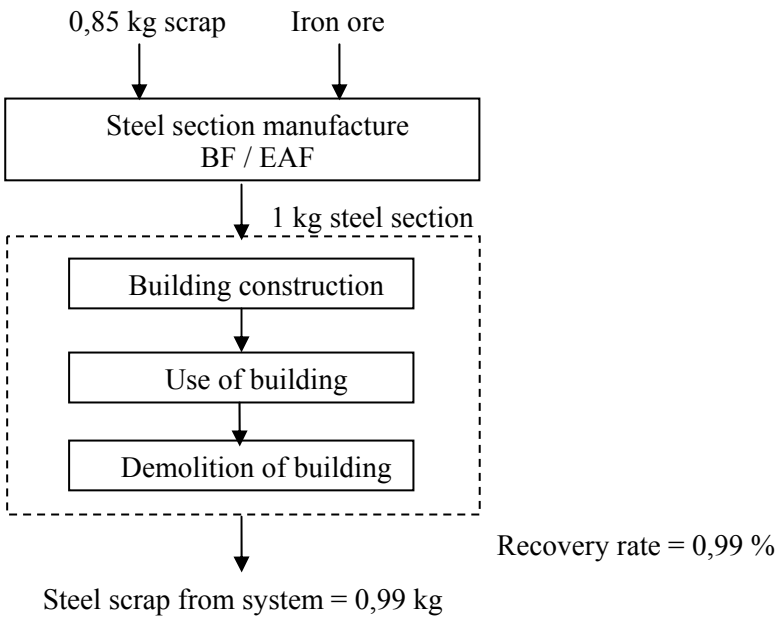

Figure 6 Life Cycle of 1 kg of steel sections, used in the structure of a building.

To calculate the LCI data for the steel section including end of life recycling it is necessary to determine the net amount of scrap produced by the life cycle system:

$$\text{Net scrap produced for 1 kg of steel section} = 0.99 - 0.85 = 0.14 \text{ kg Steel.} \quad (2)$$

By applying the scrap credit to the steel product system results in the LCI:

$$\text{Product LCI} = X' - 0.14 \times Y(X_{pr}-X_{re}) \quad (3)$$

Where X' is the average LCI for the finished product at the gate of the manufacture (X' = 1147 to CO_2-eq),
Y is the metallic yield which refers to the efficiency of the secondary process in converting scrap into steel (Y = 0.92),
(X_{pr}-X_{re}) represents the saving by replacing virgin material by recycling steel, where X_{pr} is the LCI of primary steel (X_{pr} = 2.14 to CO_2-eq) and
X_{re} is the LCI of secondary steel (X_{re} = 0.396 to CO_2-eq).

The values for the variables X', Y, X_{pr}, X_{re} above are dating from 2010.

In this paper the end-of-life scenario of the structure taken into account assumes that the original tonne of steel is recovered to 99% and becomes 0,99 tonnes of scrap, whereas 1% is lost and goes to landfill. In the next step new steel is produced with the electric arc furnace (X_{re} - emission CO_2-eq), however with a production yield of Y. Consequently from the original tonne of steel ($0{,}99 \cdot Y$) tonnes of steel are produced by the electric arc furnace and can be assembled in the second life structure of the original tonne.

As example how this procedure works for Global Warming Potential of European steel sections the GWP is calculated for the given scenario:

1 kg of section without allocation for recycling = 1,147 kg CO_2-eq
Net saving as result of recycling = 0,225 kg CO_2-eq

Final product of 1 kg section including recycling = 1,147 – 0,225 = 0,93 kg CO_2-eq

Consequently the GWP emission potential for the original tonne of steel produced by the blast furnace (X_{pr} = 2.14 to CO_2-eq) is reduced to approximately 0,93 to CO_2-eq as a maximum due to recycling.

An additional benefit from this approach is, that only a single value for both routes rests existent (Amato 1996, Brimacombe 2005, Birat 2006), which keeps the flexibility to the designer and steel fabricator to use the steel from both routes while the LCA assessment of the structure, already performed in the project stage, remains correct.

This paper however differentiates three types of LCIs for steel in the LCA: "sections": used for profiles; "rebars": used for shear studs and concrete reinforcement; and "plates": used for end plates. They are derived from WorldSteel LCIs and represent a World average from cradle to gate originating from data collection on sites between 2005 and 2009 (WorldSteel 2010).

During the deconstruction of the composite bridge, steel profiles, end plates and shear studs are easily separated. Reinforcing steel, physically linked to concrete, is more difficult to recover as already illustrated in Figure 4. The structural steel is directly transported from the demolition site to the recycling site, while reinforcing steel, embedded in the concrete, is first transported to a sorting plant, separated and finally transported to recycling sites, see Figure 7.

As a consequence, the recycling rate chosen for profiles, plates and studs is 99% and 65% for reinforcing steel, which is in line with the statistic recorded by the Steel Recycling Institute (SRI 2010) and the information gathered by (Sansom 2002).

2.3.3 Environmental profile of concrete

Data concerning the production of concrete and its components dates from 2001 and is provided by (Ecoinvent 2007). Several LCIs are available to evaluate the impact of concrete production: some gives data for the production of ready mix concrete and others for its constituents, e.g. Portland cement, sand, gravel (Ecoinvent 2007). The cement content required for this type of application is around 320kg/m^3 of concrete (Zement 2004). Within the LCIs for concrete production, the choice of cement contents is made according to Table 2.

Table 2. LCI for concrete (Ecoinvent 2007).

LCI	Cement content (kg/m^3)
Concrete, normal, at plant	300
Concrete, exacting, at plant	375

These datasets are considered as updated and trustworthy, however no Ecoinvent LCI describes the production of concrete with a cement content of 320kg/m^3. Considering that the GWP associated with concrete production is mostly linked to cement production (Hettinger 2009), the GWP associated with a concrete of 320kg/m^3 cement content is calculated from the existing LCIs, through linear regression based on cement content.

At end of life, concrete products can either be landfilled, or crushed and valorised to replace aggregates, thus reducing the need for virgin materials (Sjunnesson 2005), see Figure 4. The following scenario has been used for the EOL of reinforced concrete elements, see Figure 7:

- 34% of reinforced concrete is directly landfilled - thus embedded rebars are also 100% landfilled;
- 66% of reinforced concrete is sorted: rebars are separated from concrete - it is assumed, that 99% of the sorted rebars are recycled;
- For concrete, it has been considered that after the sorting plant, 15% of concrete is valorised and 85% is disposed.

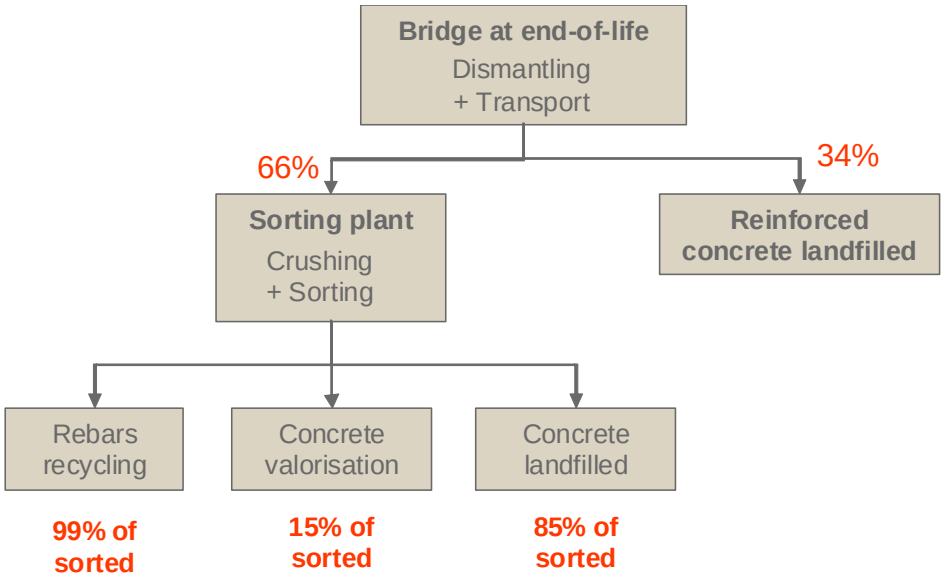

Figure 7. End of life scenario – reinforced concrete.

LCI corresponding to each EOL process are provided by the Ecoinvent database, as detailed in Table 4.

2.3.4 Environmental profiles of additional processes

Steel and concrete elements are assumed to be transported by truck only, either regular truck for steel elements and prefabricated concrete, or mixer truck for ready mixed concrete. The consumption linked to transportation is calculated taking into account partial load and empty return trips (INRETS). Steel elements are supposed to be transported on an average distance of 1000km, and prefabricated concrete on 500km. Concerning on-site concrete, a short transport distance of 50km for the ready-mixed concrete is assumed. The origin of the different parts (cement, water granulates, etc.) has not been taken into account for the analysis.

Other information (fuel production, emissions linked to transportation, etc.) is provided by the models of the consulting group PE International (PE 2006).

3 ENVIRONMENTAL IMPACT ASSESSMENT OF THE BRIDGE

3.1 *Summary of LCI*

In Table 3 and Table 4 the LCI data for the bridge assessed are summarized for each process and material as well as the source of information is specified.

Table 3. List of data and sources for steel products.

Process	LCI associated	Data source	GWP Production [kg CO_2-eq/t]
Production and recycling of steel profiles	WO-Sections – 99%	(WorldSteel 2010)	930
Production and recycling of shear studs	WO-Rebars – 99%	(WorldSteel 2010)	830
Production and recycling of steel end plates	WO-Plates – 99%	(WorldSteel 2010)	1073
Production and recycling of reinforcement	WO-Rebars – 65%	(WorldSteel 2010)	1348

Table 4. List of data and sources for other processes.

Process	LCI associated	Data source	GWP Production [kg CO_2-eq/t]
Production of concrete	Linear regression using		
	"Concrete, normal, at plant"	(Ecoinvent 2007)	112
	and "concrete exacting, at plant"	(Ecoinvent 2007)	135
Production of diesel	Diesel, at refinery	(PE / ELCD 2003)	375
Emissions - fuel combustion	truck-trailer 28-34to total / 22to payload / EURO3	(PE 2006)	3183
Separation of concrete and reinforcement	disposal, building, reinforced concrete, to sorting plant	(Ecoinvent 2002)	61
Landfill of reinforced concrete	disposal, building, reinforced concrete, to final disposal	(Ecoinvent 2002)	67
Landfill of sorted concrete	disposal, concrete, 5%water, to inert material landfill	(Ecoinvent 1995)	7
Valorization of crushed concrete	gravel, unspecified, at mine	(Ecoinvent 2001)	3

3.2 *Evaluation of the Global Warming Potential*

For each process described in Figure 4, the emissions of GHG are calculated and transformed to determine the GWP 100 associated. Figure 8 displays the results obtained for materials production and end-of-life, as well as their transportation.

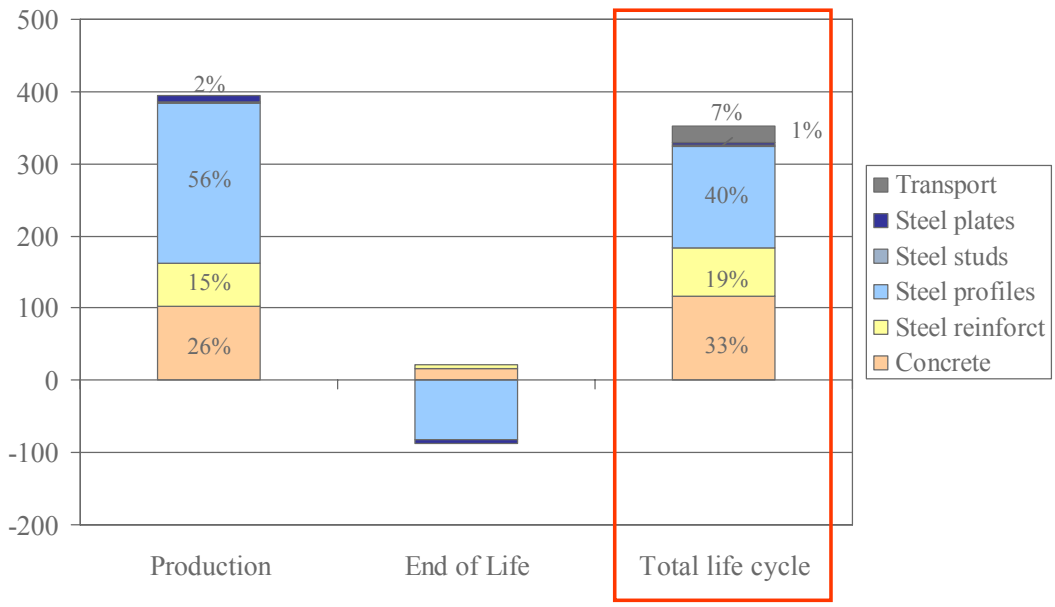

Figure 8. Global Warming Potential of a two-span composite bridge including production, transportation and end-of-life.

The GWP of the production phase is dominated by the steel elements, gathering 73% of the impacts, whereas the production of concrete represents 26%. At this stage the repartition of impacts is very different from the repartition of weight showed in Figure 3.

The end-of-life phase shows a credit for the steel elements. This benefit is much lower for reinforcing steel than for profiles, a difference that is not entirely explained by the weight difference: there are approximately 3 times more profiles than reinforcement in weight, whereas the credit for profiles recycling is more than 5 times higher than the credit for reinforcement. Actually, this difference is linked mainly to the higher recycling rate of the profiles, and also to the additional treatment necessary to separate reinforcement from concrete.

The end-of-life of concrete has a GWP impact, despite the valorization of concrete aggregates. Indeed, the necessary transformation that concrete undergoes before being valorized (mainly crushing) has larger impact than the credit provided by avoiding the production of aggregates.

As a result, the overall GWP of the composite bridge has a smaller impact than its production phase solely. Moreover, this reduction is only due to the credit associated with steel elements. The contribution of steel elements, especially elements presenting high recycling rates is greatly reduced: contribution of profiles and plates decrease from 56% to 40% and 2% to 1% respectively. Finally, the contribution of transportation of concrete and steel elements represents a rather low share of the overall results (~7%).

These results might change if the end-of-life hypotheses are modified. Another scenario is tested to evaluate the results for a 100% recycling of reinforcing steel and a 100% valorization of concrete. The consequence is that all reinforced needs to be crushed, generating a larger impact. As a result, for concrete, a 100% valorization is not sufficient to counterbalance the sorting process. On the opposite, the credit allowed to reinforcing steel is multiplied by three.

3.3 *Evaluation of the Global Warming Potential*

The main outcomes of the evaluation conducted are the following:

- The GWP profile of a composite bridge is mainly influenced by the production and end-of-life of its constituting elements.
- The recycling of steel elements avoids the production of virgin steel. With a 99% recycling rate, studs, profiles and plates generate a credit of 88 tonnes of CO_2-equivalents, representing a 21%.reduction of the life cycle impact
- Reinforced concrete has to be sorted in order to recycle reinforcing steel and valorized aggregates, a process generating GWP impacts. While these impacts are compensated by the recycling benefits of reinforcing steel, the valorization of concrete is not sufficient.
- Properly managed, the end-of-life of such bridge avoids the emission of more than 66 tonnes of CO_2-equivalents which reduces the overall life cycle impact by 16%.

4 CONCLUSIONS

Life Cycle Assessment is also appropriate to evaluate the environmental impact of bridges. Hereby a holistic approach is to be applied, considering the whole life of the bridge, from the extraction of raw materials through the manufacture and destiny at its end of life. The use phase may be neglected, as a new bridge will have a positive impact on the traffic emission.

Life Cycle Thinking is particularly of interest for the environmental evaluation of steel products, especially when the benefits of steel recycling at end-of-life of the structure are taken into account. The recycling rate of steel profiles in construction is 99% and the resulting benefit in terms of reduced GWP potential is very high. To illustrate the benefit of steel recycling properties, a case study of a composite bridge is assessed for its whole life cycle: from the production of its constituting materials (mainly steel and concrete), their transport to the bridge deconstruction and the recycling (steel) and valorization (concrete). This case study demonstrated the strong interest of using steel in bridge structures due to the recyclability, which reduces the emissions by 21% (88to CO_2-eq) in this case – the savings are equivalent to 676923km driven by a car with a CO_2 emission according to the European regulation limit for cars (130gCO_2/km).

An additional benefit from this approach is, that only a single value for both routes in steel production, blast furnace and electric arc furnace, is to be established. One single value for both routes hereby provides planning reliability to the LCA evaluator, that his assessment in the project stage remains correct for the finalized structure independently from the steel used in construction.

Overall it has to be concluded, that sustainable structures are innovative structures with a reasonable use of adequate materials in the right place, considering enhancements of each single products/material, the use phase and EOL. Nevertheless sustainable structures are not only structures with low CO_2-emissions but have in addition to comply with economical constrains, technological and process restrictions as well as respect socio-cultural requirements. Therefore sustainability starts already in the concept and design phase – an active awareness of the architect and designer is consequently essential to identify an adequate compromise between all objectives of sustainability.

5 ACKNOWLEDGEMENTS

The authors wish to express their deep gratitude to R&D Long Carbon of ArcelorMittal for its inspiring cooperation.

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Sustainable Steel-Composite Bridges

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ABSTRACT: In the worldwide infrastructure network bridges are of essential importance. The request for sustainability is especially urgent for bridges as their life is intended to cover a span of more than 100 years. Shifting from an initial cost-effective design to a lifecycle cost-effective design seems to be demanding in regard of improving maintenance, rehabilitation and renewal of these bridges also in view of the rapid growing traffic volume on bridges. In the frame of a running European research project investigations are performed applying a holistic approach combining analysis of Lifecycle Assessment (LCA), Lifecycle Cost (LCC) and Lifecycle Performance (LCP) in order to elaborate innovative solutions in steel-composite bridges as an important alternative to concrete bridges. Three types of representative highway bridges are chosen and complete case studies throughout all aspects are performed including in a second step variations and optimizations. The aim of optimization is improving durability and at the same time minimizing lifecycle costs.

1 INTRODUCTION

1.1 *Current situation and demands for sustainable bridges*

At the tender stage aspects such as structural shaping and safety, durability and environmental impact may have influence, but at present the decision is mainly made on the lowest initial costs. At least in Germany since some years it is allowed according to the contracting law (BMVVW 2006) to decide on the most successful tenderer not only on basis of the lowest initial costs but to take further criteria into consideration. The demand for sustainability catches the interest of the society at this point. A chance may be given not only to the consideration of environmental aspects but also to social and functional aspects.

Public institutions, especially owners of large infrastructures such as bridges are more and more requested by society or politics also to consider a sustainable point of view. Taking future demands such as increasing traffic volume into account should not be disregarded. Not only the traffic volume but also the gross vehicle weight rises constantly and bridge structures may need to carry 60t-vehicles, the so call gigaliner, soon. The traditionally used design concept aiming at optimized proportioning of structural members in order to achieve minimum initial construction costs does not fulfil this requirement. As maintenance, rehabilitation and renewal of existing bridges are of increasing importance for bridge authorities a revise of the decision making process based only on initial cost-effective design is needed. The necessity of sustainable and long living bridges is outstanding.

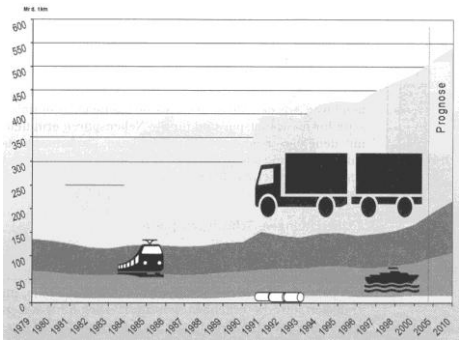


Figure 1. Development of traffic volume.

1.2 *Sustainability by lifecycle design of bridges*

Bridges are long-living structures which should be designed for 100 years and more. On one hand degradation processes such as fatigue, corrosion and carbonation are having impacts on the bridge structure and the structure must be able to face these and be kept in function till the end of life. On the other hand inspecting the bridge and thereby educed maintenance or renewal actions preserve the structure, see Figure 2. To meet sustainability criteria the entire lifecycle of bridges needs to be looked at, where impacts and required interventions have to be defined.

In the frame of the running European research project SBRI under the participation of scientists, bridge owners, consultants and industry the lifecycle performance of steel-composite bridges is analyzed with a holistic approach as described in the following paragraph. The system boundaries defined cover the production of raw materials, the construction, the operation (including maintenance etc.) and the demolition of the bridges.

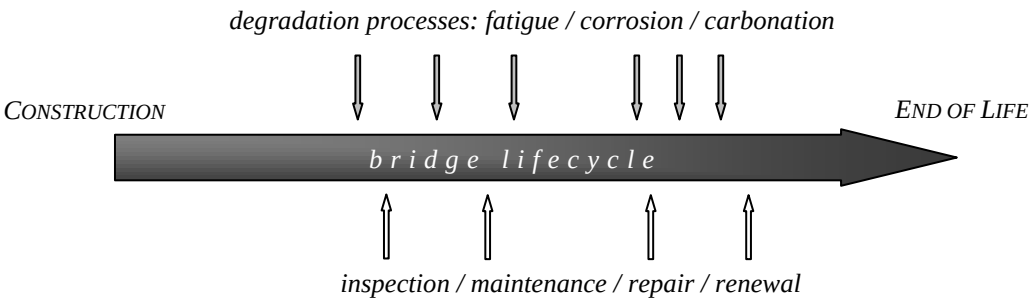


Figure 2. Sketch of the lifecycle of a bridge.

2 METHODOLOGY

2.1 *Holistic approach to steel-concrete bridges*

The present research only deals with steel-composite bridges due to the involved parties and as these type of bridges are an important alternative to concrete bridges due to the considerable advantages regarding design, construction time, durability and costs allowing to exploit the materials properties in the most efficient way, resulting in slender, lightweight, robust and aesthetically appealing bridge structures

Regarding sustainability the analysis of lifecycle performance of bridges summarizes the analysis of lifecycle costs (LCC), of emissions within the lifecycle assessment (LCA) and the analysis of the social and functional quality, see Figure 3. By means of this integral holistic approach the various influences at the different stages of the lifecycle will be captured allowing for a balanced judgement without any focus on only one design criterion.

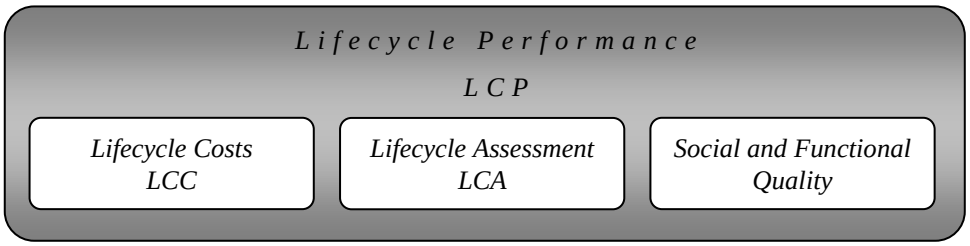


Figure 3. Lifecycle methodology.

2.2 *Lifecycle costs and user costs*

Bridges are of essential importance for the infrastructure network so that the transfer of goods and passenger traffic is unobstructed. It is obvious that, compared to buildings, economic and social aspects of bridges must be evaluated in a different way as influences occur not only on the structure itself but also on the network and its users.

In (Kuhlmann, Hauf, Maier 2010) an investigation realised for the Hessian Road and Traffic Administration has been presented showing that for bridges it is not sufficient to compare only construction costs without considering construction time, neither construction method nor the type of construction. As the construction of a bridge causes traffic interferences socio-economic costs may be caused by traffic interruptions or disturbances at bridge sites during construction. The effect of these costs can be taken into account following EWS "Empfehlungen für Wirtschaftlichkeitsuntersuchungen an Straßen". Similarly the aspect of reduced construction time can be considered by the approach of compensation costs according to ARS, a German guideline wherein additional costs are accepted for a shorter construction time. Also a method called "Ri-Wi-Brü" exists where the capitalized costs for construction, maintenance, renovation and demolition, are accounted for. However not all the various aspects have yet been covered in one single method. Therefore the goal now is to consider all costs associated to a bridge during construction, use and maintenance and to include these in one assessment covering also the different types of costs.

One focus of the analyses is laid on road user costs as these not only occur under normal traffic condition but are mainly influenced by inconvenience costs due to traffic restrictions. Such traffic restrictions may be caused by inadequate capacity due to a narrowed road, reduced speed, signal regulation or detours. Also the increasing traffic volume needs to be taken into consideration for each year as the correlation between traffic volume and road user inconvenience cost is not linear. A feasible assumption for the further traffic growth has to be taken in a definition of a plausible scenario, e.g. to increase with a fixed annual increment over ten years and then stagnate not to exceed the capacity of the road at the end.

2.3 *Lifecycle assessment LCA*

In the frame of EN ISO 14040 and 14044 the requirements to conduct a lifecycle assessment are detailed. The four phases are namely the goal and scope definition phase, the inventory analysis phase, the impact assessment phase and the interpretation phase, see Figure 4. In the interpretation phase it is important to identify significant issues and perform an evaluation by sensitivity, consistency and other checks. Conclusions and recommendations are to be drawn.

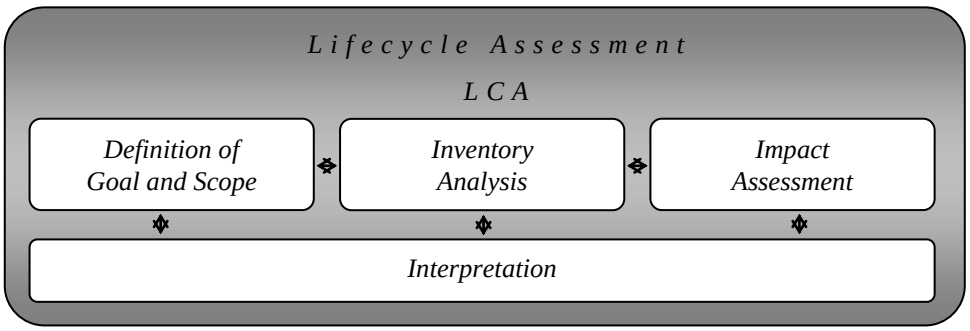


Figure 4. Lifecycle Assessment according to EN ISO 14040.

For the evaluation of a potential environmental impact, categories representing issues of concern need to be defined. To these so called impact categories resulting from lifecycle inventory analysis may be assigned. Here the eight following indicators are taken into account: abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion, human toxicity, terrestrial ecotoxicity and photochemical oxidation. For more detailed information how these indicators can be integrated into a life cycle assessment for bridges following even a probabilistic life cycle approach, see (Gervásio 2010).

2.4 *Structural performance and maintenance/rehabilitation or repair strategies*

Throughout a lifetime of bridges many influences occur that may lead to bridge deterioration and nevertheless bridge authorities need to assure the structural safety. To guarantee this, three different maintenance strategies can be defined. Carrying out minor work on a regular basis, such as cleaning of bearings and expansion joints and keeping drainage systems clean, can be

considered as a routine maintenance. Repainting of the steel structure is considered as a preventive maintenance as defects are repaired and the deterioration is slowed down. When a bridge has become structurally inadequate, major repairs and e. g. replacement of structural elements are needed as essential maintenance or repair measures.

The status of each bridge during its entire lifecycle should not fall below a critical value. The so called condition grade is compiled by the three factors of traffic safety, durability and stability. With a minimum of maintenance a so called "permitted deterioration strategy" is pursued, only very little interventions are undertaken and the end of life is reached in a status of deficiency. The opposite compared to the permitted deterioration strategy is a preventive strategy where the structure is kept in best condition due to regular maintenance. The in-between strategy reacts to detected defects by combining maintenance actions in an efficient way and is therefore called the reactive strategy. Actions can be postponed or even scheduled ahead so that points of interference are minimized.

Based on these strategies lifecycle scenarios are developed for the defined case studies.

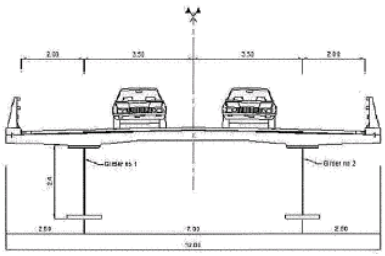
3 CASE STUDIES

3.1 *Selection of bridge types*

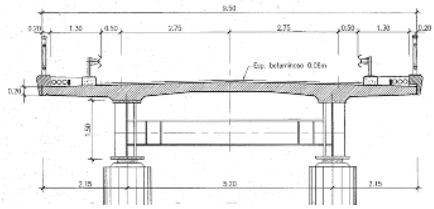
In order to evaluate this new integral approach of a combined LCA/LCC methodology for the real design process of a bridge, realistic cases studies are defined to carry out a complete design and calculation for them. Typical types of steel-composite road bridges are selected following the experience in the different countries of the partners involved (COMBRI 2009) in order to give a representative survey of the European bridge design situation.

According to the functionality of the bridge and its span lengths three groups are identified: Bridges of case A are considered to be small motorway bridges with span lengths of around 50 to 60 m. Crossings of a motorway are defined as case B and big motorway bridges with span lengths up to 120 m are considered as case C, see Figure 5.

Case A



Case B



Case C

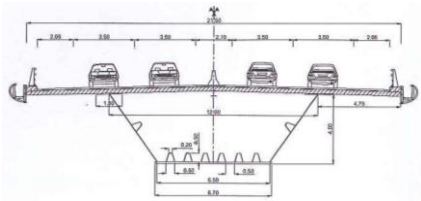


Figure 5. Bridge types.

By defining these different cases it is ensured that standard situations are analyzed and that the methodology is applied and calibrated to them. Different configurations are studied in order

to optimise structural design and choice of material (grade of steel, concrete strength etc.) for maximum cost/sustainability efficiency and also innovative solutions are applied.To elaborate influences on the lifecycle the following variations of each case are examined. The small motorway bridge of case A is designed as a twin girder bridge in case A1 which is optimized in a case A2 by the use of high strength steel. Case A3 gives allowance to increased traffic by providing three lanes in each direction. Case B was chosen to make a comparison between integral abutments, a clamping by providing two outer spans and a standard two-span bridge. The box girder composite section of Case C will be optimized by improving fatigue relevant details.

3.2 *Analysis of bridge type A*

Under the assumption that the considered steel-composite bridge type A is a newly built bridge according to current regulations and standards and constructed in a high quality, no damage or failure should occur until the regular end of service lives of the singular structural elements. The proposal of a lifetime scenario bases on data and information that are compiled in the German Building-Management-System (BMS). According to that the presumed service life and the required exchange of structural elements, measures of renewal are allocated. The combination of measures is defined with the help of catalogues of measures and costs that are available in the German Building-Management-System (BMS). Due to a ranking by priority and in terms of cost-efficiency merging of actions is foreseen. Some of these actions, such as renewal of asphalt or exchange of bearings and expansion joints, are combined by postponing single measures or scheduling them ahead. Typically every 25 years major maintenance actions need to be applied, so that for these dates the various measures can be organized simultaneously.

The LCA analyses are performed in a next step. For the material production stage the decisive impact comes from the production of concrete and steel in comparison to the other produced materials. In the construction stage traffic congestion shows the biggest input compared to transportation and use of equipment. The determined lifetime scenario is then integrated by looking at the combined maintenance actions during the operation stage.

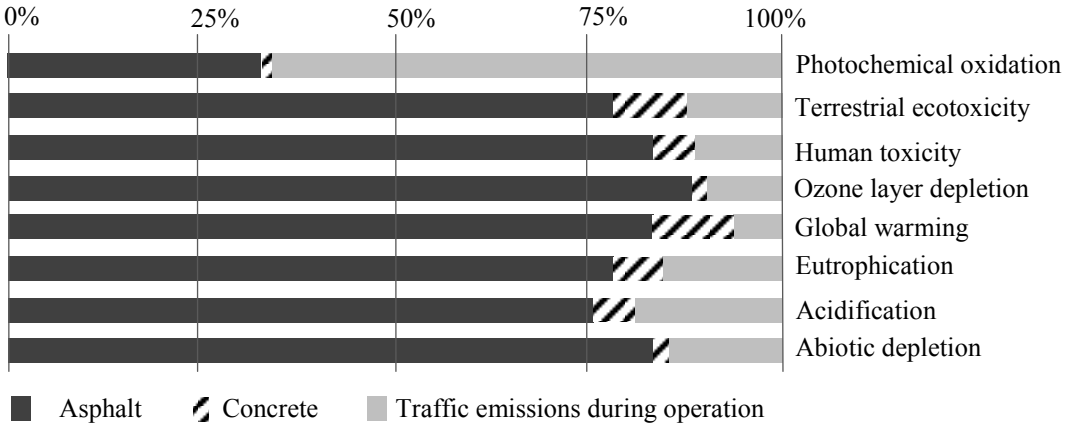


Figure 6. LCA for combined actions after 25 and 50 years (see Gervásio 2010).

Figure 6 shows the normalized results for the replacement of the bridge equipment such as expansion joints, bearings, the railing and the thereby resulting concrete work, the replacing of the asphalt and the emissions due to traffic occurring after 25 and 50 years of the assumed lifetime scenario. These results may be compared to other lifetime scenarios and be finally integrated into the integral life cycle analysis (Gervásio 2010).

As the defined bridge case A scenario does contain any information about the traffic under the bridge it has to be concluded that the maintenance of the steel and concrete structure has no major influence on the analysis of user costs. So in fact it is useful to establish scenarios based on real cases where also traffic conditions are known.

The variation A2 of bridge Type A foresees the use of high strength steel as it has been suggested also by (COMBRI). In the longitudinal view, compare Figure 7, the flanges of the main girders are built with S460 instead of S355 over the length of 1.5m at the supports of both piers.

This leads to a reduction of 15% of steel for the main girders but goes along with a 2% increase of steel S355 steel for the bracing frames. A total decrease of 13% is therefore achieved compared to the basic design of case A1. The consequences of the mass reduction which at the same time also means a reduction of welding will be investigated within the LCC and LCA analysis.

Instead of the use of the emergency lane a third lane of traffic is analysed in case A3. Looking at the steel quantity an increase of only 4% is then needed. However the increased flexibility for future traffic developments is obvious.

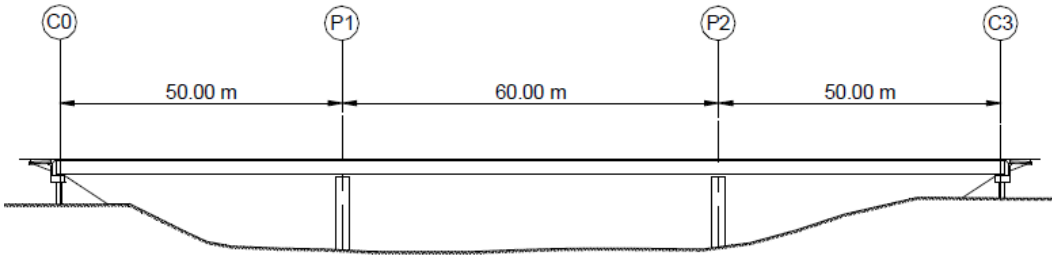


Figure 7. Span distribution of bridge Type A.

3.3 *Outlook on bridges of type B and C*

The crossing of a motorway, here considered as type B, will be looked at in next steps. As influences from traffic on top and underneath the bridge are to be taken into account the variation between an integral bridge, a two-span bridge and a three-span bridge clamping the middle span seem to be promising for optimizing the design in regard of also of user costs.

As box-girder composite bridges are mainly built in demanding situations and are therefore big structures, a close look under sustainable aspects needs to be made to these bridge types, here type C, in coming analyses.

In parallel when analysing these case studies an appropriate database as well as calculation tools are developed.

4 LIFECYCLE PERFORMANCE AND OPTIMISATION OF INSPECTION INTERVALLS

4.1 *Lifecycle performance*

In order to conduct LCA and LCC analyses, more accurate information about the lifecycle performance (LCP) for each component of bridges with respect to the long term behavior due to specific degradation problems, e.g. fatigue, corrosion and carbonation is necessary, see parameters in Figure 8. The lifetime of each component should be estimated based on the survey of existing bridges, code rules such as S-N curves for fatigue and experimental data.

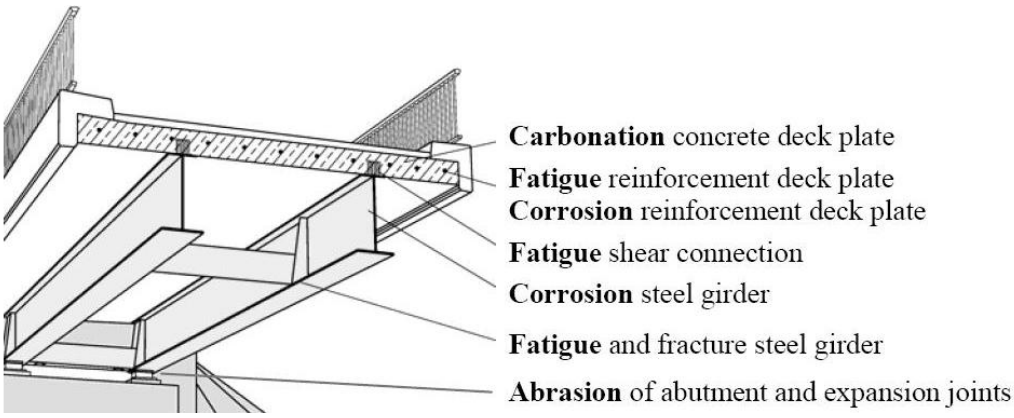


Figure 8. Typical degradation processes of steel-composite bridges.

For certain typical details, such as the fatigue behavior of the transverse stiffener welded to a tension flange (see Figure 9) or the horizontally lying studs used as shear connectors, improved knowledge is gained on the lifecycle performance by own testing,

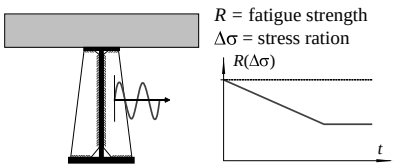


Figure 9. Fatigue degradation model of transverse stiffener.

A detailed description of the lifecycle performance has a very positive influence on the exact scheduling of inspections and maintenance. Therefore it is essential to capture the behaviour of specific details towards deterioration to reduce lifecycle costs and emissions. An optimization of inspection intervals is the goal of the comparison of non-destructive testing methods which then will be integrated into the LCA and LCC analyses.

4.2 *Non-destructive testing of fatigue details on steel girders*

Cracks due to fatigue may result in the loss of structural capacity and may cause costly maintenance actions if these are not detected in time. Inspection intervals are closely linked to the probability of detection of defects and thus influence the sustainability analysis.

Non-destructive testing methods (NDT) were applied to one steel girder of a series of test specimens with the weld detail of a transverse stiffener and a bearing plate loaded under fatigue load, see Figure 10. Cracks were made visible with magnetic particle testing (MT) comparing the use of a black suspension, a red powder and fluorescent particles under ultraviolet light. Penetration testing (PT) was performed with a red colour and yellow fluorescent colour under ultraviolet light. An optimization of detection was performed by applying the innovative solution of ultrasonic testing by phased array. As steel in bridges is coated for corrosion protection the influence of the coating was also taken into account when performing the non-destructive testing by coating half of the steel girder.

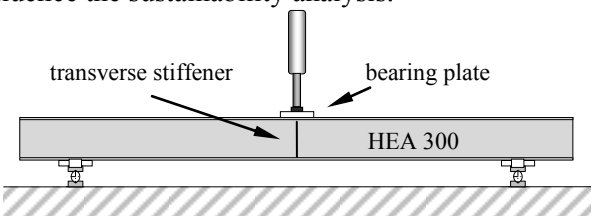


Figure 10. Test set-up for fatigue tests.

4.3 *First results of crack detection and continuation of tests*

The first crack at the bearing plate due to the fatigue load was detected by phased array after 100,000 load cycles (see Figure 11) and no other NDT method was able to show anything. After another 50,000 cycles the crack was visible with all the inspection methods differing however by the clearness of interpretation. The magnetic particle testing under ultraviolet light showed very precise and thin cracks. The red colour of the penetration testing gave an idea of the crack depth by the quantity of ink leaking out. The crack growth proceeded and detection by magnetic particles under ultraviolet light was not possible for the coated side of the girder. After 350,000 cycles the first crack at the transverse stiffener was found and failed after 520,000 cycles.

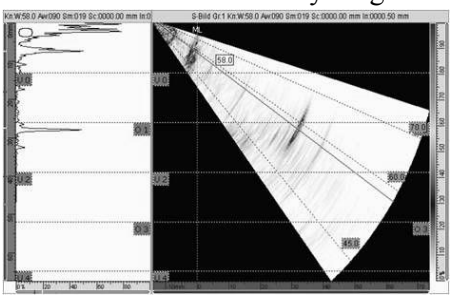


Figure 11. Detection with phased array.

It was shown that by the method of phased array it is possible to detect cracks earlier than by the common methods. As magnetic particle testing reached its limitations when being applied on coating this cannot be recommended if not a renewal of the corrosion protection is planned for the same date.

Further fatigue tests will be realised also on improved fatigue details. To extend the service life of welded details under fatigue loading promising results have been gained by Dürr (2006) with the application of ultrasonic impact treatment as post-weld treatment method. Thereby the lifetime of steel structures can be extended and expensive maintenance and repair actions may be reduced. Also for these tests the effectiveness of NDT methods will be investigated and the possible optimization of inspections interval will be determined.

5 CONCLUSION AND OUTLOOK

From the performed analysis in the frame of a running European research project it can be seen that bridges need to be optimized in a holistic way combining the environmental aspects, costs and social and functional factors throughout the entire lifecycle. Assumptions were made for the lifecycle scenario and maintenance actions. These influence not only the lifecycle assessment but also lifecycle and user costs. Optimized crack detection during inspections results in minimisation of maintenance needed.

For crossings of motorways and long spanned steel-concrete box-girder bridges the integral approach of sustainability analysis will also be performed in the following. Influences on the sustainability of bridges will be worked out and criteria and tools will be provided for decision making in the tender stage.

These items are of great importance in order to come along with the future demands on bridge structures resulting from the ever increasing traffic volume within the European road network. The research work therefore aims to point out all the benefits of steel-composite road bridges regarding sustainability.

The authors as project coordinators express their gratitude to the Research Fund for Coal and Steel of the European Commission for the project funding. They also like to underline that the presented results are based on the work of the whole project team and like to thank the partners coming form the University of Coimbra, Dillinger Hütte, Arcelor Mittal, Laboratoire Central des Ponts et Chaussees, Rambøll Denmark, Brisa Engenharia e Gestão, SETRA and BASt for their collaboration.

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Life cycle assessment for railway bridge infrastructure: a case study of Bollstaån Bridge

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ABSTRACT: The Life cycle assessment (LCA) is a comprehensive framework for analyzing the environmental impact of product or services by considering the flow of raw materials and energy over a life cycle. This paper is a review of the current knowledge associate with LCA of bridge infrastructures, and a case study of the Bollstaån railway bridge is carried out by the LCA analysis. In order to simplify the analysis, the study is performed only on the superstructure including the railway track and the steel section. The result can be further integrated with different bridge design, thus identify the dominant elements in a railway superstructure which contributes significant environmental impact. It has been noticed the concrete consumption contributes the significant impact in the GWP and AP, while for the POCP, the rail production is the major concern. The ballast manufacture, the transportation of concrete and reinforcement has ignorable impact.

1 INTRODUCTION

The construction industry comprises a large proportion for a country's economy. Currently, there is a significant attempt to combine the construction development with sustainable concept. One of the important indicators of sustainable construction is the environmental performance of the infrastructure. Specifically for the railway bridge infrastructure, for which keeps an increasing construction growth worldwide. The railway bridge infrastructures not only lasts long life time, but also involve large amount of complex activities, for instance the enormous material consumption of concrete, steel, reinforcement, transportation, energy, maintenance and disposal scenarios. Thus it is vital for the decision-makers and public make a fair decision based on the solid environmental evaluation of material and energy flows. The Life cycle assessment (LCA) is a comprehensive framework for analyzing the environmental impact of product or services by considering the flow of raw materials and energy into a system over a life cycle.

This paper implements an accounting LCA methodology for evaluating the Bollstaån Bridge, a railway bridge located in Kramfors, Sweden. The LCA analysis is focused on the construction stage, while the maintenance and disposal stage is out of scope. In order to simplify the analysis, the study is performed only on the bridge superstructure including the railway track and concrete slab. The result can be easily integrated with different bridge main body design, thus identify the dominant elements in a railway superstructure which contributes significant environmental impact. Several environmental impact categories has been studied, for instance, Global Warming Potential (GWP), Photochemical Ozone Creation Potential (POCP) and Acidification Potential (AP). The functional unit choose for studying is: within an assumed life time 60 years, the 1 km superstructure of Bollstaån Bridge in the longitudinal direction.

2 LITERATURE REVIEW OF LIFE CYCLE ASSESSMENT FOR BRIDGES

2.1 *The framework of Life cycle assessment*

Life cycle assessment is a comprehensive framework for assessing environmental impacts of a product or service through its total life cycle (ISO14040, 2006). The term 'life cycle' refers to the sense that a holistic assessment of the product is performed from the raw material extraction phase, through manufacture phase, use phase until the final disposal phase, including all related transportation process, as presented in Figure 1.

The methodology of LCA is standardized by the ISO 14040 and ISO14044 series guidelines, it includes four phases: Goal and Scope phase, life cycle inventory phase, life cycle impact assessment phase, and result interpretation (ISO14040, 2006):

- *Goal Definition and Scoping phase* is the process to define the boundaries and purpose of the study, identify environmental effects to be reviewed for the assessment.
- Inventory Analysis phase is to input the material flow and energy into the defined study system, thus obtain the environmental releases including air emissions, solid waste disposal, waste water discharges.
- *Impact Assessment phase* is to assess the environmental loading and impact categories by characterization, normalization, weighting and grouping procedure, on the basis of inventory analysis results.
- *Interpretation phase* is to explain and present the results of the inventory analysis phase and impact assessment phase to make a fair and clear result, identify the uncertainty and assumptions of the study.

2.2 *Literature survey of Life cycle assessment for bridges*

The increasing high-speed railway track development has concerned people to look into the environmental performance of different transportation infrastructures, from a life-cycle perspective. Although LCA has been widely applied in industrial domain, there is limit implementation in bridge infrastructure field, thus it has high potential for the further research. The following literature is relevant studies in the scope of railway bridge structure.

Lee et al. (2008) applied the life cycle assessment method on two rail track systems: gravel ballast and the concrete track system. Those track system are constructed between Seoul and Busan in South Korea. The analysis compasses the whole life-cycle of the system from the raw material extraction to the maintenance activities, within a service life of 20 years. The result shows that the ballast track system had a better environmental performance than the concrete track system. The major environmental contributor was the ties, the fasteners and the ballast for the ballasted track, and the ready mixed concrete, the ties and the fasteners for the concrete track.

Kato et al. (2006) assessed the environmental impacts of public transport systems including the track system, the infrastructure and the rolling stock. The whole life cycle was under evaluation from the raw material extraction, through construction, maintenance phase until the end of the life. Several air emissions were studied such as CO_2, NO_X and SO_2. It has been concluded that high capacity, high-speed and medium demand passenger transport system cause the lowest environmental impacts.

Jonsson (2005) evaluated the Swedish railway transport system through the whole life cycle including the construction maintenance and demolition of the infrastructure; the studied category was carried out for the energy use only. It has been found that the indirect energy accounted for large percentage of the total life-cycle energy around 64% to 66% percent. For the case study of the Bothnia line in Sweden, it has been concluded that the energy for construction is more than that for the Swedish train traffic operation.

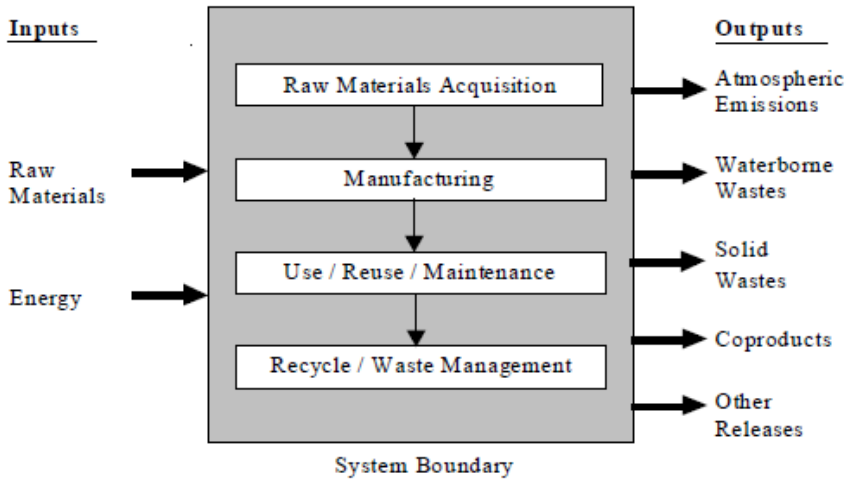

Figure 1. Life cycle stages (EPA, 1993&2006).

3 CASE STUDY OF THE BOLLSTAÅN RAILWAY BRIDGE

A case study is carried out for evaluating the environmental impact of the Bollstaån railway bridge located in Kramfors, Sweden. The purpose of the study is to apply the LCA methodology for studying the environmental impact generated from Bollstaån Bridge based on the realistic design. Thus identify the dominant structural components that contribute significant impact. The bridge is a steel-concrete composite railway bridge with ballast single track. The total length is 26.13m and width is 6.64m, as presented in Figure 2. An attribution LCA was performed for evaluating the environmental profile of the bridge superstructure including the railway track and the bridge slab with steel sections. In order to ease the analysis, the functional unit of the study is defined as 1 km superstructure along the longitudinal direction of the bridge. The boundary of the study is confined in the construction stage of the structure, as 'cradle to gate'. Several environmental emissions including CO_2, SO_2, NO_x, N_2O, CH_4 was studied, and environmental impact categories of Global Warming Potential (GWP), Photochemical Ozone Creation Potential (POCP) and Acidification Potential (AP) are also studied. The material quantity of studied structure elements is shown as:

- *Rail:* The rail type 60E1 is used in the Bollstaån Bridge, the single rail track mass is 60*2kg/m=120 kg/m. The transportation distance of rail is assumed as 30 km by truck.
- *Ballast:* the ballast is simplified to a rectangular cuboids with dimensions 6.64 m wide by 0.6m high. Its length is 26.13 m, i.e. the length of the bridge. The weight density for the ballast is 20 kN/m3. The ballast weight along the bridge is 7.9 ton/m. The transportation distance of ballast is assumed as 100 km by train freight.
- *Bridge slab:* The bridge slab consists of concrete and reinforcement, the quantity of the concrete is calculated from the drawing manual as 0.28m^3, and the total amount of reinforcement thus is 1.18 m^3/m based on BBK04, the minimum reinforcement content in concrete slab is 0.25%, and thus the reinforcement is 23 kg/m. The transportation distance of concrete is assumed as 30 km by truck and 100 km by train for reinforcement.

3.1 *Life cycle inventory analysis*

The life cycle inventory (LCI) data was extracted from Stripple (2001) and Ecoinvent (2001) database, as presented in Table 1. The data was obtained by considering the cradle to gate process, as from the raw material extraction process till the product manufacture process, with the consideration of raw material flow, energy input and transportation processes, several air emission categories were considered, for instance CO_2, CH_4, NH_3, NO_x, SO_2 and CO, which will further assigned into different impact categories by the classification and characterization method.

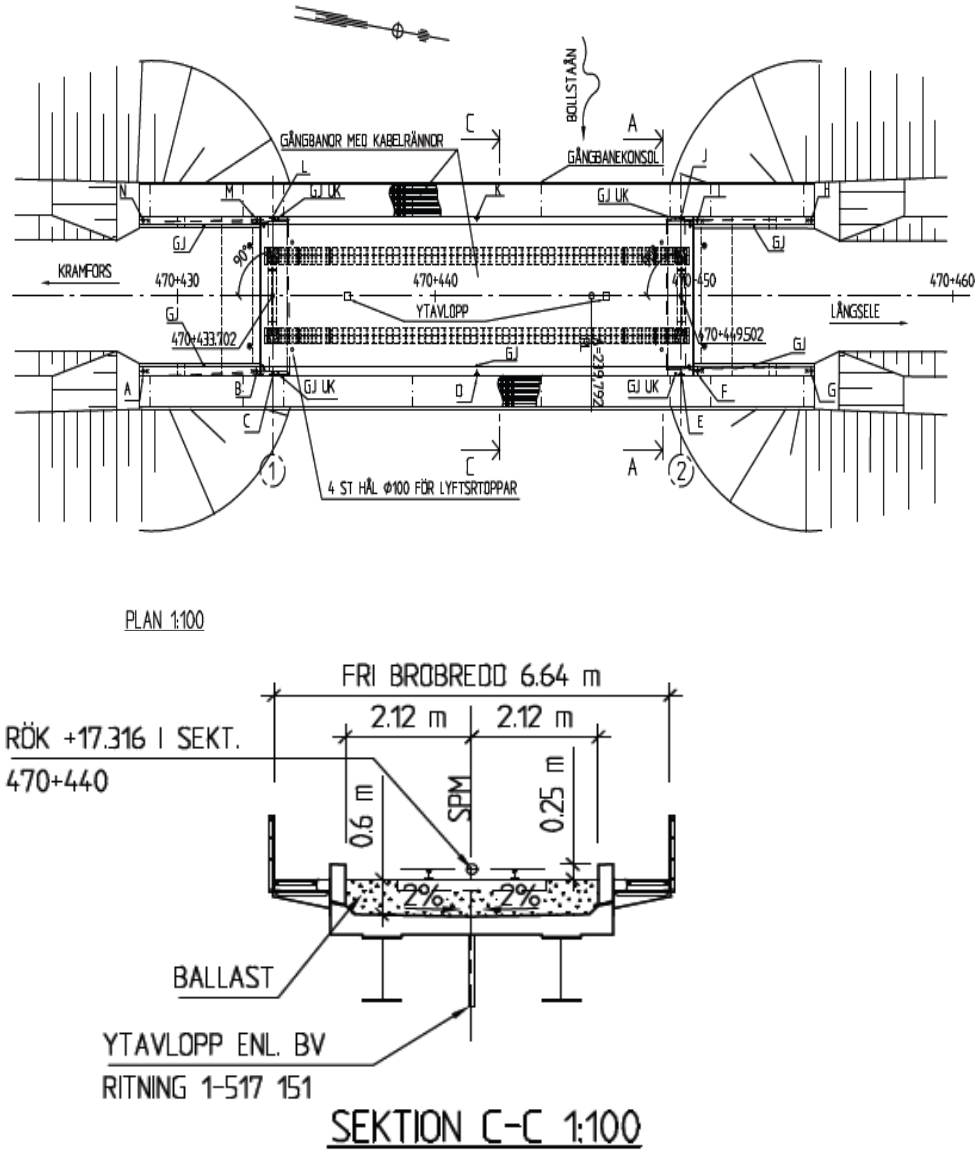

Figure 2. The plan view and cross section of Bollstaån railway bridge (Banverket, 2008).

Table 1. Life cycle inventory of raw material (Classen M., et al., 2009) and Stripple (2001).

		CO2 kg	CH4 kg	NH3 kg	NOx kg	SO2 kg	CO kg
Crushed aggregates	/ton	1.42E+00	3.82E-06	0.00E+00	1.23E-04	7.88E-04	1.49E-03
reinforcement steel	/kg	2.22E+00	9.17E-03	0.00E+00	4.94E-03	7.48E-03	1.02E-03
Concrete	/m3	3.13E+02	1.29E-02	1.59E-03	8.24E-01	4.32E-01	3.91E-01
truck transportation	/tkm	3.94E-02	3.84E-06	2.50E-07	4.18E-04	1.25E-06	8.20E-05
rail transportation	/tkm	7.12E-03	2.94E-07	4.52E-08	1.24E-04	1.36E-06	3.57E-05
Construction steel	/kg	8.90E-01	6.01E-07	3.05E-06	2.10E-03	1.74E-03	0.0243

3.2 *Characterization of LCI data*

For the environmental impact evaluation, only classification and characterization is performed, while the normalization, weighting and grouping process are excluded from the scope. The characterization factors are obtained from CML (2002) as presented in Table 2, the considered environmental category including Global Warming Potential (GWP), Photochemical Ozone Creation Potential (POCP) and Acidification Potential (AP). Within each environmental impact category, the emissions are calculated to the same unit and summarized based on the LCI result.

Table 2. Characterization factor of LCI data (CML 2002).

Main characterization factors

	GWP	POCP	AP
CO		0.03	
NO_x		0.028	0.70
SO_x			1.00
CH_4	21.00	0.007	
CO_2	1.00		
N_2O	310.00		0.50
HCl			0.88

3.3 *Result presentation*

The characterization result of three environmental categories GWP, POCP and AP is presented in Figure 3. While the normalization, grouping and weighting process are out of the scope in this study. It has been noticed the concrete consumption contributes the significant impact in the category of GWP and AP, while for the POCP impact category, the rail production causes the major concern. The process of ballast manufacture, the transportation of concrete, rail, ballast and reinforcement has ignorable impact in all three categories. Finally, both of rail and the concrete manufacture procedure lead to a large share of the environmental impact in GWP, POCP and AP.

4 CONCLUSION

This paper reviewed the current literatures regarding the life cycle assessment methodology and existing research on bridge infrastructures. It has been concluded from the current literature review that the environmental impact is actually a combined effect influenced by several factors: for instance, the material selection, bridge type, the energy mixture, involved transportation processes, the frequency of maintenance activities and demolishes strategy. The major environmental impact is generated from the material manufacture, the construction and the traffic disturbance due to the closure of the infrastructure.

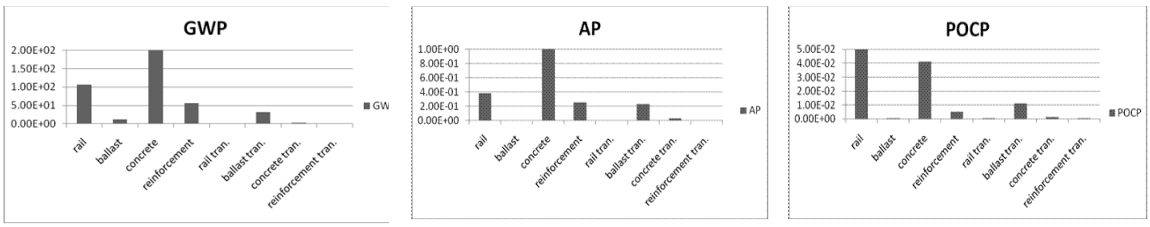

Figure 3. Environmental impact result of Bollstaån Bridge (tran. refer to transportation).

The case study of the Bollstaån Bridge located at Kramfors, Sweden was analyzed by the LCA methodology, several air emissions of CO_2, CH_4, NH_3, NO_x, SO_2 and CO and environmental impacts of GWP, AP and POCP were included in the study. With the classification and cha-

racterization processes, it has been found that the concrete consumption contributes to the most significant impact in the GWP and AP categories, while the rail production is the major concern for POCP impact. The ballast manufacture, the transportation processes of concrete and reinforcement causes ignorable impact in all three categories. However, the transportation process was based on the assumption, which could cause considerable impact due to increased transportation distances and material quantities.

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Adaptation to Climate Change in Finnish Concrete Buildings – Preliminary Study

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ABSTRACT: The impact of climate change to Finnish climate was studied in the Finnish Meteorological Institute's ACCLIM research. In the assessment of the impact of climate change to concrete buildings, the starting hypotheses are the conclusions of the ACCLIM research on climate change during the next 100 years. According to made condition assessments carried out last 15 years, 42.7 % of Finnish concrete facades and was seen visual frost damages. Again, the protective pore ratio is less than 0.15 in about 70 % of concrete facades depending on the surface type of concrete facade. Again, 59.2 % of Finnish concrete facades were seen visual corrosion damages. The corrosion of reinforcement was induced by carbonation of concrete and small cover depths of reinforcement. Despite unsatisfactory material properties, the deterioration has been rather limited for now. Moisture behavior and environmental stress conditions have a strong impact on frost damage of concrete and corrosion rate of reinforcement in carbonated concrete. The climate change will have only harmful effects to service life of existing concrete facades and balconies.

1 INTRODUCTION

1.1 *Background and starting hypotheses*

Concrete facades exposed to outdoor climate are deteriorated by several different degradation mechanisms, whose progress depend on many structural, exposure and material factors. Degradation may limit the service life of structures and, therefore, the possibility of retaining the present or original appearance of buildings and suburbs. Compared with the rest of Europe the Finnish building stock is relatively young, more than 60 % of Finnish building stock has been built in the 1960's or later. There are huge amount of technically similar concrete buildings in suburban areas, because since the 1960's a total of about 44 million square meters of concrete-panel facades have been built in Finland as well as almost a million concrete balconies, Vainio et al (2005).

Despite of the quite young age of the Finnish concrete building stock, several problems have been encountered in their maintenance and repair. The structures have deteriorated due to several different deterioration mechanisms whose progress depends on many structural, exposure and material factors. Thus, the service lives of structures vary widely. In some cases the structures have required remarkable and often unexpected, technically significant and costly repairs less than 10 years after their completion. For this reason many new methods have been developed in Finland for maintaining and repairing these concrete structures during the last 20 years. The methods include a condition investigation practice and its extensive utilization, rational repair methods and their selection, as well as first-rate repair products and appropriate instructions for managing repair projects.

The climate change itself has been studied widely all over the world for several years and many research programs have been executed during this time. The impact of climate change to

Finnish climate was studied in the Finnish Meteorological Institute's ACCLIM research. In the assessment of the impact of climate change to concrete buildings, the starting hypotheses are the conclusions of the ACCLIM research on climate change during the next 100 years.

Because of big amount of those existing concrete buildings, it is very important economical issue for Finland, how those buildings will adapt to climate change.

1.2 *Structures of concrete facades and balconies*

Prefabricated concrete facades have been the most common facade type in residential buildings in Finland since the late 1960's, at least in blocks of flats. A typical concrete element consists of an outer layer, thermal insulation and an inner layer. The outer and inner layers are connected together by trusses. The outer layer is typically between 40 and 85 mm thick, and the strength of concrete is typically near C20. The thermal insulation is usually mineral wool with a design thickness of 70 to 140 mm. Due to the compaction of thermal insulation, the actual thickness is usually between 40 and 100 mm. The thickness of the inner layer is normally from 150 to 160 mm (load bearing element) or 70 mm (non-load bearing elements).

The most common type of balcony from late 1960's in Finland consist on side walls, slab and parapet elements which are prefabricated from concrete. Those balcony elements consist so called balcony-tower, which has own foundations and the whole tower has been connected to buildings frame only for horizontal loads. Typical thickness of side wall element is normally from 150 to 160 mm and in parapets from 70 to 85 mm. Parapets usually have quite heavy reinforcement near both surfaces.

1.3 *Objective*

The objective of this pre-study was to assess, based on current information, the applicability of today's concrete facades and balconies and renovation methods for those structures in the climate conditions of the future, and to get an idea of what research is needed for adapting the current building stock to climate change.

2 RESEARCH MATERIAL

The research material consist of the database of deterioration and material properties of existing Finnish concrete facade panels built up during 1961 to 1996, and weather observations since 1961 made by Finnish Meteorological Institute (FMI). The influence of climate change to Finnish concrete buildings will be anticipated based on the results of FMI's ACCLIM research.

2.1 *Database*

Condition assessment systematic for concrete facades and balconies has been developed in Finland since the mid-1980's. A large body of data on implemented repair projects has been accumulated in the form of documents prepared in connection with condition assessments. About a thousand five hundred precast concrete apartment blocks have been subjected to a condition assessment, and painstakingly documented material on each one exists, including the buildings' structures and accurate reports on observed damage and need for repairs based on accurate field surveys and laboratory analyses.

The condition assessment data from 946 buildings has been gathered to a database. Those condition assessment reports have been collected from companies which have conducted such investigations as well as from property companies owned by cities.

2.2 *Present weather data*

Weather data consists of annual liquid precipitation i.e. rain and wet snow. Both of them can be capillary adsorbed to pore structure of concrete. Wind directions and wind speed during rain and in all times (including also snowfall and dry weather) during September to April was gathered,

too. All weather data was gathered from Jyväskylä (inland), Vantaa (south costal area) and Turku (coast line) since 1961.

2.3 *Finnish outdoor climate in the future*

Several scenarios and climate models has been studied in FMI's ACCLIM research. Based on these studies some conclusions have been made regarding estimates for adaptation studies. In case of concrete buildings following changes in climate are the most important (Jylhä et al. 2009):

- More than 95 % probability the mean temperature will be 2 to 6 °C higher than now until the end of this century. Temperature increases 3 to 9 degrees at wintertime and 1 to 5 degrees at summertime.
- Accompanied with increases in temperature, the annual precipitation will also increase 10 to 40 % at wintertime and 0 to 20 % at summertime by the end of this century. The change in precipitation will be bigger in North Finland than southern parts.
- Wintertime freezing point days, with daily minimum temperature below zero, and maximum temperature above zero, will at first become more frequent on the whole country. Towards the end of this century, they continue to increase in the north and east, but start to decrease in the southwest. The mean annual number of freezing point days will then be larger than currently only locally in the north.
- The amount of precipitation as well as the amount rainy days will increase at wintertime. Bigger proportion of annual precipitation will also be rain or wet snow. In southern Finland, the frequency of summertime wet days may decrease.

3 DETERIORATION OF FINNISH CONCRETE BUILDINGS

The most common degradation mechanisms causing the need to repair concrete facades, and concrete structures in general, are corrosion of reinforcement due to carbonation or chlorides as well as insufficient frost resistance of concrete which leads to, for instance, frost damage (Pentti et al. 1998).

These very well known degradation mechanisms may result in, for instance, reduced bearing capacity or bonding reliability of structures. Experience tells that defective performance of structural joints and connection details generally causes localised damage thereby accelerating local propagation of deterioration.

3.1 *Corrosion of reinforcement*

Reinforcing bars in concrete are normally well protected from corrosion due to the high alkalinity of the concrete pore water. Corrosion may start when the passivity is destroyed, either by chloride penetration or due to the lowering of the pH in the carbonated concrete. Steel corrosion in carbonated concrete or in chloride migrated concrete has been long and widely studied by Tuutti (1982), Parrott (1987), Schiessl et al (1994), Richardson (1988), Broomfield (1997), Mattila (2003) etc.

Chloride-induced corrosion is not problem in Finnish concrete facades or balconies. Only four cases out of 946 buildings chloride content were high enough for corrosion. In those cases chlorides were used as an accelerator in fresh concrete and manufacturing of those concrete facade panels was taken place at winter time on construction site. When carbonation induced corrosion is under study, it has to be finding out the distribution of cover depths of steel bars and carbonation of concrete.

Concrete facades: The most typical carbonation depths of concrete facades constructed in the 1970's or earlier, is nowadays around 10 and 20 mm if the concrete quality is normal. Concrete facades covered with ceramic or brick tiles can be carbonated only thorough the cement based pointing of tiles. Also paintings used on concrete facades have resistance against the diffusion of carbon dioxide. The average carbonation speed of different concrete facades is shown in figure 1.

According to figure 1, average carbonation depth is in the concrete facade made in the year 1970 now between 6 and 17 mm depending on the surface finishing of concrete. However, there is a lot of scattering in carbonation rate also in each group of surface finishing.

The depth of the concrete cover on reinforcement varies a lot, depending on the manufacturing of concrete panels and quality of labour work. Cover depth of reinforcement varies between 0 and over 50 mm. Determining the suitable repair method for concrete facade, the amount of cover depths under 10 mm is critical in most of the cases. Typical amount of small cover depths is 5 to 10 per cent of all reinforcement in facades. In most cases the smallest cover depths are in ceramic tile finished facades, where reinforcement is situated just behind the tiles. Carbonation of concrete has widely achieved the reinforcement of all concrete facades made during 1960's and 1970's. And corrosion has been possible for 20 to 30 years for now.

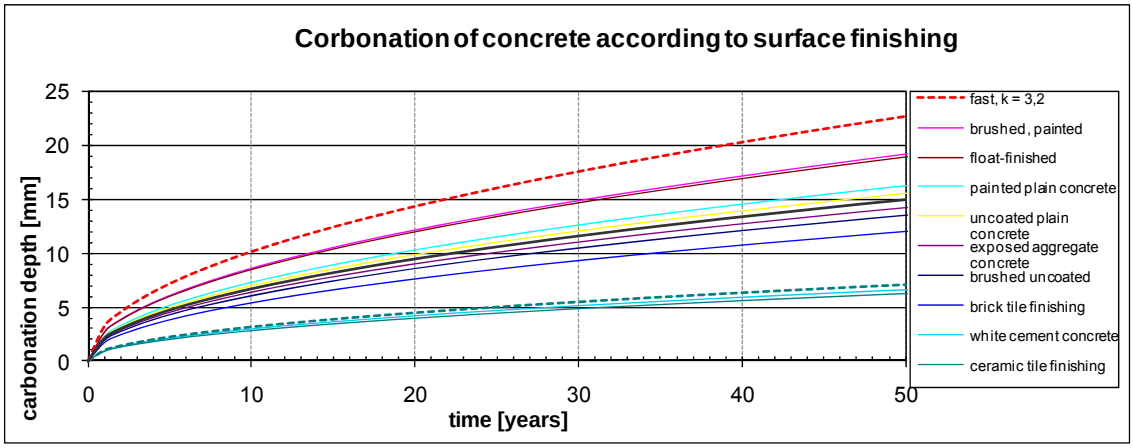

Figure 1. Average carbonation speed of concrete has a lot of variation according to surface finishing.

Concrete balconies: According to the database, average carbonation factor k [mm/√a] in balcony side walls is 2.60 in outer surface and 2.91 in inner surface to same extent in parapets are 2.10 and 2.15. The standard deviation in carbonation factor is relatively high; it is between 1.31 and 1.51 as mentioned cases. Carbonation factors are in general remarkable smaller in buildings made 1990 and after. This is mostly consequence on raising the concrete strength up to C30-C45. Carbonation front can proceed faster in inner surfaces of concrete structures because rainwater does not close its pore structure from time to time.

The distribution of cover depths of steel bars in balcony frame elements is shown in figure 2. If it is aim to use so called light repair methods, like patch repairs, it have to be looked the amount cover depths which are ≤ 10 mm. Carbonation of concrete is in many cases advanced more than mentioned 10 mm, steel bars deeper than that causes very seldom visible corrosion damage, because the diameter in ordinary concrete elements varies usually between 6-10 mm and is mostly 12 mm.

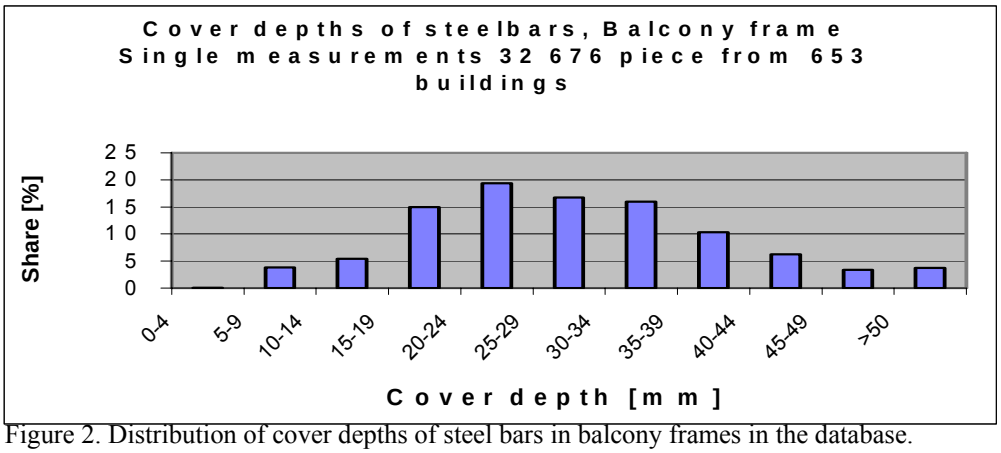

Figure 2. Distribution of cover depths of steel bars in balcony frames in the database.

3.2 *Frost resistance of concrete*

Concrete is a porous material whose pore system may, depending on the conditions, hold varying amounts of water. As the water in the pore system freezes, it expands about 9 % by volume which creates hydraulic pressure in the system (Pigeon & Pleau 1995). If the level of water saturation of the system is high, the overpressure cannot escape into air-filled pores and thus damage the internal structure of the concrete resulting in its degradation. Far advanced frost damage leads to total loss of concrete strength.

The frost resistance of concrete can be ensured by air-entraining which creates a sufficient amount of permanently air-filled so-called protective pores where the pressure from the freezing dilation of water can escape. Finnish guidelines for the air-entraining of facade concrete mixes were issued in 1976 (Anon. 2002). According to those guidelines, protective pore ratio [p_r] should be ≥ 0.20 in normal Finnish outdoor climate.

Concrete facades: According to made condition assessments of existing concrete facades, the protective pore ratio of concrete very rarely fulfils the requirements of Finnish national building codes ($p_r \geq 0.20$). The protective pore ratio is less than 0.15 in about 70 % of concrete facades depending on the surface type of concrete facade. The distribution of protective pore coefficient of most typical used different surface finishing is shown in figure 3.

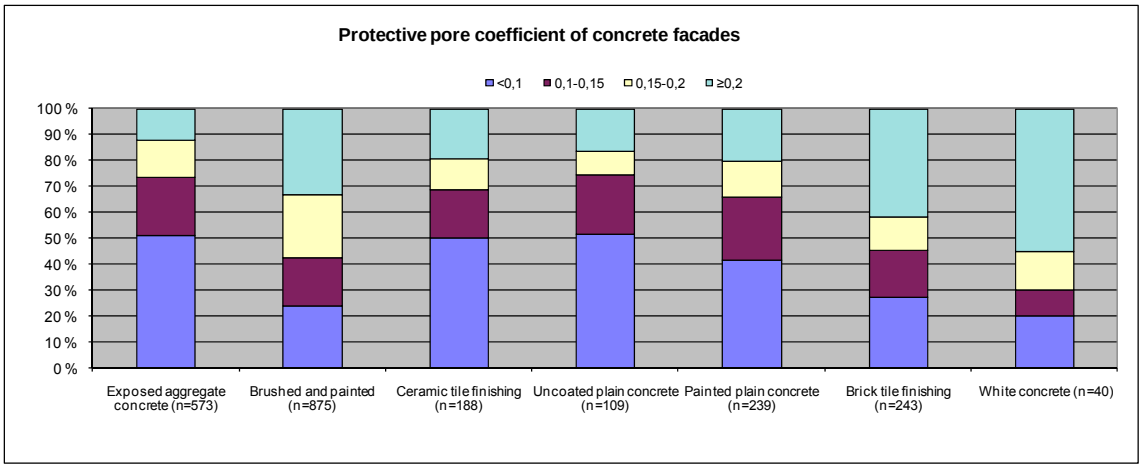

Figure 3. Protective pore coefficient of most typically used surface finishing in Finnish concrete facades.

Concrete balconies: According to condition investigations in Finnish balconies p_r is < 0.10 in 59 % of samples, between 0.10 and 0.14 in 19 % of samples and between 0.15 and 0.19 in 11 % of samples. Total number of samples in the database is 1907. Distribution of protective pore ratio is slowly getting better year after year since 1981 because of consistent air-entraining in concrete mixes used outdoor climate.

3.3 *Deterioration of concrete buildings in present climate*

According to the database 59.2 % of Finnish concrete facades were seen visual corrosion damages during condition assessment. 53.5 % of those were local, and 5.7 % were wide spread. Corresponding figures for balconies are a little higher; 66.2 % visual damages, 50.8 % of them are local and 15.4 % wide spread.

The corrosion of reinforcement was induced by carbonation of concrete and small cover depths of reinforcement. Much more visual corrosion damage was seen in coastal area than inland. Despite small cover depths of reinforcement in carbonated concrete, 40.8 per cent of facades and 33.8 per cent of balconies could not seen any visual corrosion damage.

The corrosion rate has strong dependence on moisture content in carbonated concrete. According to Mattila and Pentti (2004) density of corrosion current is high in uncovered concrete if the annual rainfall is 480 mm or higher. In figure 4 the annual liquid precipitation, i.e. rain or wet snow, in Finland is shown.

The amount of annual rainfall is not uniformly distributed to all facades. The distribution of rainfall depends on the height of the building and also prevailing wind directions during rain. The upper parts and corners of facades get more rainfall than lower and central parts. Prevailing wind directions and wind speeds have a strong influence on the distribution of rainfall on a building. Most of the liquid precipitation in wintertime comes with southerly to westerly winds. Rain events with wind from other directions have been rare, see figure 5.

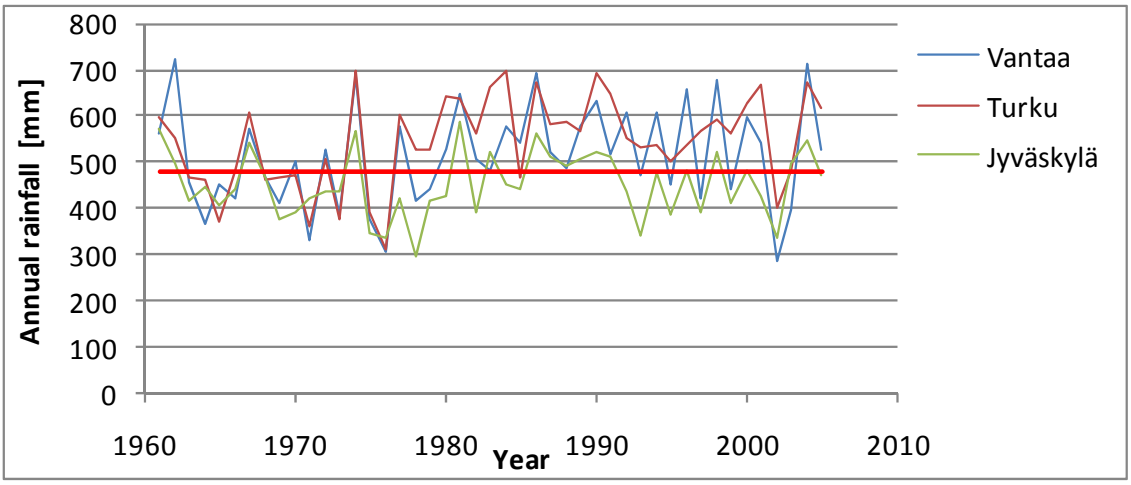

Figure 4. Annual liquid precipitation in Jyväskylä (inland), Vantaa (south costal area) and Turku (coast line) during 1961 to 2005. The horizontal line expresses the annual rainfall that leads to faster corrosion rate.

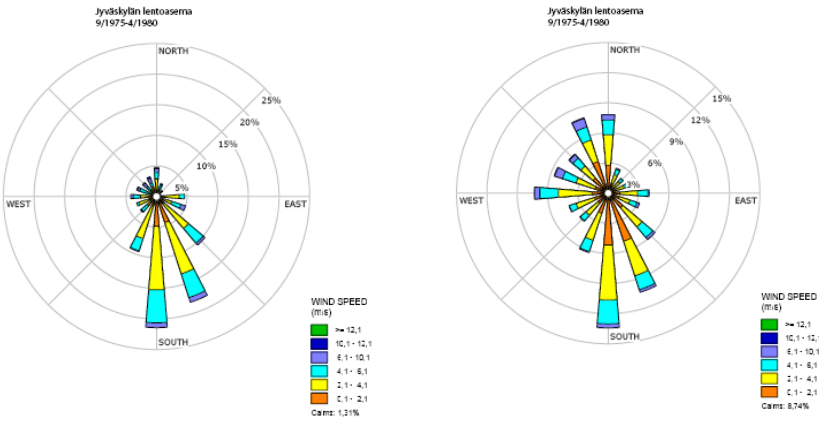

Figure 5. Prevailing wind directions in wintertime during liquid precipitation on the left and in all times including snowfall and dry weather on the right. Weather data is measured at Jyväskylä airport during Sept. 1975 to Apr. 1980.

Hardly any corrosion damage can be seen on the north or east facades despite of reinforcement is situated in carbonated concrete as well as on the south and west facades. The high outdoor relative humidity in Finland during winter time is not sufficient to upraise the humidity of carbonated concrete high enough for corrosion. Thus, the high corrosion rate needs also rainfall. In Finland, prevailing wind direction during rainfall in winter is southerly to westerly. Snowfall cannot be adsorbed in the pore structure of concrete. This is a reasonable explanation for more corrosion damage on southern and western facades than northern and eastern.

Situation is similar with frost damage of concrete; hardly any damage can be observed on the north or east facades despite of insufficient frost resistance of concrete as well as on the south and west facades.

4 INFLUENCE OF CLIMATE CHANGE

According to Jylhä et al. (2009), the climate change will have only harmful effects to service life of existing concrete facades and balconies. Progress of corrosion of reinforcement and frost damage of concrete are suspended on existing moisture content of concrete, which will increase in the future climate.

4.1 *Corrosion rate of reinforcement*

Visible damage appears first on the spots where the concrete cover is smallest and the moisture content of concrete is highest. According to Tuutti (1982) relative humidity of concrete has a strong influence on corrosion speed. The rate of corrosion proceeds significantly only if the relative humidity of concrete exceeds 80 %. In typical Finnish outdoor climate during September to April, relative humidity in concrete facades is between 90 and 95 %. This intend corrosion rate of 0.1 to 1 $\mu A/cm^2$ respectively. Increasing of annual liquid precipitation will increase corrosion rate of reinforcement situated in carbonated concrete respectively.

Raining and wet snow has come with southern to western winds for now. Only snowfall has become from north. If the increased rain and wet snow will furthermore come with same winds than now, it will only increase the corrosion rate on the same facades. But if liquid precipitation will come with northern winds, like snowfall, the amount of corrosion will increase rapidly and widely also on the northern facades, where corrosion rate of reinforcement in carbonated concrete has been insignificant until these days.

4.2 *Frost damage of concrete*

In Finnish facades and balconies has been used insufficient frost resistant concrete, as discussed earlier, particularly built before the year 1981. Protective pore coefficient is less than 0.10 in average 70 per cent of those concrete facades and balconies. And approximately half of whole existing concrete building stock has been built during 1960 to 1979.

Increase of rain together with increasing annual freeze-thaw cycles will increase the extent and rate of frost damages in concrete. The climate stress concerning annual freeze-thaw cycles has been more severe in coastal area than inland until now. It has been estimated, that climate in inland will remain today's coastal climate. The result of that will be more and wide spread frost damages.

Frost damages appears mostly on western to southern facades because of prevailing wind directions during rain as well as corrosion damages. If rain will come in the future with northern winds, like snowfall, the amount of frost damages will increase rapidly and widely also on the northern facades, where frost damages are now relative rare.

4.3 *Extending service life with protective coatings*

Protective repair methods are suitable mainly for structures where deterioration has just begun and the damage is not widespread. Possible protective repair methods suitable for concrete facades and balconies are divided into: painting over the old paint, protective painting after removal of old paints and thorough patch repair and protective painting.

According to Mattila & Pentti (2004), the corrosion rate in carbonated concrete is possible decrease significantly with protective coatings .With protective coatings it is possible to decrease remarkably the moisture content of concrete structure. In the monitoring of corrosion rate the moisture content decreased to a level which the disintegration of concrete due freeze-thaw exposure does not propagate any further.

If the existing structures are more severely damaged, protective repair methods are no longer effective. In case of balconies, whole structure is usually demolished and replaced with new concrete balconies. In principle it is also possible to cover balcony structures with different metal cassettes etc., but in practice the costs of those repairs are same or even higher than new concrete balconies. In case of facades, new facade with additional thermal insulation is installed on the damaged facades in the first place.

5 CONCLUSIONS

Moisture behavior and environmental stress conditions have a strong impact on frost damage of concrete and corrosion rate of reinforcement in carbonated concrete. For instance, the stress on concrete facade depends on the existence of proper waterproofing and prevailing wind direction during the rain.

Concrete used in Finnish balconies is not frost resistant, 89 % of protective pore ratios in concrete balconies are lower than 0.20 and 78 % are lower than 0.15. In facades about 70 % of protective pore ratios are lower than 0.15. Despite this 56-70 % of buildings depending on buildings location has not any visible frost damage.

Again, the carbonation of concrete has widely advanced in the facades made in 1970's or earlier. The corrosion of reinforcement has been possible approximately last 20 to 30 years in those facades and balconies. Despite insufficient cover depths of concrete and far advanced carbonation of concrete, visually seen corrosion damages are relative rare. Corrosion damages appear mostly on facades, which get more rain. In Finland those are upper parts of southern and western facades.

It is possible to have good results with thorough patch repair and protective coatings with balcony glazing in most of the cases, because these protective measures decrease effectively moisture content in concrete and this slows corrosion rate 30-80 % and frost damage stops completely. Again, it has been estimated it is possible to get 30 years more service life for concrete balconies with protective measures mentioned before compared with doing any measures.

This is remarkable result for property owners and in perspective of global climate change. It has been estimated, that heavy rains and freeze-thaw actions will increase during following decades remarkably. If those protective measures are used early enough in those concrete structures, perhaps all Finnish concrete balconies do not have to demolish and rebuild at all.

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Climate change effects on the robustness of building stock

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ABSTRACT: Climate change can affect the health and safety of the built environment. Over the last two decades, international scientific community focused on the potential impacts of greenhouse gas emissions from human activities on the global climate. Few studies have focused on the possible impact of climate change on the health and safety of built environment. Buildings and other engineering structures (e.g. communication and electric power infrastructure, etc.) should be able to remain safe and stable for their designed lifetime. The paper presents the main factors related to the climate change that affect the robustness of building stock. A case study is presented and conclusions regarding the evaluation of the existing structures are underlined.

1 INTRODUCTIONS

During the last two decades, the international scientific community and international organizations, e.g. World Meteorological Organization (WMO), Intergovernmental Panel on Climate Change (IPCC), have focused the implications of climate change on the increased intensity and frequency of meteorological hazards. The IPCC Fourth Assessment Report (IPCC Report, 2007) stated that "warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level". The European Construction Technology Platform (ECTP) defined a vision for a sustainable and competitive construction sector by 2030. This initiative aims to achieve leadership in competitiveness, addressing major technological challenges that face the construction industry over the coming decades within research targets. Key themes include sustainability of the construction industry, safety for construction workers and society in general and improvements in efficiency and productivity in supplying chains. Other studies that focused on the possible impact of climate change on the health and safety of built environment are the programs and activities initiated and supported by UNESCO World Heritage Centre (WHC), e.g. Impacts of Climate Change on World Heritage.

Buildings and other engineering structures should be able to remain safe and stable for their designed lifetime. The safety margins expressed by the general condition of structural reliability may be given by the following equation:

$$E_d < R_d \tag{1}$$

where E_d is the load effect and R_d is the resistance.

Climate change may influence the return period of extreme weather events which results in an increase of loads Ed, while changes in temperature, humidity, levels of precipitation, wind and emissions reduce the durability of the materials and their resistance R_d (Figure 1). The consequences of climate change on the natural environment require long-term actions. On the contrary, the impact of climate change on the severity of climate loads requires urgent actions as the consequences in terms of loss of lives and damages can be catastrophic. The safety margins and

robustness of constructions provided by technical regulations and standards should therefore be continuously updated so that the designed level of reliability is maintained. The experience of the last three decades shown the losses from the extreme weather events have more than doubled (Munich Re, 2008).

a) b)

Figure 1. Climate change effects: a) increased frequency and intensity of weather extremes; b) reduced durability of materials.

The severity of storms and tornadoes increased several times in Europe, both in number and intensity, during the 20th century, causing collapses and damages of building and facilities. Heavy snowfalls and drifting from high winds, or ice accumulation might cause severe structural accidents and significant losses. For example, winter 2005/2006, with dramatic structural failures and fatalities in Katowice and Bad Reichenhall, winter 2009/2010, when snow and ice hit airports, roads and railways (Figure 2). Extreme rainfall can also cause considerable fatalities and damage, especially to road and railway systems (e.g. Madeira, February 2010, more than 50 fatalities and heavily damages; France, in February, May and June 2010, worst floods to hit southern France since 1827; Romania, in June-July, worst flood to hit Romania in four decades).

a) b)

Figure 2. Damages due to snow load: a) sport hall in Bad Reichenhall, Germany; b) Exhibition hall, Kattowitz, Poland.

Temperature increase may cause failure or damages of large span structures. Moisture associated with temperature variations affects the mechanical properties and durability of building materials. Mechanical properties of soil suffer from intense rainfall, moisture and temperature change, and affect the infrastructure reliability. Among other effects, floods are responsible for most bridge failures; the scour and exposure of piers affect the bridge equilibrium. Similar effects occur in case of bank and coastal protections or in case of retaining walls. Starting from the CEE Construction Products Directive (89/106/CEE), it is the time to initiate the systematic survey of climate change effects against constructions, on the aim to provide a coherent approach, including definition and characterization of actions, quantification of the climate-affected material properties, evaluation of the reliability and durability of structures, providing reference criteria and background studies for technical regulations and, finally, proposing intervention strategies.

The paper presents the main factors related to the climate change that affect the robustness of building stock. A case study is also presented and conclusions regarding the evaluation of the

existing structures are underlined.

2 RISK ON BUILT STOCK DUE TO CLIMATE CHANGE

The Report presented during the 30th Session of WHC (Vilnius 2006) emphasized the risk and impacts on the cultural heritage due to climate change. Unfortunately, with few exceptions, there are no codified models to quantify the residual mechanical properties of construction materials due to different climate actions.

Most of the impact subjects are belonging, in fact, to the built environment (see Table 1). However, even today for instance in Eurocode 1 (EN 1991), Part 3 related to snow, Part 4 related to wind and Part 5 related to thermal actions, that are based on statistic data recorded prior 90's, remain in most of cases below the actual values. Also, there are no codified models - with small exception - to quantify the residual mechanical properties of construction materials altered due to different climate actions.

Table 1. Climate change risk and impact on built stock.

Climate indicator	Climate change risk	Physical, social and cultural impacts on cultural heritage
Atmospheric moisture change	Flooding (sea, river) Intense rainfall Changes in soil chemistry Ground water changes Changes in humidity cycles	Subsoil instability, ground subsidence Relative humidity cycles/shock causing, splitting, cracking, flaking and dusting of materials and surfaces Corrosion of metals
Temperature change	Diurnal, seasonal, extreme events (heat waves, snow loading) Changes in freeze-thaw and ice storms, and increase in wet frost	Deterioration of facades due to thermal stress Damage inside brick, stone, ceramics that has got wet and frozen within material before drying Inappropriate adaptation to allow structures to remain in use: roofs failure, pipelines, electric, and communication networks failure, etc
Sea level rises	Coastal flooding Sea water incursion	Coastal erosion/loss Permanent submersion of low lying areas
Wind	Wind-driven rain Wind-transported salt Winds, gusts and changes in direction	Static and dynamic loading of historic or archaeological structures Structural damage and collapse Deterioration of surfaces due to erosion
Climate and pollution acting together	pH precipitation Changes in deposition of pollutants	Corrosion of metals
Climate and biological effects	Proliferation of invasive species Spread of existing and new species of insects (e.g. termites)	Collapse of structural timber and timber finishes

The research needs to focus theoretical and methodical frameworks within following scientific thematic areas:

- Climate change effects with incidence on durability of building materials and reliability of constructions: Acquisition and interpretation of relevant scientific data related to climate changes, expressed in terms of climate variables, e.g. precipitations, temperature, humidity, wind (based meteorological records for last two decades existing at the specialized National bodies), and evaluation of their impact on building stock, by means of relevant study cases in order to sustain the recommendations for upgrading relevant Parts of Eurocode 1;
- Models for characterization of mechanical properties of building materials subjected to progressive degradation induced by climate effects;
- Risk Based Models and Performance Based Criteria for evaluation and robust design of structures

• Intervention strategies to preserve and/or enhance safety and durability of building stock, built heritage included, and new constructions in order to face climate change effects along their design lifetime.

As an example with the reference to Eurocode 1, Actions on structures - Part 1-3: General actions - Snow loads (EN1993-1-3), there is a potential topic related to the snow fall, which may affect in different ways the design of the buildings. Here, it is necessary to clarify several issues, i.e. the areas were the exceptional snow fall may affect each country, the intensity of the exceptional snow and the possible combination with exceptional snow drift.

As a response, CEN/TC 250 decided in 2009 to form an ad-hoc group on "Robustness", due to the concerns related to the limitations of the Eurocode provisions (EN 1991-1-7) to ensure the structural robustness. The main problems refer to the definition of robustness (see clause 3.3 Accidental design situations) and material related demands from the loading standards. Eventually, extreme climate induced actions (snow, winds, etc) are, in fact, accidental actions. Some preliminary conclusions have shown that clearer description of accidental actions and the development of sets of material dependant (prescriptive) measurements in dependency of the consequence classes to ensure robustness are needed. The proposals for harmonized material are expected in May 2011, while amendments to be incorporated in EN1991 are expected for the period 2013-2015.

3 CASE STUDY: DAMAGE EVALUATION OF AN EXISTING BUILDING DUE TO SNOW ACCUMULATION ON ROOF

3.1 *Description of the building*

The steel structure building is located in Bucharest, Romania, and was designed and constructed in 2004. The building consists of two parts, separated by a small gap to allow for independent behavior. The first unit is 120 meters long, 72 meters wide and 14 meters height. The second unit is 180 meters long, 78 meters wide and 10 meters height (Figure 3).

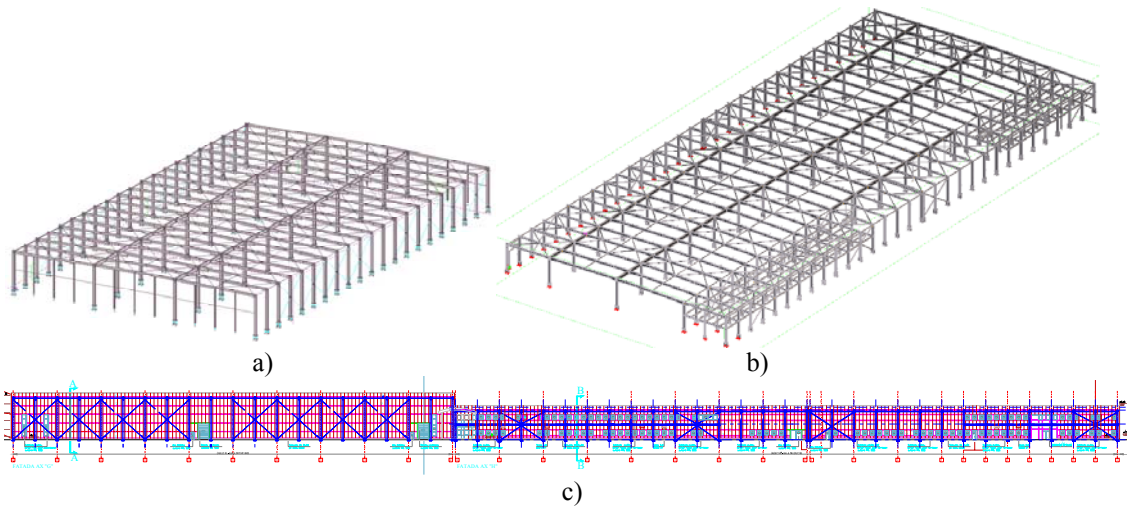

Figure 3. Views of the steel building: a) unit 1; b) unit 2; c) the assembly of the building.

Columns and beams are made with built-up sections. Columns are rigidly connected at the base by means of anchoring bolts. Beam-to-column connections are with bolts and extended end plates. The roof purlins and wall rails are made from light cold formed Z elements. Sheathing panels are used for roof and walls.

3.2 *Damage of building due to accumulation of snow*

In February 2010, during a strong snowfall and blizzard, the roof panels of the unit 2 started to deflect beyond the limit due to the snow accumulation at the contact with the unit 1. The immediate inspection on the roof revealed the snow depth was almost equal to the difference in height between the two units, i.e. four meters. On the current areas of the roof, the snow was at about 1

meter thick. In order to prevent the collapse of the roof at the contact between the two units, it was decided to remove the snow accumulation. Due to the large span, it proved to be more efficient to remove the snow through the smoke vents and skylights on the roof (Figure 4).

Figure 4. a) Accumulation of snow on the roof; b) snow was removed through the vents; c) improvised temporarily supports; d) roof after the snow was removed from the joint area.

A close inspection shown the deflections of the roof panels reduced significantly after the removal of the snow, but with significant damages. The purlins were completely damaged due to lateral torsional buckling. As it continued to snow, it was decided to temporarily add new purlins along the first span of the affected lower unit, at half distance compared to the original solution, also to protect the roof panels against new snow accumulations. Fortunately, the snow fall reduced in intensity and there was no accumulation of fresh snow.

Figure 5. Temporarily purlins along the affected span.

3.3 *Evaluation of structure integrity*

After an agreement with the owner, it was decided to make a close inspection of the structure, including:

- visual inspection of the entire structure: main frame elements and connections, purlins, panels, roof bracings

- nondestructive testing (NDT) of the welds in most stressed areas of the connections
- evaluation of the structure safety according to new code provisions for loads and design: the snow load building code in function at the design (STAS 10101/21-92) time was replaced in 2005 by a new one, aligned to Eurocode (CR 1-1-3-2005).

The inspection of the main structural elements (beams, columns) shown there are no damages. Some bolts from the beam-to-column connections were replaced as they were very much stressed during the accumulation of the snow. The only elements that were affected were the purlins and the roof panels from the lower unit, at the joint with the taller one. It was decided to replace them with new elements. Moreover, it was decided to strengthen also the second span, even it was not affected.

The NDTs of the welds have shown no cracks and a good behavior. Due to the quality of the execution, the connections were able to resist the increase of the loads beyond the design ones.

According to the snow load building code in function at the design (STAS 10101/21-92), the maximum accumulation of snow for that particular roof shape was 2.5 times the uniform snow, which led to a factored snow of 4.8 KN/m^2 (equivalent to a layer of 1.9 meters of snow for a bulk weight density of 2.5kN/m^2). According to the new code, maximum accumulation of snow for that particular roof shape was 4 times the uniform snow, but cumulated with an increase of the ground snow load from 1.5kN/m to 2.0kN/m^2 (due to the increase of the return period from 10 yrs to 50 yrs), the factored snow amounted 10.5 KN/m^2 or an equivalent layer of 4.2 meters of snow, exactly the height difference between the two units. It is obvious that the original design snow load was smaller than actual one, while the evaluation according to the new code was very closed to the real drifted snow. But what could happen if the unevenness of the roof was larger? According to the EN 1991-1-3, in case of certain roof and site arrangements, exceptional snow drift loads can be assumed to act locally. It this case, the shape coefficient can reach values up to 8 but this drifted snow needs to be considered as exceptional snow and treated as accidental action. Based on the results of the structural analysis, in order to increase the capacity of the connections along the first two spans of the lower units, the beam-to-column connections and beam-to-beam connections were strengthened by increasing the bolt grade from 10.9 to 12.9 and by adding some welded gusset plates.

4 CONCLUSIONS

Technical regulations and building technologies should be continuously improved to enhance robustness and to ensure the designed reliability of constructions. It is necessary to evaluate the effects of different climate scenarios and, on this basis, to elaborate and propose practical tools to predict in what extent the existing but also new constructions are prepared to meet future climate challenges, and what protective measures to apply in order to guarantee their reliability. The consequences of climate change on the natural environment (sea level, global temperature, etc.) require long-term actions. On the contrary, the impact of climate change on the severity of climate loads requires urgent actions as the consequences in terms of loss of lives and damages can be catastrophic.

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Environmental expenditures of households

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ABSTRACT: The paper presents the basic definitions and survey results of environmental expenditures of households. These surveys have been conducted since 1975 and are compatible with Eurostat methodology. Expenditure in this sector includes costs of environmental services and costs of purchase, installation and construction connected product.

1 INTRODUCTION

In the paper, some information on the expenditure of households, which is one of the 4 economic sectors, prepared by Polish Society with the purpose of protecting the environment will be detailed.
Environmental protection expenditure is the sum of capital and current expenditure for the undertaking of environmental protection activities. Environmental protection is an action or activity (which involves the use of equipment, labour, manufacturing techniques and practices, information networks or products) where the main purpose is to collect, treat, reduce, prevent, or eliminate pollutants and pollution or any other degradation of the environment resulting from the operating activity of the company. Investment expenditure refers to financial or material costs, which aim at creating new permanent resources or improving (reconstruction, extension, restoration, adaptation or modernization) the existing objects of permanent property. It also means costs of so called first investment equipment. Presented division of investment costs is developed according to the rules of national accounting system, compliant with the “SNA 1993” recommendations. Investment expenditure can be divided into permanent resources and other costs.

For several dozen years environmental scientists all over the world have been facing the problem of identification, classification and collection of information about the amount of expenditure on the environment. In 1994 Eurostat, the EU Statistical Bureau published the first manual on The European System for the Collection of Economic Information o the Environment (SERIEE). It is an attempt at the classification and definition of expenditure on the environment. According to the manual expenditure on environment is the expenditure incurred in three main sectors of national economy, namely economic sector, public sector and households sector. Households are considered a specific group of end users being on the one hand the receivers of the services related with environmental protection (sewage collection, wastes disposal) and on the other hand, the consumers of environmental protection products. Such products were divided into two groups:

- the so-called "related" products directly serving environmental protection (e.g. purchase of catalytic converters for cars or domestic waste-water treatment plants); and,

– adapted products which by definition are more expensive that traditional products (e.g. lead-free fuel, products with a high degree of bio-degradation); environmental costs here are the additional costs of the purchase of such products.

One of the Eurostat working groups prepared the final report on *Expenditure on the Environment by Private Households and in the Services Sector* which offered a classification of environmental protection activities of private households (Fig. 1).

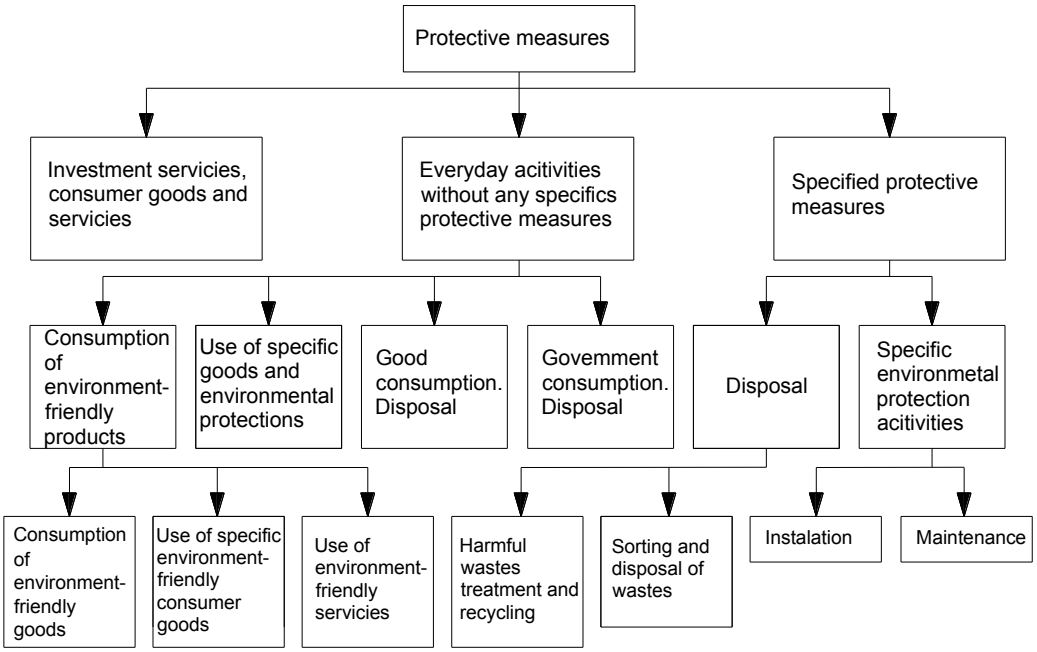

Figure 1. Classification of environmental protection activities of private households.

The EU experts suggested that the statistical survey in the household sector should cover only the costs of services related with environmental protection. They decided that collection of information about expenditure on the purchase of products serving environmental protection was too labour-consuming and costly. However, Poland as an OECD country is obliged every year to present data on its expenditure on the environment in the form of an OECD questionnaire and on the Eurostat Pollution Abatement and Control Expenditure (PAC) questionnaire. One of the sections of that questionnaire is the expenditure on the environment by households, where charges are only one element of the expenditure. In the households sector, as opposed to the other sectors, there is no clear distinction between capital expenditure and running expenses. Due to the specific nature of households activities the former and the latter are treated as one. Classification of households expenditure on the environment in accordance with the requirements of Eurostat and OECD is presented in Figure 2. In Poland the methodology of examination of the running costs of environmental protection, including the expenditure by households, was developed in 1996 and adopted by the Ministry of Environment and the Chief of Statistical Office.

2 METHODOLOGY OF THE HOUSEHOLDS EXPENDITURE ON THE ENVIRONMENT SURVEY

The purpose of the survey was to assess the amount of expenditure on the environment by Polish households in the year 2009.

The expenditure on the environment being the subject of the work was divided into:

1. Costs of services related with environmental protection:

– Collection, discharge and treatment of sewage; and
– Wastes (garbage, sewage sludge) disposal.

2. Expenditure on the purchase and installation of the equipment and products used directly for the purpose of environmental protection:
- As regards atmosphere protection:
  - Heat consumption meters and thermo regulators;
  - Modernization of central heating systems for the entire building and for a single apartment;
  - Installation of equipment for the treatment of fuel gases;
  - Purchase and installation of energy-saving windows;
  - Additional insulation for the building protecting against cold;
- As regards water protection:
  - Connection to the public sewer;
  - Construction of individual wastewater treatment plants;
- As regards soil protection:
  - Domestic wastes disposal equipment;
- As regards biodiversity and landscape protection:
  - Tree and bush planting;
  - House facade repairs;
- As regards noise and vibrations control:
  - Purchase and installation of noise reducing windows;
  - Fences and live fences, noise and vibrations reducing screens;
- As regards radiation protection:
  - Installation of terrestrial and electromagnetic radiation protection shields.

The survey was carried out on a representative sample of 1300 Polish households selected randomly by the Chief Statistical Office for the purpose of examination of Polish households budgets. The survey was carried out by adequately trained employees of the Chief Statistical office in the fourth quarter of 2009. Information about expenditure on the environment was collected for the period of the first three quarters of the year 2009.

The survey covered 6 groups selected in accordance with their social and economic status, namely:
- Households of workers – 44,6 per cent of the sample;
- Households of farmers with additional source of income – 4,3 per cent of the sample;
- Households of farmers – 5,7 per cent of the sample
- Households of self-employed people – 6,1 per cent of the sample;
- Households of the retired and pensioners – 35,2 per cent of the sample;
- Households supported from non-profit sources – 4,1 per cent of the sample.

Expenditure (capital expenditure and running expenses) on					
Water and soil protection	Wastes management	Atmosphere protection	Noise control	Biodiversity and landscape protection	Other areas of environmental protection

(-) minus

Public and economic sector subsidies

+ (plus)

Charges in respect of:					
Water and soil protection	Wastes management	Atmosphere protection	Noise control	Biodiversity and landscape protection	Other areas of environmental protection

= (equals)

Expenditure on the environment

Figure 2. Classification of households expenditure on the environment in accordance with the requirements of Eurostat and OE.

3. ANALYSIS OF 2009 EXPENDITURE ON THE ENVIRONMENT BY SURVEYED HOUSEHOLDS

The expenditure on the environment by the surveyed households was examined from the point of view:

- environmental components;
- type of building;
- social and economic status;
- voivodship.

The total expenditure on the environment by the surveyed households amounted to 953,5 thousand PLN and 23,25 per cent out of that amount was the cost of services related with environmental protection (Fig. 3).

Most of the costs of services related with environmental protection, i.e. 67,1 per cent was the cost of collection or discharge of sewage to the public sewer or the costs of sewage treatment.

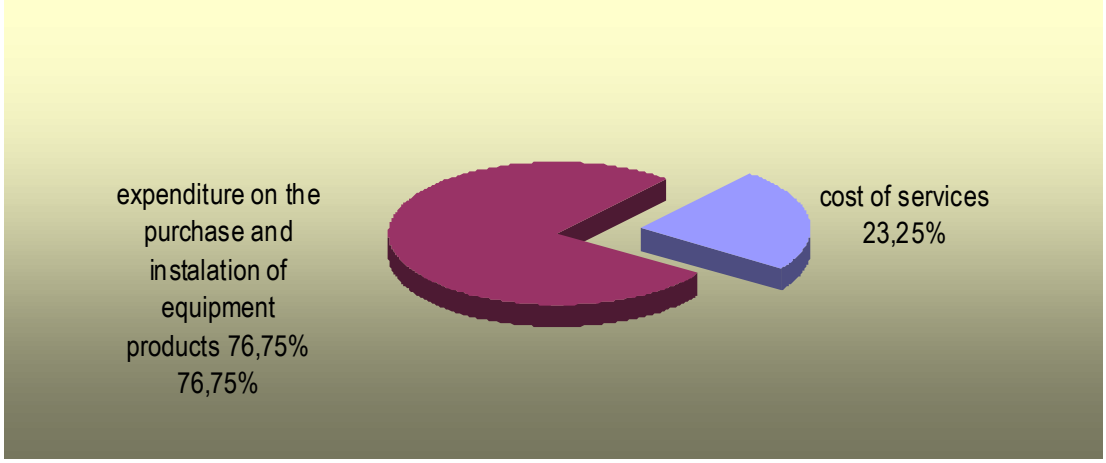

Figure 3. General structure of expenditure on the environment by the surveyed households.

Most of the expenditure on purchase and installation of the equipment and products used directly for the purpose of environmental protection, namely 72,2 per cent was used for atmosphere protection. A detailed structure of the expenditure by environmental components is presented in Fig. 4.

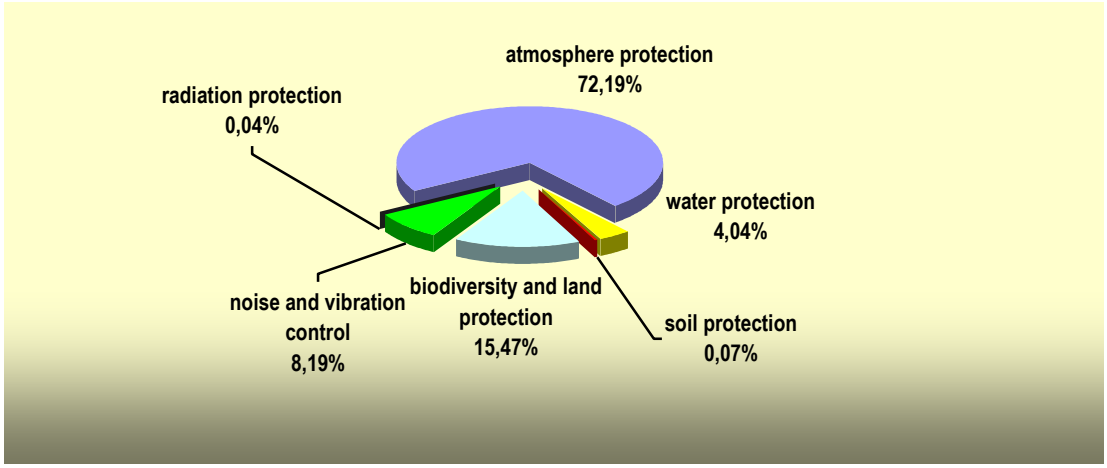

Figure 4. The structure of the expenditure for purchase and installation of the equipment and products used directly for the purpose of environmental protection in the surveyed households.

The structure of the expenditure of the surveyed households for individual areas of environmental protection was presented in Table 1 below, whereas the average expenditure on the en-

vironment by an individual household covered by the survey (if applicable) is presented in Table 2.

Table 1. The structure of the expenditure for purchase and installation of the equipment and products directly for the purpose of environmental protection in individual areas [%].

Type of expenditure	Structure	
Atmosphere protection		
Installation of heat consumption meters and thermo requlators	1.97	100.0
Modernisation of central heating systems for the entire building and for an single apartment	20.76	
Installation of equipment for the treatment of fuel gases	0.84	
Purchase and installation of energy-saving windows	39.97	
Additional insulation for the building protecting against cold	28.11	
Purchase of catalytic converters for private cars which were not equipped with the device when purchased	0.77	
Purchase of gas installation for private cars	2.80	
Purchase and repair of exhaust pipes in motor vehicles	1.52	
Examination of the composition of motor vehicles exhausts and feed system regulation	3.27	
Water protection		
Connection to the public sewer	96.62	100.0
Construction of individual wastewater treatment plants	3.38	
Soil protection		
Domestic wastes disposal equipment	100.0	100.0
Biodiversity and landscape protection		
Tree and bush planting	27.71	100.0
House facade repairs	72.29	
Noise and vibrations control		
Purchase and installation of noise reducing windows	62.03	100.0
Fences and live fences, noise and vibrations reducing screens	37.97	
Radiation protection		
Installation of terrestrial and electromagnetic radiation protection shields	100.'	100.0

It should be noted, however, that the rates of charges for the services related with the environmental protection depended on the type of a building. For the purpose of the survey two main groups of dwelling were defined, namely a multi-family apartment house (561 households) and a single-family house (433 households). Moreover, in the case of 18 households the delivered information was the total cost of environmental protection products and services for their house (a single-family house), garage, summer house and bungalow. The average services charges for different types of buildings (if applicable) are presented in Fig. 5.

Many owners of single-family houses, mainly in the country, most probably used to discharge their sewage directly on the farmland and the most popular way of wastes disposal was burning thereof or taking it to an unauthorised dumping ground to avoid the costs.

On average it was a single-family household that incurred the highest expenditure on the environment (including the costs of services) in the first three quarters of the year 2009 (1,430 PLN – 1 PLN = 0,25 EUR). The inhabitants of a multi-family apartment house paid on average 565 PLN. The money was used mainly for (apart from the services charges):

- The purchase and installation of energy-saving windows and the house facade repairs in a multi-family apartment house;
- and additional insulation for the building protecting against cold, the purchase and installation of energy-saving windows and the house facade repairs - in a single-family house.

Table 2 Average expenditure on the environment of individual households during the first three quarters of 2009 (in PLN).

Type of expenditure	Number of households paying such costs	Amount	
		On average	Group average
Services related with environmental protection			
Collection, discharge and treatment of sewage	824	181	110
Wastes (garbage, sewage sludge) disposal	823	89	
Purchase and installation of the equipment and products used directly for the purpose of environmental protection			
Atmosphere protection			
Installation of heat consumption meters and thermoregula-	43	242	1,761
Modernisation of central heating systems for the entire building and for a single apartment	41	2,67	
Installation of equipment for the treatment of flue gases	7	631	
Purchase and installation of energy-saving windows	66	3.19	
Additional insulation for the building protecting against cold	39	3,80	
Purchase of catalytic converters for private cars which were not equipped with the device when purchased	2	2,02	
Purchase of gas installation for private cars	10	1,47	
Purchase and repair of exhaust pipes in motor vehicles	42	192	
Examination of the composition of motor vehicles exhausts and feed system regulation	50	345	
Water protection			
Connection to the public sewer	17	1,68	1,644
Construction of individual wastewater treatment plants	1	1,00	
Soil protection			
Domestic wastes disposal equipment	2	265	265
Biodiversity and landscape protection			
Tree and bush planting	140	224	1,232
House facade repairs	25	6,87	
Noise and vibrations control			
Purchase and installation of noise reducing windows	16	2,32	2,068
Fences and live fences, noise and vibrations reducinq	13	1,75	
Radiation protection			
Installation of terrestrial and electromagnetic radiation protection shields	2	150	150

The amount of charges for the services related with environmental protection were independent from the social and economic status of the members of the household. However, the highest, on average, expenditure on the purchase and installation of the equipment and products

used directly for the purpose of environmental protection was recorded in the households of self-employed people (to the exception of farmers), namely 1,281 PLN, whereas the lowest i.e. 123 PLN in the households supported from nonprofit sources. The average expenditure on the environment (services charges excluded) by source of income is presented in Fig. 6.

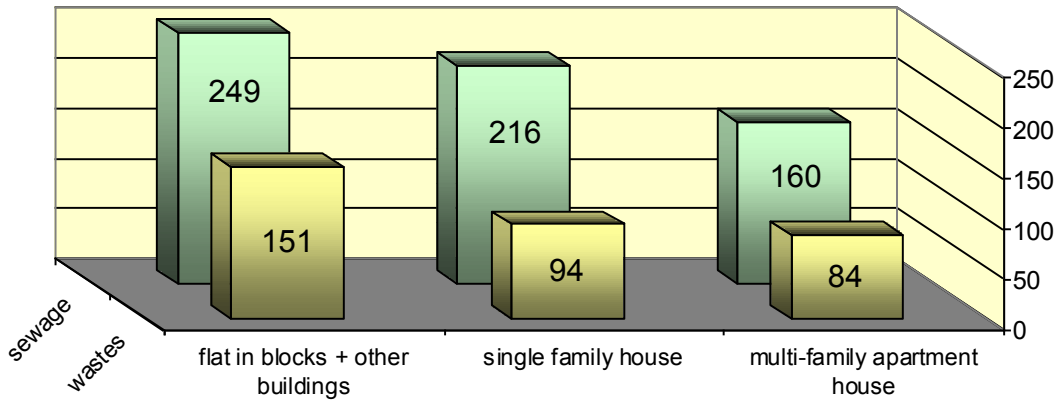

Figure 5. Cost of environmental protection services for different types of building (PLN).

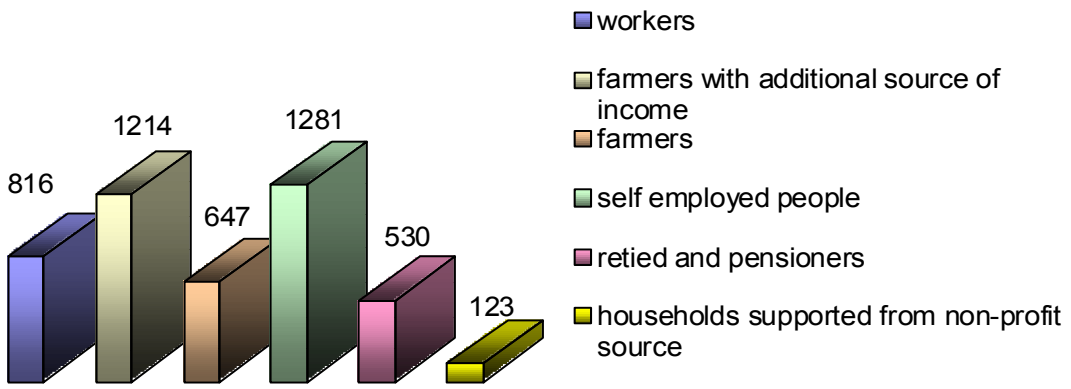

Figure 6. The amount of expenditure on the purchase and installation of the equipment and products used directly for the purpose of environmental protection by source of income in all surveyed households (PLN).

4. CONCLUSIONS

Calculations of expenditure on the environment by households allowed for comparing the amounts of expenditure on the environment in each sector of Polish economy. Most of the money in the household sector was used for the atmosphere protection and biodiversity and landscape protection (72,2 and 15,5 per cent respectively), whereas the smallest expenditure in the households sector was recorded for water and soil protection (4,04 and 0,07 per-cent). In the total expenditure on the water protection as much as 96,6 per-cent was used on the connection to the public sewer and in the expenditure on the atmosphere protection as much as 40 per cent of expenditure was used on the purchase and installation of energy-saving windows. The structure of expenditure on the environment in households sector was similar to economic sector.

And also according to the reports of Eurostat, that wastewater treatment expenditure is in second place mostly, while in Poland, it is the main beneficiary of environmental expenditure of specialised producers.

The share of investments in total investments and current expenditures, for EFTA countries and Turkey, can be defined to the EU-25 average as more or less close to.

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Effects of wall's masonry-density on decrement factor & time lag

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ABSTRACT: In this study the effect of wall's masonry-density on decrement factor and time lag is thoroughly investigated. The non-linear dependencies between the volumetric heat capacity and the thermal conductivity of a representative masonry material are taken into account in order to extort valuable results that regard the thermal behaviour of building envelopes. For all examined wall configurations, insulation is assumed to be placed as one layer on the outer surface, the inner surface or in the mid-centre of the wall; thus, three typical wall configurations are assessed. The work is carried out by using a dynamic thermal-network model and the analysis is based on the well-known equivalences between the thermal and electrical laws. As it is shown, the balance between the thermal resistance and the thermal capacity of masonry has a very profound effect on the thermal response of wall formations. Consequently, the dynamic thermal characteristics of the examined wall installations show significant variations. Moreover, the location of the insulation is critical towards saving energy and reducing the environmental impact.

1 INTRODUCTION

The building envelope is a critical component of any facility, while it both protects the residents and plays a major role in regulating the indoor environment. The appropriate utilization of the thermal characteristics of vertical surfaces that comprise building envelopes is decisive in order to produce an adequate indoor environment and reduce the energy requirements for heating, cooling and ventilation. The decrease of energy demands is vital in an attempt to prevent the waste of valuable energy resources and produce a sustainable built environment.

Typically, building façade structures are formed and retained by individual material units laid in and bound together by mortar. In the Southern European region the most typical type of unit material that forms wall masonry surfaces is the ceramic brick. The thermal capacity C of a brick layer, most of which have hollow cores, is generally sufficient. Their incorporation improves the volumetric heat capacity (thermal mass) of the entire building structure. In addition, the indoor thermal comfort conditions, during the cooling or heating period, are enhanced due to a steadier indoor environment that is produced. On the other hand, the thermal resistance R of a brick layers is low causing extensive heat flows and thermal losses for the climate in question, when temperature differences between the indoor and outdoor environment are high. The thermal resistance of masonry walls can be increased by thickening the wall; however, insulating a mass wall in a composite construction is the most rational solution. Hence, due to the low values of thermal conductivity k the insulation materials can reduce thermal exchanges and avoid degradation of indoor thermal comfort conditions.

As it is clear, the efficiency and the energy requirements of a building system depend on how well materials hold the heat, how fast heat propagates through materials and the fluctuation of

the outdoor conditions. This last issue is decisive and depends on the local spatial circumstances, in addition to the time instances through the year period. It is important to point out, that the effect of the thermal resistance is always critical, while the influence of the thermal mass is mainly significant when the outdoor temperatures cycle above and below indoor temperatures, within a 24-hour period. Therefore, high mass walls are most beneficial in moderate climates that have high daily temperature swings and nearly all areas with significant cooling loads can be promoted from the thermal mass of wall systems. This is valid, for a large part of a year, for buildings located in the Mediterranean area. Consequently, for wall configurations with equivalent thermal resistance and variable thermal mass the heating and cooling energy requirements vary considerably; high-mass wall systems cause less heat exchanges compared to low-mass wall systems (passive building design). Then again, the thermal response for opaque surfaces with the same thermal resistance and thermal mass can differ extensively due to the position and distribution of the employed materials (allocation of masonry and insulation). The above issues are analysed in detail at several studies (Asan 2000), (Kontoleon et al. 2007).

In the present study the effect of the masonry-density, of several multi-layer wall configurations, on decrement factor and time lag is analysed. The non-linear dependencies among the volumetric heat capacity and the thermal conductivity of a typical masonry material are considered in order to extract helpful results that refer to the thermal performance and response of building wall configurations. According to these dependencies, the variation – decrease/increase of the coefficient of thermal conductivity and density, of masonry, increases/decreases with a concrete rate the thermal resistance of the material, while, in a parallel manner decreases/increases with a smaller rate the thermal capacity of the material. The insulation layer is assumed to be placed as one layer on the outer surface, the inner surface or in the mid-centre of the wall; as a consequence, three typical wall configurations are examined. The investigation is accomplished by employing a dynamic thermal-network model and the analysis is supported by the familiar equivalences among the thermal and electrical circuits. The model simulates heat transfer by conduction through the wall and considers convection boundary conditions under specific forcing functions at the wall outer and inner surfaces. As it is revealed, the equilibrium between the thermal resistance and the thermal capacity of masonry modifies essentially the thermal response of wall installations (dynamic thermal characteristics). Additionally, the position of the insulation is decisive towards reducing the energy requirements of buildings and preventing the irrational waste of natural environmental resources.

2 DEFINITION OF DECREMENT FACTOR & TIME LAG

The temperature profiles at the outdoor environment of a building change periodically during a day period. These profiles are derived by the sol-air concept that specifies the exterior diurnal forcing function. During this transient process, a heat wave flows from outside to inside through a wall and the temperature profiles vary. The spread of the heat wave depends on the temperature difference between the outdoor environment T_{sa} and the internal space T_{in}, as well as on several parameters that are specified in section 3 (geometrical properties, thermo-physical properties and allocation of materials) (Tsilingiris 2006).

The decreasing ratio of the heat wave temperature amplitudes during this transient process is defined as decrement factor, f. Furthermore, the time it takes for a heat wave, with period P (24-hour cyclic period) to propagate from side to side of a wall is defined as time lag or phase lag, φ. Consequently, the dynamic thermal characteristics of wall surfaces are expressed by the following equations (Asan et al. 1998):

$$f = \frac{T_{i,\max} - T_{i,\min}}{T_{e,\max} - T_{e,\min}} \tag{1}$$

$$\phi = t_{Ti,\max} - t_{Te,\max} \tag{2}$$

where $t_{Ti,max}$ and $t_{Te,max}$ signify the time points when inside and outside temperatures are at their peaks, respectively. Moreover, $T_{i,max}$, $T_{i,min}$, $T_{e,max}$, and $T_{e,min}$ denote the maximum and minimum temperatures on both wall surfaces.

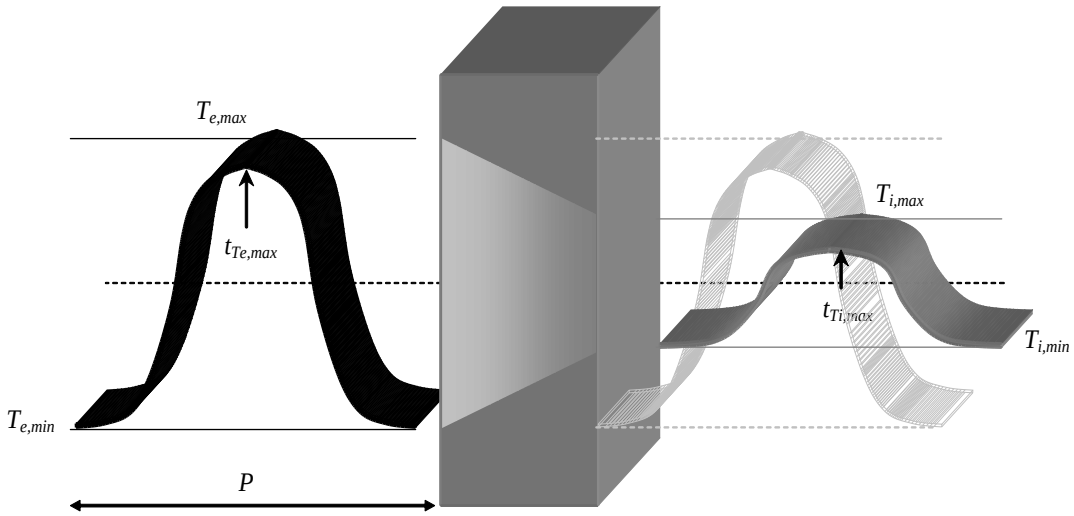

Figure 1. Heat wave propagation through a wall surface, during a day period.

The above thermal inertia parameters are illustrated in Figure 1, for the case of a sinusoidal heat wave (periodic forcing function) that propagates from the exterior to the interior of a single layer wall surface. The evaluation of time lag and decrement factor, mainly for buildings with stable climate and with wide outdoor temperature swings, is important in order to diminish the energy demands and provide comfort indoor conditions. It is essential to point out, that masonry materials are characterized by their capability to store energy in their thermal mass and cause a shift (delay) of the temperature profiles from outside to inside. This is caused by the high thermal conductivity and volumetric heat capacity of masonry materials. On the other hand, insulation materials, due to their low thermal conductivity and volumetric heat capacity, respond like heat barriers decreasing significantly the temperature fluctuations in the direction of the heat flow path.

3 DYNAMIC THERMAL BEHAVIOUR OF AN OPAQUE SURFACE

The assessment of the dynamic behaviour of an opaque surface has an important bearing when considering the design of building envelopes. The efficiency of an envelope, in order to reduce energy demands and improve the indoor environment is primarily related with the appropriate outline of wall surfaces that cover a large proportion of the entire area of the building shell. Wall surfaces are usually multi-layer configurations comprising several building materials with detailed geometrical and thermo-physical properties. These properties are the surface area A, the layer thickness d, the thermal conductivity k, the density ρ and the specific heat c_p; the values of the above properties are important in order to design well the building envelope and, eventually, improve its thermal response. Then again, the position and distribution of the materials (masonry and insulation) is an integral part of a proper building design.

For the determination of the dynamic behaviour of a wall surface, it is necessary to take into account its thermal capacity (heat storage within the thermal mass), in addition to its thermal resistance. The thermal capacity of a wall is specified by the volumetric heat capacity $\rho \cdot c_p$ (product of specific heat with density), while the thermal resistance of a wall is delineated by the thermal conductivity k. For a homogeneous material of thickness d the heat flow rate in the time domain and in the x direction of decreasing temperatures is controlled by the *Fourier equation* (Kontoleon et al. 2008):

$$k \cdot \frac{\partial^2 T}{\partial x^2} = \rho \cdot c_p \cdot \frac{\partial T}{\partial t} \tag{3}$$

In order to solve this equation two boundary conditions and an initial condition are required.

- The boundary conditions on both sides of the wall, based on *Newton's law*, are:

$$\frac{\partial T}{\partial x} = \frac{h_e}{k} \cdot (T_{sa} - T_{x=0}) \tag{4}$$

$$\frac{\partial T}{\partial x} = \frac{h_i}{k} \cdot (T_{x=d} - T_{in}) \tag{5}$$

where h_e and h_i are the heat transfer coefficients, due to combined convection and radiation, in the exterior and interior surfaces of the wall. Additionally, temperatures $T_{x=0}$ and $T_{x=d}$ correspond to the outer and inner surfaces (wall boundaries), while T_{sa} is the sol-air temperature and T_{in} is the forced indoor air temperature.

- The steady-state solution at $t = 0$ is considered as the obliged initial condition. Moreover, a five-day period is used for simulations in order to eliminate the effect of initial conditions.

4 TRANSIENT THERMAL ANALYSIS & CIRCUIT MODELLING

In this paper, a lumped thermal-network model is introduced in order to simulate the heat transfer mechanisms and the process of heat storage through the multi-layer wall configuration. The circuit is derived by taking into account the analogies between the thermal and electrical laws; accordingly, node voltages and branch currents correspond to temperatures and heat flows, respectively. The modelling allows the interpretation and arrangement of the related equations on the basis of a "*physical circuit analog*" that combines the topological and algebraic data of the problem. The outline of the thermal-network model employed in this study is shown in Figure 2.

As it is seen, the modelling of a wall configuration employs a one-dimensional lumped circuit that consists of a finite number of distributed thermal resistances and capacitances. Each section layer j comprises two thermal resistances R_j and a single lumped heat capacitance C_j at the mid-node. The model contains all the essential features that characterize the discrete problem. The number of sections (n) in the x-axes is large enough to ensure a tolerable precision of the assessments. Additionally, the one-dimensional simplification (transverse heat-flows negligible) is applied, as it is proved to be a realistic approximation. The values of the elements in the RC-sections are determined on the basis of the thermo-physical properties and geometry of the materials involved (Lombard et al. 1999):

$$R_j = \frac{d_j}{2 \cdot k_j \cdot A} \tag{6}$$

$$C_j = \rho_j \cdot c_{p,j} \cdot d_j \cdot A \tag{7}$$

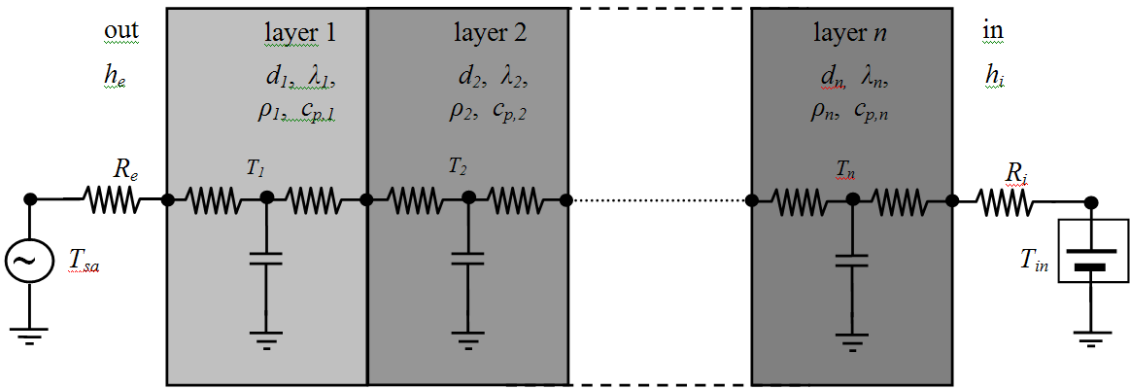

Figure 2. Thermal-network model of a multi-layer wall configuration (n layers).

The *RC*-sections of the wall layers are linked to the exterior and the interior environment (explicit boundary conditions) with the heat transfer resistances R_e and R_i.

$$R_e = \frac{1}{h_e \cdot A} \tag{8}$$

$$R_i = \frac{1}{h_i \cdot A} \tag{9}$$

These heat transfer resistances refer to combined effect of convection and radiation. The heat transfer coefficient initial values, which were considered for the outdoor and indoor environmental conditions of the wall, are respectively h_e = 16.67 W/m^2·K and h_i = 8.33 W/m^2·K.

At last, the forcing functions acting on both wall boundaries, T_{sa} outside and T_{in} inside, are modelled with a waveform voltage source (periodic boundary conditions – sinusoidal oscillation) and an even voltage source (normal boundary conditions – constant value), correspondingly. The sol-air temperature values are assumed to vary from 0 ^{o}C to 1 ^{o}C, while the indoor temperature values are unvarying at 0.5 ^{o}C.

5 RESULTS & DISCUSSION

In this section the effect of masonry-density on the characteristic magnitudes of the dynamic thermal characteristics f and φ of wall configurations is thoroughly examined. The studied characteristic arrangements of complex wall formation cross sections, have a total thickness d = 27 cm and are composed from: (a) masonry – perforated bricks (*M*) as one layer of thickness d_M = 18 cm or as two layers of equal thickness d_M = 9 cm, with variable thermo-physical properties, (b) insulation – expanded polystyrene (*I*) as one layer of thickness d_I = 5 cm, with k = 0.03 W/m·K, ρ = 50 kg/m^3 and c_p = 1000 J/kg·K and (c) wall coating (*C*) on both exterior and interior boundaries of the wall with a thickness d_C = 2 cm, and having k = 1 W/m·K, ρ = 2000 kg/m^3 and c_p = 1000 J/kg·K. The insulation layer is assumed to be placed as one layer on the outer surface, the inner surface or in the mid-centre of the wall; hence, three typical wall configurations are examined that are denoted as *IM*, *MI* and *MIM*. Then again, the non-linear dependencies among the volumetric heat capacity and the thermal conductivity of masonry material are considered in order to extract useful results that concern the dynamic thermal behaviour of wall installations.

The above correlations for the masonry are illustrated in Figure 3. According to these graphical representations, the deviation – decrease/increase of the coefficient of thermal conductivity and density, of masonry, increases/decreases with a solid rate the total thermal resistance R of the material, while, in a parallel manner decreases/increases with a slighter rate the total thermal capacity C of the material.

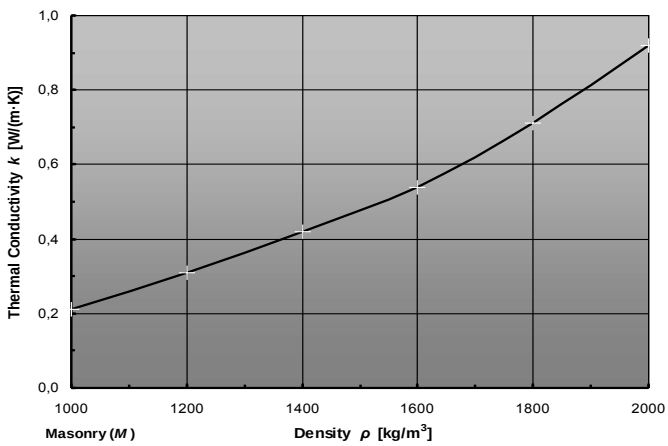

Figure 3. Nomographs of the change of the coefficient of thermal conductivity k as a function of density ρ, for the masonry material of the wall formations.

5.1 *Decrement factor values by employing the thermal-network model*

The values of the coefficient of decrement factor f as a function of the density ρ of the perforated bricks and for cross sectional configurations of wall formations having the insulation material concentrated in one layer, are given in Figure 4. More particularly, the assemblies which are investigated are *IM*, *MI* and *MIM*.

As for configuration *IM* (placement of the insulation layer in the exterior wall surface), an increase in masonry density ρ results to a parallel increase of the values of the coefficient of decrement factor f, therefore its degradation. It is critical to point out that low decrement factor values are essential in order to decline the indoor temperature variations and produce a stable environment. Thus, while for a density ρ = 1000 kg/m^3 of the perforated bricks, the value of decrement factor is f = 0.0108 (minimum value), for ρ = 2000 kg/m^3 the value is f = 0.0167 (maximum value). The same thermal response as above applies for configurations *MI* and *MIM*, and the numerical values of the decrement factor are respectively f = 0.0119, f = 0.0181 for a density ρ = 1000kg/m^3 (minimum values) and f = 0.0217, f = 0.0252 for ρ = 2000 kg/m^3 (maximum values).

From the above results and their graphical representations it is obvious that there is a declination of the values of the decrement factor f with the increase of density ρ, between the configurations *IM* and *MI*. However, the results for the decrement factor f for the configurations *MI* and *MIM* converge. At last, for the configurations *IM* and *MIM*, the values of the decrement factor f neither converge nor diverge between them. In all the cases, the best values of the coefficient of decrement factor f are obtained for the configurations having the insulation material placed in the external surface (configuration *IM*).After that follow the configurations *MI* and *MIM*. Thus, the classification of the results concerning the decrement factor is $f_{MIM} > f_{MI} > f_{IM}$.

In addition, as it can be seen in the curves, the dynamic thermal behaviour of all wall configurations is not linear. Therefore, for the assumed wall formations, the participation of the heavy masonry material as well as of the insulation and coating materials differentiates to a great degree their thermal response. More specifically, due to the change of the thermo-physical properties of masonry (increase/decrease), the relative change (descent/ascent) of the total thermal capacitance C of the wall formation is significant compared to the total thermal resistance R of the wall formation.

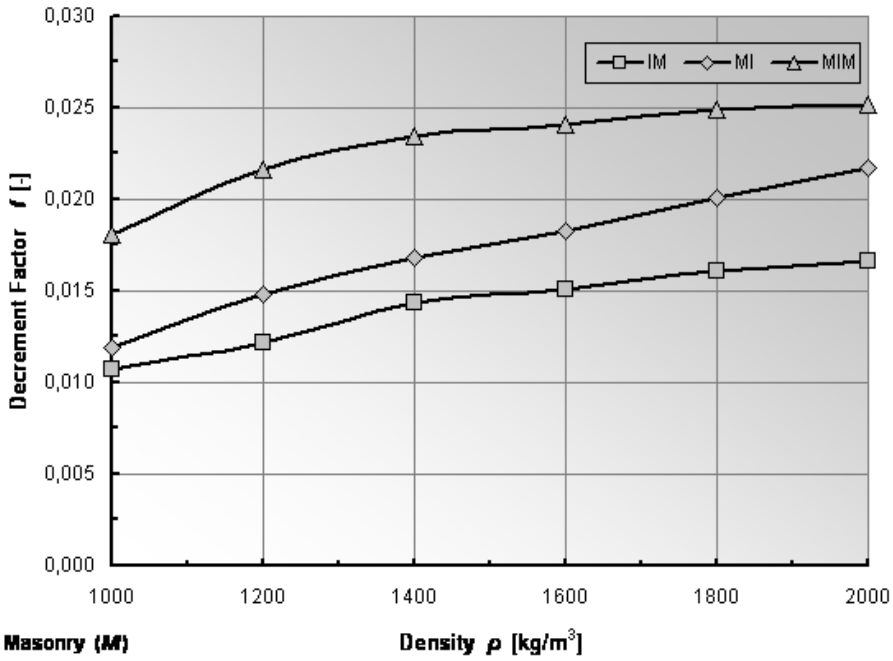

Figure 4. Variation of the decrement factor f values as a function of the masonry density ρ.

5.2 *Time lag values by employing the thermal-network model*

The values of the coefficient of time lag φ as a function of the density ρ of the perforated bricks and for cross sectional configurations of wall formations having the insulation material concentrated in one layer, are illustrated in Figure 5. Hence, the installations which are studied are *IM*, *MI* and *MIM*.

For the configuration *IM* (position of insulation layer in the external surface of the wall), an increase of masonry density ρ leads to a decrease of the values of time lag φ, that is its degradation. For this reason, while for a density ρ = 1000 kg/m^3 of perforated bricks, the value of time lag is φ = 9.27 h (maximum value), for ρ = 2000 kg/m^3 the value is φ = 7.43 h (minimum value). As for the configurations *MI* and *MIM*, there is an analogy with the above in their thermal behaviour and the numerical values of time lag are respectively φ = 8.94 h, φ = 9.14 h for a density ρ = 1000 kg/m^3 (highest values) and φ = 6.97 h, φ =8 .15 h for ρ = 2000 kg/m^3 (lowest values).

As it is deduced, from the graphs, for an increase in the density ρ, the values of time lag φ between the configurations *IM* and *MI* neither converge not diverge between them. On the contrary, it is observed that for the configurations *MI* and *MIM* there is a divergence between the results of time lag φ. As for the configurations *IM* and *MIM*, the time lag values φ, initially converge between them, leading to a coincidence of their values for a numerical value of density ρ = 1200 kg/m^3. After that, and for density values ρ > 1200 kg/m^3, time lag values φ diverge between them. As shown from the diagrams, the classification of the results, for the time lag values φ of the configurations which have been analysed, is not the same within the value width in which the density ρ changes. Thus, for ρ < 1200 kg/m^3 it holds $\varphi_{IM} > \varphi_{MIM} > \varphi_{MI}$, while for ρ > 1200 kg/m^3 it is φMIM>φIM>φMI. Because of this, there is an interchange in the classification of results between the configurations *IM* and *MIM*.

Furthermore, as it is clear by the curves, the dynamic thermal behaviour of all wall configurations is not linear. Thus, for the examined wall formations, the involvement of the heavy masonry material as well as of the insulation and coating materials modifies to a large scale their thermal response. As a result, due to the shift of the thermo-physical properties of masonry (increase/decrease), the comparative alteration (descent/ascent) of the total thermal capacitance *C* of the wall formation is important compared to the total thermal resistance *R* of the wall formation.

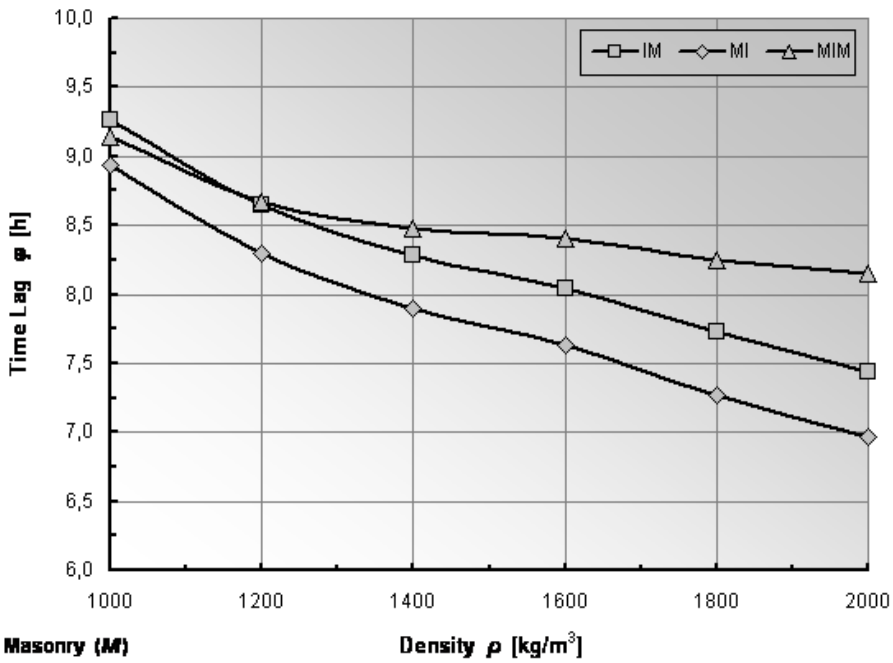

Figure 5. Variation of the time lag φ values as a function of the masonry density ρ.

6 CONCLUSIONS

In the present work the effect of wall's masonry density on decrement factor and time lag is investigated for a number of insulated wall configurations. The assessment of the dynamic thermal characteristics for typical multi-layer wall configurations shows an immense importance for stable climates with wide outdoor temperature variations. A thermal-network model is developed, which is based on the nodal method, and transient analyses are carried out for the determination of the above thermal inertia parameters.

As it is shown, the analogies involving the thermal resistance and the thermal capacity of a masonry material modify fundamentally the thermal response of wall installations. Hence, it has been exposed that the masonry density has a very profound effect on the decrement factor and time lag outcomes, during this transient heat process. In addition, the position of the insulation is critical towards dropping the energy requirements of buildings and preventing the irrational waste of natural environmental resources.

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Examination of Shading-Photovoltaic Building Components from the Viewpoint of Sustainability

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ABSTRACT: Sustainability of buildings has important effects on global warming while efficient use of energy is a way to achieve sustainability of buildings. Photovoltaic components that are used on buildings have important effects on energy efficiency, hence sustainability of buildings. When they are used as shading devices, they also help create comfort conditions in the building while decreasing the energy demand. Therefore impact of shading-photovoltaic components, which are used on buildings, on sustainability is examined in this study from the viewpoint of energy efficiency. This is done by examining the energy production and solar control of shading-photovoltaic elements over a window of a building in Izmir. First, shading analysis is done and design of the system is optimized. Then, electricity production and necessary tilt angle of the components for the optimum output are calculated by using the simulation program PVSYST. After this, results are discussed from the viewpoint of sustainability.

1 INTRODUCTION

Sustainability of buildings has important effects on the global warming and efficient use of energy is a way to achieve the sustainability of buildings. About half of the energy used in a country is used on buildings. Therefore, decreasing the energy use on buildings will have a significant effect on sustainability of the buildings. Photovoltaic components which are used on buildings have important effects on energy efficiency, hence sustainability of buildings, due to the fact that they decrease energy use in a building by their electricity production directly from solar energy. When these photovoltaic components are used as shading devices over windows, they also help create comfort conditions in the building, and this decreases the energy demand in the building due to the fact that people do not need to use air conditioners or other devices in order to achieve comfort conditions. Therefore impact of photovoltaic components which are used on buildings as shading devices on the sustainability is examined in this study from the viewpoint of energy efficiency. This is done by examining the energy production and solar control effect of shading-photovoltaic components over a window of a building in Izmir. First of all shading analyses are done in order to achieve a more comfortable interior and as a result the design of the shading-photovoltaic (PV) components is optimized. After this step, electricity production and the necessary tilt angle of these photovoltaic components for the optimum energy production are calculated by using the simulation program PVSYST. After this, the results are discussed from the viewpoint of sustainability. In the end, the sustainability degree of photovoltaic components used on buildings as shading devices is achieved on a specific case-study.

2 SYSTEM ESTABLISHMENT AND THE METHODS USED

2.1 *Shading-Photovoltaic Components*

The shading elements can be used as composed of photovoltaic (PV) elements. This is one of the most efficient ways of using PV components in architecture due to the fact that by this way of using, they would produce energy (electricity) with the solar energy that they prevent getting into the building and heating up the interior. The only point that should be considered is that they should not prevent the necessary solar radiation getting into the window to heat up the interior in winter. For this purpose, shading elements can be constructed as moving elements, not fixed ones.

In order to reach the highest efficiency with the shading-PV components, PV cells, therefore PV modules should have a certain orientation (azimuth) and tilt angle. The orientation can be optimized with the use of shading analysis and the tilt angle can be optimized with the use of a simulation program. In this study, the orientation is fixed due to the mounting on an existing building, and the tilt angle of the PV components are determined with the use of the simulation program PVSYST in order to maximize the energy production.

2.2 *Shading analysis*

As Olgyay & Olgyay stated in their book (1973), "the problem of controlling his environment and creating conditions favorable to his aims and activities is as old as man himself. Through the ages men have sought, in the building of shelter, to fulfill two basic human needs - protection from the elements and provision of an atmosphere favorable to spiritual endeavor. (p.v.)" Therefore it is important to achieve comfort conditions in building interiors in order to fulfill a basic human need. If it is not created by the architect, the residents create it themselves, using generally fossil-fuel energy resources like air-conditioners in the *overheated period* and different kinds of heating systems in the *underheated period*. This would make the *Carbon Footprint* of the building get higher due to the fossil energy use. But this would be lowered by the use of solar control.

For this reason, the orientation of the building and especially the window in question is important. The optimum orientation of a building for creating comfort conditions in the interior can be determined with the use of shading analysis. They are done with the use of sun-path diagram and the mask together. The sun-path diagram is the path of the sun throughout a year, and it is different for every latitude. There are circular lines which represent the path of the sun during a day; but the sun travels along each of these lines on two days of a year. These days are stated on the diagram. The climatic data should be integrated onto the sun-path diagram before the analysis. There are three different areas in this data when applied onto the sun-path diagram; first one is dark-hatched, second is light-hatched and the third is not hatched. The dark-hatched area represents the days of the year on which shading is necessary on both days of the year. The light-hatched area represents the days of the year on which shading is necessary on one day while it is not necessary on the other day of the year. The area without hatch represents the days of the year on which no shading is required, solar radiation is required on both days to heat up the interior. The dark-hatched area and one-day of the light-hatched area are called as "*overheated period*". The area with no-hatch and the other day of the light-hatched area are called as "*underheated period*". The analysis also shows the exact dates at which shading is necessary or not, and solar radiation is required at which hours of the day. Therefore different possibilities of shading are possible and it is seen with this analysis.

When shading analysis is done, the optimum orientation is found to be 13° East from South (is shortly called as "13°EfS") (Altin, 2005, p.108). But the best orientation for the highest efficiency of the PV modules is facing directly towards South. Therefore an optimization is necessary for finding the optimum tilt angle for the given orientation of the case study.

2.3 *Simulation program PVSYST*

There are several simulation programs throughout the world for the simulation of PV systems. One of the most accepted of these is PVSYST. Therefore PVSYST is used in this study for calculating the energy that would be produced. There are three modules in the program which are pre-

sizing, simulation and tools. The pre-sizing module of the PVSYST program is used here to get the though results of the tilt angle of the modules and the total annual energy yield of the system.

The optimum tilt angle of the shading-PV components are calculated by using PVSYST simulation program because the orientation of the PV components are fixed and different from South orientation, it is 23°WfS. In addition, the system design and the total annual energy yield calculation was done with the use of PVSYST. The program gives approximately correct results when they are compared with the examples that are realized.

3 SHADING-PHOTOVOLTAIC COMPONENTS ON A CASE STUDY

The case study: A room (room number: B29d, in the basement floor) in Dokuz Eylul University Faculty of Architecture building has been selected as a case study here. The reason why this room has been selected is that it has a poor level of comfort conditions due to its orientation. It is overheated by the solar gain most of the time in a year and it uses air-conditioners for about 6 months in a year. Since this is a huge amount of energy, it needs shading devices to maintain the comfort conditions and lower the energy demand. By this way, both the quality of life inside will get better and the operational costs will get lower, thus ending in lowering the carbon footprint. And this will help having sustainability.

First of all, the room's window which is facing northwest is analyzed from the viewpoint of comfort conditions. After this, these shading devices are simulated with the use of PVSYST simulation program in order to calculate how much electricity these shading devices would produce in a year.

3.1 *The shading analysis*

The shading analysis is done for the shading-PV system. As a result, the shading-PV system is designed. The shading analysis for the existing window without shading is as the following:

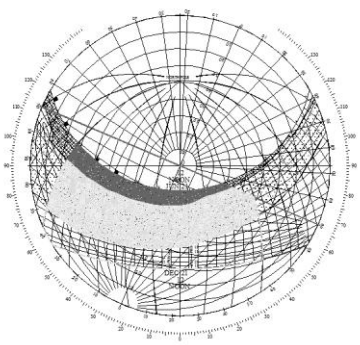

Figure 1. The shading analysis for the existing window without shading elements.

The percentages of the shading degrees in the tables are the sum of all the area that are positively shaded or not shaded. Positive shading represents the area in which shading is done where necessary and no shading is done where not necessary. Likewise, negative shading represents the area in which shading is done where not necessary and there was no shading where it is necessary.

While preparing the analysis, only the shading-element angles between 30° and 70° have been held. This is due to the fact that angles of higher than 70° do not protect the window while the angles of lower than 30° are difficult to apply. Only the angle 0° is good, but it is the angle of the blinds and/or curtains and they cannot be fixed, they must be changed all the time. But this is not the subject of this study. Therefore, only the angles of between 30° - 70° are analyzed in this study.

Another point is that only the office hours of between 9:00 and 17:00 are taken into consideration due to the fact that the case study room is being used only between these hours of weekdays.

The existing situation of the window is given in Table 1 in order to show the situation only. In the following tables (Tables 2-4), these values will be given on top just to remember them and for comparison.

Table 1. Shading values of the existing window without shading elements.

	Positive shading % (for both of the days)	Negative shading % (for both of the days)
Existing window (without any shading system)	0.59	0.41

Table 2. Shading values of the window with shading-PV elements only over the window.

	Positive shading % (for both of the days)	Negative shading % (for both of the days)
Existing window (without any shading system)	0.59	0.41
30°	0.59	0.41
40°	0.63	0.37
50°	0.66	0.34
60°	0.66	0.34
70°	0.62	0.38

Table 3. Shading values of the window with continuous shading-PV elements.

	Positive shading % (for both of the days)	Negative shading % (for both of the days)
Existing window (without any shading system)	0.59	0.41
30°	0.54	0.46
40°	0.63	0.37
50°	0.69	0.31
60°	0.69	0.31
70°	0.62	0.38

Table 4. Shading values of the window with both shading walls near the window having 35° angle with the facade and the shading-PV elements over the window.

	Positive shading % (for both of the days)	Negative shading % (for both of the days)
Existing window (without any shading system)	0.59	0.41
30°	0.54	0.46
40°	0.62	0.38
50°	0.66	0.34
60°	0.66	0.34
70°	0.62	0.38

Shading values of the window with shading-PV elements only over the window: In this solution, shading elements are placed only over the window. In the end, the best shading results are obtained at 50° and 60° angle of shading elements with 66% positive and 34% negative shading results.

Shading values of the window with continuous shading-PV elements: In this solution, shading elements are placed continuously all over the uppermost part of window level. In the end, the best shading results are obtained at 50° and 60° angle of shading elements with 69% positive and 31% negative shading results.

Shading values of the window with both shading walls near the window having 35° angle with the facade and the shading-PV elements over the window: In this solution, shading elements are placed both over the window and also shading walls are placed near both ends of the window as an addition. In the end, the best shading results are obtained at 50° and 60° angle of

shading elements with 66% positive and 34% negative shading results. All these three solutions are shown in the Figures 2, 3 and 4, from below.

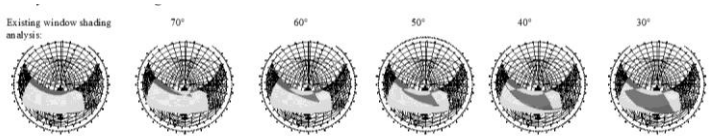

Figure 2. The shading analysis for the window with shading-PV elements only over the window.

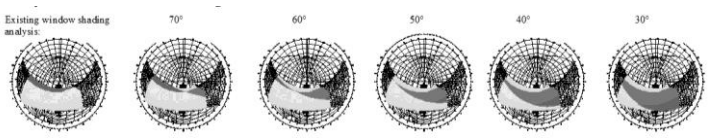

Figure 3. The shading analysis for the window with continuous shading-PV elements.

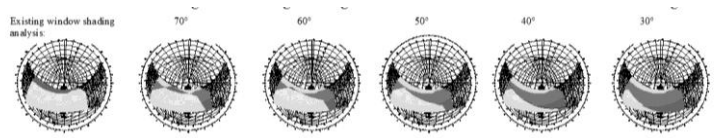

Figure 4. The shading analysis for the window with both shading walls near the window having 35° angle with the facade and the shading-PV elements over the window.

As a result, the angle of the shading-PV panels should be set to 40° or 50° in order to get the best shading results. Therefore the angle of the shading-PV components is taken as 50° in order to let the mounting be easier thus more economic. By this design, most of the area in the over-heated period (mostly summer time) is shaded while most of the area in the underheated period (mostly wintertime) is not shaded thus getting the necessary solar radiation. After this decision, the simulation should be done in order to calculate the amount of energy that these shading-PV elements would produce annually.

3.2 *Use of Simulation Program PVSYST*

In the shading-PV system, it is designed to use 6 m^2 of PV panels. These panels should have 30° tilt angle since this is the optimum tilt angle for PV panels roughly to obtain the highest efficiency (Altin, 2005, p.170). The orientation (azimuth) of the panels is the same with the façade and it is 23°. The panels are polycrystalline PV panels.

The results are as the following: The module cost is 5 Euro/Wp. Nominal power is 0,6 kW. Annual energy yield (the system output) is 943 kWh/year. Total investment is 5804 Euro while energy cost is 0.57 Euro/kWh. The global horizontal irradiation is 4,6 kWh/m^2day and the global irradiation on the tilted plane is 5,1 kWh/m^2day.

3.3 *Energy (assessment/evaluation/comparison)*

The total annual energy yield of this system for this case study is 943 kWh. If the electricity price for the Turkey for houses which is in use from the 1st of December 2010, 19.572 Kr (0.19572 TL) is used, it can be calculated that 943 kWh x 0,19572 TL = 184,56 TL per year (approximately 92,28 Euro) will not be paid to the grid for the 943kWh energy produced by the shading-PV system by using the unwanted solar radiation while creating a more comfortable interior. But the real gain is the comfort conditions in the building.

If the same system is attached to all of the windows in this façade, the total amount of energy yield will be a significant amount in addition to lowering the air-conditioner use, because all the rooms in this façade has the same poor comfort conditions and air-conditioners are being used in all of these rooms for about six months in a year to maintain the necessary comfort conditions.

"The electricity produced by every square meter of PV can effectively displace emissions of more than 2 tonnes of CO_2 to the atmosphere over its lifetime." (Roaf, 2003, p.195) The total area of shading-PV components in the case study is about 6 m^2, than it can be said that the shading-PV system in this case study would displace more than 12 tonnes of CO_2 to the atmosphere over its lifetime.

As stated in the same book (Roaf, 2003, p.197), a PV system case having an energy production of 3093 kWh per year avoids the release of 1.84 tonnes CO_2 per year. Since the case study here has an energy production of about 943 kWh per year, than it can be concluded that the shading-PV system in this case study would avoid the release of about 0.56 tonnes (560 kg) CO_2 per year.

In another resource (Gültekin, 2009, p.37), it is said that 1 kWp of solar cells displaces about 1190 kg of CO_2. The proposed shading-PV system in this case study is calculated as 0.6 kWp. Therefore, according to the thesis, it displaces about 714 kg of CO_2.

If it is taken as 600 kg of CO_2 emission per year approximately, the approximate total CO_2 emission of the system could be calculated as:
600 kg × 20 years (generally accepted standard lifetime of a PV system) = 12,000 kg that is equal to the calculation result of the equation given in Roaf's book. Therefore it can be said that the given values and calculations are nearly the same. Thus the CO_2 emission that the shading-PV system could avoid release to the atmosphere would be around 600 kg per year.

4 CONCLUSION

It is very important for a building to have a shading system for the solar control and maintaining comfort conditions in the interior with the use of this system. Therefore a case study is examined in this study in order to show the importance of the shading systems that have PV panels on them as the cladding element. These systems have double function: one is the solar control and the other is energy production. Therefore they decrease the energy demand of the building while producing part of that energy demand. Even all of the energy demand could be produced by using bigger PV panels and a bigger system. Therefore, using shading-PV systems on the buildings help maintaining sustainability of that building. The best point is that they can be integrated onto any building (existing or new) anytime. Therefore it can be said that shading-PV system is a good way of achieving sustainability of the buildings.

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Façade Modules for Eco-Efficient Refurbishment of Buildings: Glazing Thermal Performance to Guimarães Climate

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ABSTRACT: During the last decades façade technologies have undergone to substantial innovations by integrating specific elements to adapt the mediation of the outside conditions to user requirements. This work reports the results of an ongoing investigation on a new façade system concept called "Façade Modules for Eco-Efficient Refurbishment of Buildings" and initially developed for Portugal. In this phase glazing modules made of high performance glasses were studied. Some results of thermal performance simulation for the Portuguese Guimarães city climate will be presented considering the use of three types of glazing modules and analyzing the influence of some parameters in heating and cooling energy needs for one room (size 25m²). Computational simulation was done with the Design Builder software considering the following parameters: three different double glazing types; two envelope types and four solar orientations. The results were obtained for heating and cooling energy needs and were compared to all glazing types. It can be noted a better performance to glazing compositions that combines solar control and self-cleaning glass with extra clear glass. The results indicated a decrease of heating energy needs by the use of self-cleaning glass and clear float glass. Additionally cooling energy needs decrease was observed by the use of a green solar control glass with low-e glass.

1 INTRODUCTION

1.1 *New Façades Systems*

Recent studies have discussed the possibilities of improving energy performance of old existent buildings by their sustainable restoration and/or retrofitting, using new envelopes. Energy performances and building energy quality can be achieved by high performance envelopes.

Façades are privileged components to propose solutions since they have a major influence in the energy consumption of building and in occupants comfort because they have elements that contribute significantly to the heat transfer. To achieve a good project quality it is necessary to search for new façade technologies, to identify parameters and environmental variables that can support the process to obtain adapted solutions to reach energy efficiency and adequate conditions of environmental comfort for occupants.

One workable solution in such situation is, e.g., the use of “dynamic” façade systems whose properties can be actively controlled to achieve the desired operating behavior in response to the indoor and outdoor changing conditions. In the considered “best new solutions” the façades play multiple and complementary roles in providing natural ventilation, daylight and thermal tempering. But this requires a high degree of integration that must be thought already in the early stage of the design process. It also suggests levels of technology integration that are not routinely practiced in buildings, although they are consistently achieved in other manufacturing sectors such as the automotive and aircraft industries (Selkowitz et al. 2003b).

Nowadays, the integration of several functions in recent developments in the façade technology area is important. The façade defines the potential of the building more than any another element and it should be flexible as such. This flexibility could be reached in several ways, for example, in terms of techniques, implementation of solutions with mobile, replaceable and exchanged elements.

1.1.1 Façade Innovations

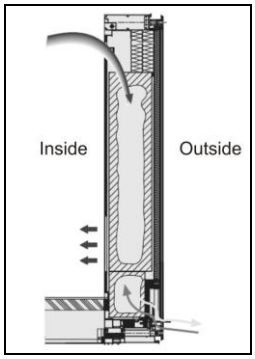
In recent decades façade technologies have undergone to substantial innovations both in quality of materials/components and the overall design concept of the façade system by integrating specific elements to adapt the mediation of the outside conditions to user requirements. These improvements include passive technologies, such as multi layered glazing, sun protections, ventilation, Trombe walls, etc. (Castrillón, 2009).

The "intelligent glass façades" including the glass performance, such as the late development of reflective, low-e, self-cleaning, absorbent, etc. had a relevant development in the last years. Façade types have been suffering an important development and they are being diffused more and more, including new technologies, besides passive and active solutions of climatic adaptation (Compagno, 2002).

The ultimate development is the "interactive façade". It should respond intelligently and reliably to the changing outdoor conditions and internal performance needs. It should exploit available natural energies for lighting, heating and ventilation should be able to provide large energy savings compared to conventional technologies, and at the same time maintain optimal indoor visual and thermal comfort conditions. As photovoltaic costs are expected to decrease in the near future, these onsite power systems will be integrated within the glass skin and these façades will become local, non-polluting energy suppliers to the building. The potential for facilitating sustainable building operations in the future by exploiting these concepts is therefore great (Selkowitz et al. 2003a).

The current philosophy is to design the envelope with responsive, interactive systems, also often called "intelligent envelopes". The envelope systems should react sensibly to the changes in the exterior climate and adjust solar gain, daylighting, heat loss and ventilation to the changing needs of the occupants and the building (Wigginton et al. 2002). As an example, one type of modern system of façades can be mentioned, the Capricorn (Fig. 1a, b).


a



b

Figure 1. Capricorn Haus Façade, Düsseldorf (a) and section façade detail (b).
Reference: FSL, 2010.

The Capricorn Haus Düsseldorf has an exterior façade with integrated active components. The design of the façade includes transparent and opaque components, combining visibility, natural light and reduction of solar gains, when compared to conventional curtain walls. The Capricorn Haus façade incorporates all the technology and equipment to regulate the indoor climate.

Another example is the Kansai Electric Power in Osaka, Japan. In this building, the energy consumption is estimated to be reduced by 30% less than conventional office building. "Eco-Frame" columns and beams jutted out by 1.8m outside from the window surface, shows effects of eaves to block the direct solar radiation during 10AM to 2PM, the peak period of the cooling

load in the summer time. Low-e glass, which has a high performance in a direct solar radiation blocking and insulation, is adopted in a window to reduce an inflow of heat from exterior. By adopting these technologies, a cooling load in perimeter zone is greatly reduced (2/3 of a perimeter annual load to standard used in Japan), so that an air conditioning system for perimeter zone such as a fan-coil unit becomes unnecessarily (Fig. 2a, b) (Aschehoug & Andersen, 2008).


a

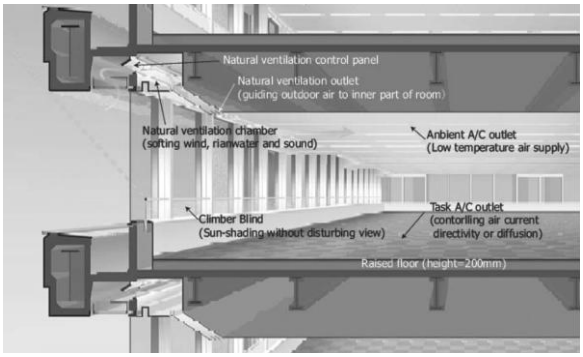


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Figure 2. Kansai Electric Power, Osaka – Japão, 2005 (a) and Façade Detail (b).
Reference: Aschehoug & Andersen, 2008.

The Nikken Sekkei in Tokyo building presented a total energy use about 50% reduction compared to reference with a "Window system responding outside environment". The development of this system started from the redesign of old Japan "Bamboo blind" as sun shade from strong west sun of summer under such a condition (Fig.3a, b) The architects and the engineers achieved coexisting of securing the flexibility of the design and the energy saving by the collaboration, and aimed at the construction of "Integrated system of “construction” and “equipment”. This system combines the electromotion exterior blind and a double-layer electric heater glass, and has controlled these automatically by the open network system.


a

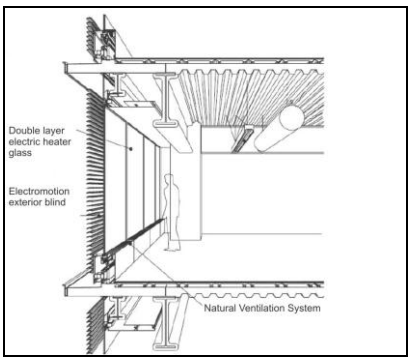

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Figure 3. Nikken Sekkei Tokyo Building (2003) (a) and Façade Detail (b).
Reference: Aschehoug & Andersen, 2008.

The ideal goal would be the development of a dynamic and flexible façade system in way to adapt to the climatic changes, to the occupants requirements and, however, to adapt to the building. An improvement would be the development of a system that facilitated the assembly of the façade, containing passive elements, glazing and reception of solar energy to improve the comfort conditions in agreement with the climatic needs and be mounted in agreement with the solar orientations and wanted functions.

This work presents partial results of an ongoing investigation about glazing modules of a new façade system: "Façade Modules for Eco-efficient Refurbishment of Buildings" on the development (Sacht et al. 2010a).

2 OBJECTIVES

This work reports the results of an ongoing investigation on a new façade system concept called "Façade Modules for Eco-Efficient Refurbishment of Buildings" and initially developed for Portugal. In this phase glazing modules composed by high performance glasses were studied. This paper presents some results of thermal performance simulation for the Portuguese climate of Guimarães city, considering the use of three types of glazing modules and analyzing the influence of glazing in heating and cooling energy needs for one isolated cell.

3 METODHOLOGY

3.1 *Overview*

In this initial investigation a model (25 m²) was computationally simulated with the software Design Builder (graphical interface for EnergyPlus). Initial simulations were made considering the following parameters: (i) three different glazing types, (ii) four solar orientations and (iii) two envelopes: a Portuguese traditional system (double masonry) and a light gauge steel framing system (LGSF). For validation purposes, the heating and cooling energy needs values obtained by thermal simulations were compared with the ones calculated in accordance with the Portuguese energy building performance regulation, "*Regulamento das Características do Comportamento Térmico dos Edifícios - RCCTE*" (RCCTE, 2006).

For the simulation of thermal performance the Portuguese climate was analyzed, in this case, Guimarães city climate. Simulations were done for four solar orientations (north, south, east and west), considering the annual period, and the following parameters were used in the analysis (Table 1).

Table 1. Climates for Computational Simulation.

Climate	Climatic Zone		Energy Needs	
	Winter	Summer	Heating (kWh/m².year)	Cooling (kWh/m².year)
Guimarães	I_2	V_2	81,64	18,00

3.2 *Standard Model Definition and Envelopes*

The "standard model" was defined considering a one-storey isolated cell, with regular geometry 5,0 x 5,0 (25 m²), a ceiling height of 2,80 m, and a total dimension of 2,5 x 2,5 (6,25 m²) for the façade glazing modules composition (Fig. 4). These dimensions followed the recommendations of the Portuguese Urban Building Regulation "*Regulamento Geral das Edificações Urbanas*" (RGEU, 2007).

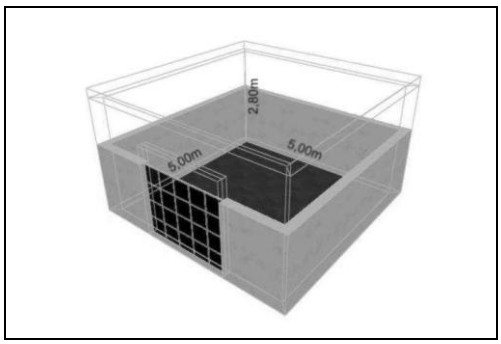


Figure 4. Standard Model.

A Portuguese conventional construction system (double-wall masonry) and a light gauge steel framing system (LGSF) were considered in the model for the opaque envelope. The LGSF envelope composition was based in the work of Santos et al (2009). The traditional system is composed by lightweight concrete slabs and insulation (stone wool), external walls in double masonry with interior insulation and cement mortar plaster. The light gauge steel framing system is also composed by lightweight concrete slabs and others insulation components

(expanded polystyrene - EPS), and EIFS (External Insulation and Finish System), OSB boards, stone wool and gypsum plasterboard was used in the walls. Table 2 presents the overall heat transfer coefficient values - U-factor (W/m² ºC) for Portuguese conventional construction system and light gauge steel framing system.

Table 2. Overall Heat Transfer Coefficient (W/m² ºC)

Heat Transfer Coefficient (W/m² ºC)		
Element-Envelope	Portuguese Conventional System	
	Total Thickness	U (W/m²ºC)
External Walls	0.365	0.46
Roof Slab	0.280	0.55
Element-Envelope	Light Gauge Steel Framing System	
	Total Thickness	U (W/m²ºC)
External Walls	0.200	0.14
Roof Slab	0.333	0.22

3.3 *Glazing Types*

Important factors must be observed in the glazing choose as: solar factor (or g-value), solar heat gain coefficient, shading coefficient, and visible transmittance, furthermore U-factor resultant of glazing composition. The glasses selected for the standard façade module simulations are from Saint-Gobain Glass. Table 4 presents the mainly properties, where Cool Lite KNT 155 green is a solar control tempered glass, manufactured by depositing of metallic oxides coating; Bioclean is a self-cleaning glass; Planilux is a multi-purpose clear float glass; Planitherm Total is a low-emissivity (low-e) glass and Planitherm Futur Ultra N is a glass with emissivity extremely low.

Table 4. Glass types for standard module.

Glass Types					
Properties	Cool Lite KNT 155 Green	Bioclean	Planilux	Planitherm Total	Planitherm Futur Ultra N
Thickness	4 mm	4 mm	4 mm	4 mm	4 mm
Solar Factor g	0.45	0.84	0.85	0.66	0.63
Shading Coefficient	0.52	0.97	0.98	0.78	0.72
Visible Transmittance	0.47	0.87	0.90	0.85	0.88
U (W/m²K)	5.75	5.87	5.80	5.74	5.73

Table 5 presents the glazing compositions based on the glasses types presented in Table 4. These glasses were used in the computational simulations in Design Builder software to obtain heating and cooling energy needs to Guimarães city. Furthermore, a 12 mm air layer between outermost and inner panes was considered. It should be noted that these values were obtained from Window 6.2.33.0 software (LBNL, 2010).

Table 5. Glazing Compositions

Glazing Compositions			
Glazings	Outermost Pane	Inner Pane	U (W/m²K)*
Glazing 04	Cool Lite KNT 155 Green	Planitherm Futur Ultra N	1.66
Glazing 07	Bioclean	Planilux	2.72
Glazing 09	Planilux	Planitherm Total	1.80

4 RESULTS

The heating and cooling energy needs for four solar orientations (north, south, east and west), considering the annual period, are presented. The analysis of the results is done based on the heating and cooling energy needs estimation for Guimarães city performed according the RCCTE energy calculation method.

4.1 *Heating Energy Needs*

All glazing types analyzed for Guimarães climate presented heating energy necessity lower than the ones calculated according to RCCTE (81.64 kWh/ m².year) for a model with characteristic and shape factor previously mentioned (Fig.5a, b). In thermal simulations were considered as envelope the Portuguese conventional system (double-wall masonry) and LGSF system. Glazing 07 presented better results in comparison with the other glazing types. It was observed that the heating energy needs presented approximate values for the both analyzed envelopes.

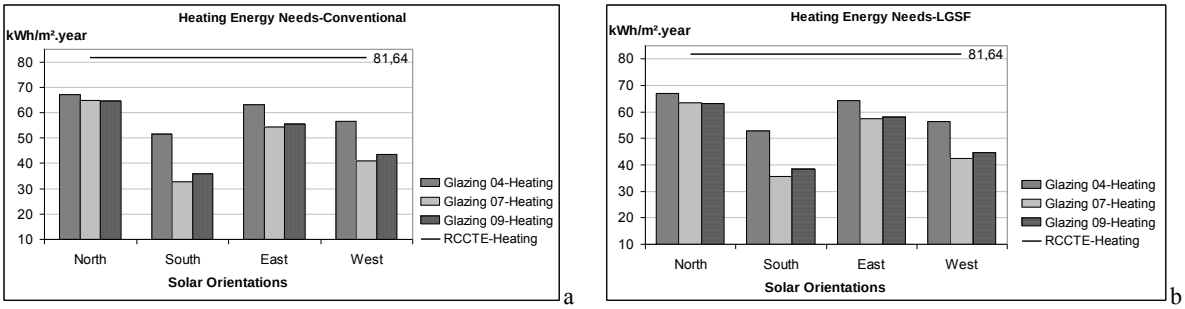


Figure 5. Heating Energy Needs. Conventional System (a) and LGSF System (b).

4.2 *Cooling Energy Needs*

Cooling energy needs for Guimarães were according to RCCTE (18 kWh/ m².year) only for glazing 04. This analysis considered just the conventional envelope and did not take into account the west solar orientation. The results obtained for LGSF envelope were below the ones estimated according to RCCTE for the most analyzed glazing types. The performed analysis did not take into account the glazing 07 and 09 for west solar orientation (Fig. 6a, b). It was observed that only the glazing 04 (Cool Lite KNT 155 Green 4 mm - Planitherm Futur Ultra N 4 mm) presented lower than RCCTE predicted value. It was observed that the cooling energy needs presented lower values to LGSF envelope.

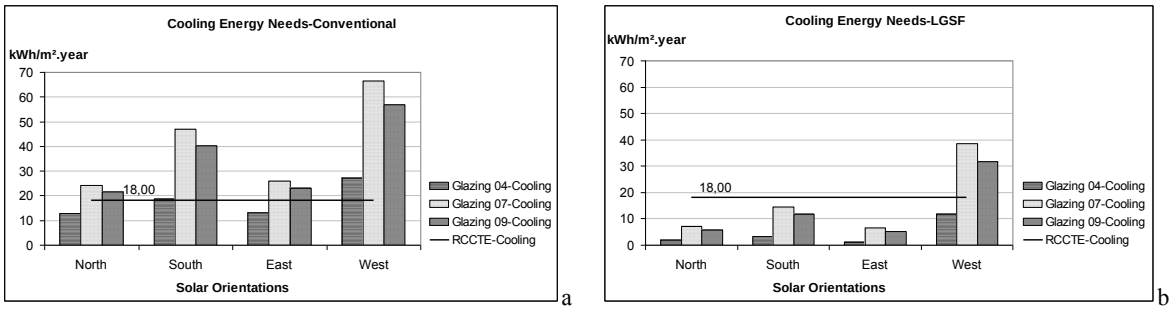
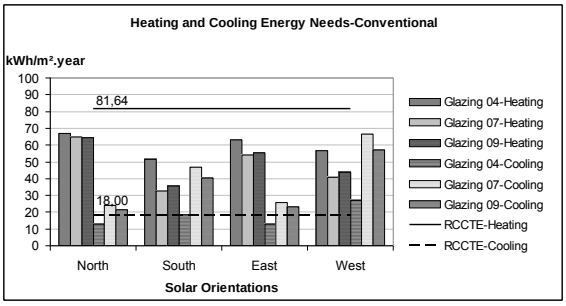


Figure 6. Cooling Energy Needs. Conventional System (a) and LGSF System (b).

Figure 7 presents heating and cooling energy needs for the conventional system and LGSF envelopes. In this case, it is possible to observe both glazings performances for the results presented previously: better results for glazing 07 and 04 concerning to heating energy and cooling energy needs, respectively.



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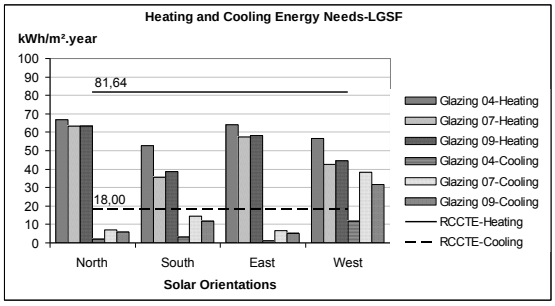

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Figure 7. Heating and Cooling Energy Needs. Conventional System (a) and LGSF System (b).

5 CONCLUSIONS

The energy simulations for the three glazing types and for the Guimarães climate were done in this research. The results showed that all glazing types presented heating energy needs lower than the maximum limits according to the Portuguese energy building performance regulation RCCTE. In this case, Glazing 07 (Bioclean 4 mm - Planilux 4 mm) stood out due to the smallest heating energy need when compared with the others, but presented a considerable increase of the cooling energy needs. It was observed that the heating energy needs were similar to both of the envelopes analyzed in this work, but the cooling energy needs were lower for the LGSF envelope.

Concerning the cooling energy needs, Glazing 04 (KNT 155 Cool Lite Green 4 mm - Planitherm Futur Ultra N 4 mm) stood out for presenting values below the ones allowed by the Portuguese energy regulation according - RCCTE.

According to RCCTE, seven months is the period of heating season for Guimarães climate. It means that during seven months per year heating is necessary to maintain comfortable conditions. Based on this period, the use of Glazing 07 in the façade modules can be indicated, due to the good performance to decrease the heating energy needs. However, Glazing 04 presented cooling and heating energy needs according to the RCCTE in spite of not presenting the better thermal performance to heating energy need.

As expected for these façade modules application, the addition of other types of passive solutions (besides those presented in this paper), contribute for the energy consumption reduction with systems HVAC and lighting in the buildings. The presented system will enable the conception of versatile, innovative and attractive modules for refurbishment solutions and new buildings, allowing to the architects an application of this façade solution in their projects.

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Energy Efficient Design Support Systems: a case-based probabilistic approach

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ABSTRACT: The conceptual phase of building design is widely acclaimed to be a multidisciplinary complex decision making activity, where multiple divergent requirements (e.g. low costs, reliable structural stability, high energy efficiency, high comfort levels, etc.) and the inherent complexity of the design (e.g. structural typologies and technologies, functional arrangements, envelopes technologies, budgets distribution, etc.) make the exploration of design alternatives and the consolidation of actual solutions a very complex and error prone process. So far, the energetic performances are considered almost exclusively during the final validation phases. Nevertheless, many essential building features that are defined during the conceptual design phases, have substantial influence on the buildings' energetic performance. For example many volumetric and formal features, such as overhang or other shape factors, considerably affect buildings' energetic consumption. Usually designers don't have a real control over these complex kind of relationships during the conceptual design phase.
Common simulation software performing building energetic analysis doesn't fulfill designers' needs because they require the complete definition of the building model, that is usually unavailable during the preliminary design phase. The integration of thermal design in the early conceptual phases therefore requires new complementary approaches that empower the designers' capabilities of evaluating design alternatives, thus improving the effectiveness of the design solution.
This paper proposes a new methodology for the development of thermal design support systems that allows the exploration of design alternatives during the buildings conception and the execution of scenario analysis in terms of effective energetic performance. The proposed approach uses a large set of simulated design cases to generate, by means of statistical induction, a design space for the thermal building design. Cases express both design parameters and energetic performance of the simulated buildings, calculated by means of common simulation software. The induction algorithm computes the relationships that occur among the energetic performance parameters and the building features on a statistical basis.
The resulting prototype Bayesian model will be described and exemplified in order to evaluate the effectiveness of the proposed support system in common conceptual design scenarios.

1 INTRODUCTION

1.1 *Supporting Thermal Design*

Recent studies have widely demonstrated that supporting designers in decision making requires systems that are able to foster the problem framing process, empowering the designer with a scenario analysis that could easily provide an overview of the design space as it is actually defined at the present design stage, and could point out the repercussion of any design choices on the expected performances.

In the case of thermal design, it is very difficult to evaluate the current state of the design and to quantify the effects of any single choice concerning one or more building features (e.g. orientation, shape variation, etc.) on the overall performance. This is generally due to:

- the unavailability of thermal models which reflect the actual status of the design process, combining both parameters that have been defined precisely with the others for which only the ranges of variation are known (the default value approach has been demonstrated to be the source of a lot of mistakes - Wasilowski et al., 2009);
- the complexity of the thermal exchange dynamics which are determined by multiple effects that are combined non-linearly and in a history dependent way, hindering any rule of thumb estimation;
- the impossibility to calculate the thermal dynamics of zones that are not completely defined, as it is generally in the early design phases.

The analytical approach that is the basis of common energetic software do not solve these issues. Designers need support systems that allow scenario analysis, to clearly identifying the parameters involved, their relevance and reciprocal dependencies, and to estimate building energetic performance. This paper proposes a methodology for the definition of a synthetic model for the building thermal design problem space, capable of being the basis for the development of design support systems.

A prototype version of the thermal design support systems was developed and it allows the exploration of design alternatives during the buildings conception and the execution of scenario analysis in terms of effective energetic performance.

1.2 *On the Combinatory Nature of the Thermal Design Domain*

So far the research literature proposes many studies, usually based on sensitivity analysis, that are aimed at investigating the energetic behavior of the building in relation to various factors like, for instance, the optimum location and distribution of insulation in wall with various orientation, the distribution of heat capacities, etc. (Ourghi et al. 2007) (Al Anzi et al., 2009) developed a simplified method for the prediction and the management of the energetic impact of the building shape. Other researches (Tsilingiris, 2006) propose appropriate numerical solution for the theoretical investigation of thermal processes involving the influence of heat capacity and its spatial distribution on the transient thermal behavior of the building. The analytical approach of this kind of researches allows on one hand to obtain very detailed results, but, on the other hand, the guideline outcome is usually very specific and it's not clear how it can be exploited to new design problems.

In fact the energetic behavior of a building is a highly dynamic and non linear process (especially in relation to overheating situations). This entails that the role and the relevance of each factor change dynamically in relation the role and the relevance of the others. Consequently the design of the thermal behavior of an environment is a process that has a high combinatory nature. The domain variables cannot be easily isolated, as they combine themselves mutually with hardly predictable results.

2 A PROBABILISTIC EXTENSION OF CASE BASED DESIGN

In this section we will discuss how Bayesian Networks (BN) (Kjaerulff et al., 2008) can be used to implement design decision support systems by extending the Case Based Design (CBD) approach in order to provide support to design decision in a high combinatory problem space. In particular it will show how BN can be applied to encoding design knowledge by integrating consolidated domain theories, explicitly stated through analytical equations, with the implicit relationships occurring among the parameters denoting a case base. Initially the main features of both the paradigms are briefly described then their integration will be detailed.

2.1 *Case Based Design*

The inherent complexity of the design process comes from the 'ill-structured' nature of design problems (Simon, 1973). Ill-structured problems are problems where the problem space is not

known a prior but it is defined in parallel with the solution process. The more the design evolves towards a solution, the more its relevant aspects are figured out and used as the basis for further developments. From a designer's viewpoint, this means that the design process spirals through stages of appreciation, action, and re-appreciation. This distinctive design character has been called co-evolution (Cross et al., 2001) (Maher, 1996). Starting from a cognitive perspective, (Schön, 1983) essentially expresses the same concept when he considers, "designing a reflective conversation with the materials of a design situation", where the practitioner's effort to solve the reframed problem yields new discoveries which call for new 'reflection-in-action'. Structured observation of designers' behavior (Cross, 2004) showed that designers seem to act very inefficiently in term of the time and effort spent in the definition of the problem. This is only an apparent deficiency, rather the ability of identifying and focusing on the relevant issues are among the key features of designers' expertise (De Grassi, 1999). The concept of problem framing fully captures the nature of this activity. Problem framing means the ability to structure a problem space by pointing out relevant issues and the interconnecting relationships. A fundamental role in problem framing is played by the designers' experience, which allows for a rapid and effective recall of information supporting the identification of the problem structure and a rapid generation of solution hypothesis.

CBD (Maher, 1995) (Oxman,1994) (Kolodner, 1993) is a well known approach to design problem solving, that addresses the issue of problem framing by providing a mean for supporting relevance analysis and solution sketching, through reminding of past design cases. CBD falls under the more general category of reasoning by analogy. Analogical reasoning is based on the idea that past experiences sharing similarities with the current problem may provide insight or assistance for framing the new problem correctly and drawing out valuable solutions. Along this line, CBD provides a means for supporting design by reminding designers of previous cases that could prove to be of help in new situations. CBD makes use of a database made up of previous design episodes, or case base, usually represented as sets of features arranged in problem – solution pairs. Cases having relevant analogies with the current problem are recalled from the database and ranked according to similarity metrics. The most promising solutions are then used to suggest strategies aimed at deriving the real design solution.

CBD is a valuable approach for supporting problem framing, avoiding generating design solutions from scratch and reflecting the typical design activity of explaining and critiquing the current status by referencing to past designs. Nevertheless, from a decision support standpoint, CBD is rather inefficient because it uses one or few cases at a time for driving designers' decisions. In CBD, the entire statistics contained in the design base are not at the designers' fingertips because CBD systems cannot provide an overall view of design parameters' interdependencies as they are implicitly stated in the case base. Consequently, CBD offers a limited support to critiquing design decisions through the exploration of different design scenarios.

2.2 *Bayesian Networks*

BN are actually one of the most successful technologies for the implementation of decision support systems. In this section we outlines some very basic aspects of BN. The reader can refer to the literature for a detailed description. BN are essentially a graphical representation of a set of statistical dependencies among a set of probabilistic variables and give a concise representation of any full joint probability distribution. More specifically a BN is a directed acyclic graph in which:

- A set of discrete or continuous random variables makes up the nodes of the graph.
- A set of directed links connect pairs of nodes $<X_i,X_j>$ and represents conditional dependency between X_i and X_j. Node Xi is said to be parent of X_j and, conversely, node X_j is said to be child of X_i.
- Each node has a conditional probability distribution $P(X_i|parents(X_i))$.

Figure 1 illustrates a fragment of a Bayesian Network. Each node can be associated to a monitor showing the node's conditional probability distribution.

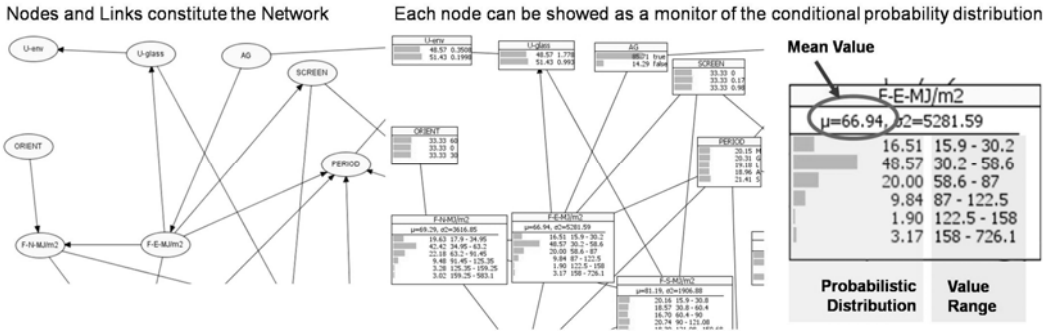

Figure 1. A fragment of Bayesian Network in the two modalities.

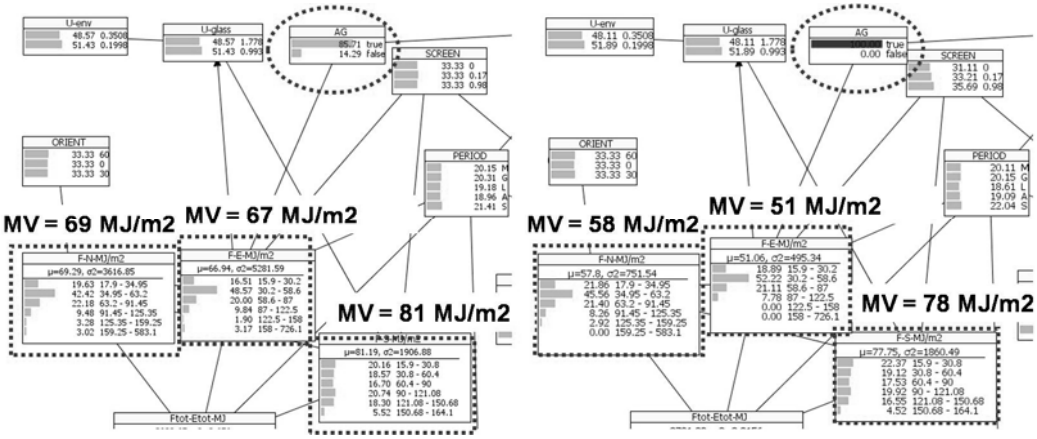

Figure 2. A fragment of Bayesian Network in the two states: in (b) the node "AG" is observed (one value fixed) and it changes the probability distributions of other nodes.

BN are directed acyclic graphs. This means that it is not possible to lay-out links in such a way that they form a path staring from node X and returning to it. The topology of the network specifies directly any conditional dependencies among its nodes and, indirectly, their conditional independencies. One node is said to be observed if its distribution has been fixed. When one node is 'observed' the BN updates the probability distribution on the rest of the network variables and the basis of the observed information. For example the observation of node "AG" in figure 2(b) causes the updating of the probability distributions of the other nodes. Conditional independencies can be pointed out through some simple rules:

1. A node is conditionally independent of its non-descendant, when its parents are observed.
2. A node of all other nodes in the networks when its parents, children and children's parents are observed (this se of node is called the Markov blanket).

2.3 *Integration CBD and BN*

Embedding design cases into BNs has been achieved simply by:

- using a particular star shaped structure for the BN (see figure 3 and figure 4) that was designed to get either the necessary information support and a good computational efficiency;
- quantifying the conditional dependence relations via the standard learning algorithm (EM Learning), through a number set of design cases that was the results of large simulation campaigns.

The resulting probabilistic CBD system puts at the designers' fingertips the statistics of the whole design case base. Once a designer describes the current design problem and the working context by observing BN nodes, then the BN updates the probability distributions of all the other nodes. In this way the BN points out the whole statistics of the design space, providing for example a complete statistics of the performance levels that could be achieved and of the related

technological set-up. This allows the designer to make further decisions and/or to retract the current ones, so that he/she can easily explore different design scenarios. This is indeed a more effective decision support than providing a hint for a single design solution. The strength of this approach is that it can support the modeling of the design problem at different scales, and it can combines also incrementally different design problems in case they share some domain variables.

The real value of this approach depends on the effectiveness of the representation of the design cases with respect to the thermal design domain. If the design cases are described with the right set of parameters and they are a good sample of the issues that generally emerge during the design process, than the support provided by this class of system is high. Therefore the definition of the design domain or, in other words, of the set of parameters that describes a design case, has been a key aspect of this research.

The prototypical probabilistic CBD system presented in this paper concerns the Thermal Summer Design of buildings in Mediterranean Climate. It has been built on the basis of a large set of design cases that:

- have been selected according to their relevance in terms of the efficiency in the summer period,
- have been described through both design parameters (e.g. volume, S/V ratio, transmittances, etc.) and parameters concerning the building energetic performance (e.g. Energy need for cooling, etc.).

Once the set of design cases has been simulated, the EM learning algorithm computes the relationships that occur among the energetic performance parameters and the building features on a statistical basis. In the next sections the details of the definition of the case base will be detailed and a typical design scenario will be described.

3 THE CASE BASE

3.1 *The representation of the design case*

In order to obtain the necessary level of detail in the information support, the level of the analysis that have been chosen in this example is that of a single thermal zone. Nevertheless some parameters concerning the features and behaviors of the building, the thermal zone belongs to, have been inserted as well. In this way it is possible singling-out specific situations, while the witting of design choices and their optimization are fostered. This process was guided by a scenario analysis. It pointed out that in order to support designers in the evaluation of design alternatives, the probabilistic CBD system should:

- provide the information for describing configuration alternatives (e.g. geometrical, formal, technological, usage related, climatic parameters…);
- express the overall performance of each thermal zone and/or of the building in terms of energetic consumption (e.g. energy needs for cooling and/or heating);
- support designers in the comprehension of actual thermal phenomenon, enabling the identification of the factors and elements that entail a greater impact on final thermal performance (e.g. energetic contribution of each component).

These three classes of parameter have been detailed for each building element, design factor and performance, providing, at the end, the structure of the case base parameters.

3.2 *The prototype database*

The selected parameters are: Location = {*Torino, Ancona, Valencia, Atene, Palermo, Casablanca*}, User destination ={*residential*, *office, hospital*}, Shadings = {*true* , *false*}, Construction Typology (4 different combinations) and Orientation = {*25, 60*}. 200 configurations of a building made of two zones have been generated by combining these five parameters. For each configuration the thermal performance data was derived by means of the EnergyPlus software. The results were post-processed obtaining the monthly energetic behaviors for 7 months (from April to October). At the end a database of 1400 cases was generated.

4 PROTOTYPE BAYESIAN NETWORK

4.1 *Network Development*

In order to limit the computational complexity, the network was structured in a star shaped two level hierarchy, having essentially one root node 'Z-case', representing all the alternative configurations (200 cases in the prototype). The other parent node 'period', identifies the reference month for the thermal analysis (7 states in this prototype). The leaf parameters are then grouped in sub-networks in relation to the information type: building configuration data and main types of energetic contributions (e.g. Gains from windows, Internal Gains…) (Fig. 3).

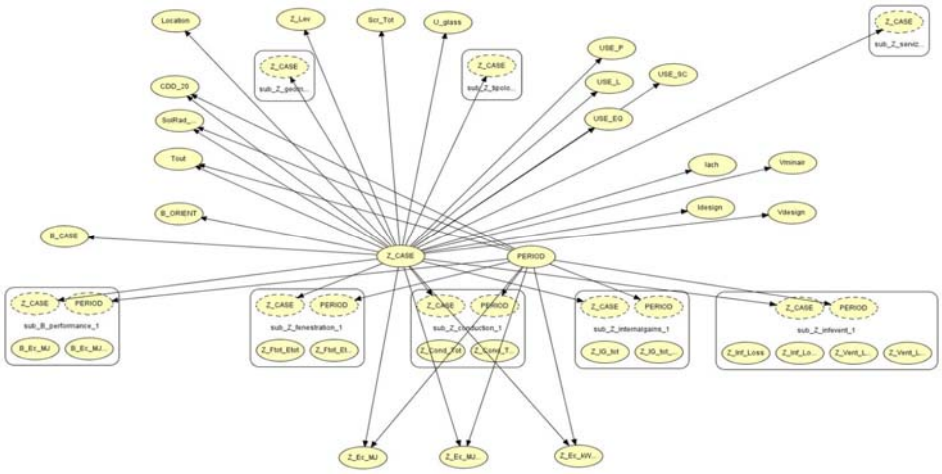

Figure 3. Prototype network about Thermal Summer Design in Mediterranean Climate.

4.2 *Scenario Example*

The resulting prototype was used for testing the methodological approach through some design scenarios. The following design scenario has been applied. During the initial conception of a building an architect is facing morphological issues. In particular, he has already defined some overall features (Volume, shape, etc.), and he is analyzing some alternative options concerning the orientation of the volumes at the first floor level (see figure 4). In this kind of situations if a designer would have evaluated the energetic performance of alternative configurations via simulation software, he had to define features that he didn't faced yet (e.g. window positioning, materials, etc.). So he would have incurred in severe disturbance of its process since he had to interrupt the conceiving phase and pass to a quite hard constrained analytical phase. On the contrary by using the Bayesian probabilistic CBD system he can rapidly:

- fix the actual state of the configuration, even if the information set is not complete (e.g. he fixes location, zone level, analysis period) (Fig. 4);
- browse the building performance in alternative configurations of design variables simply "clicking" their state.

So with a couple of clicks he can get to an estimation of the energy need for cooling, that is the mean value of all the cases associated to his selection, for two different orientations.

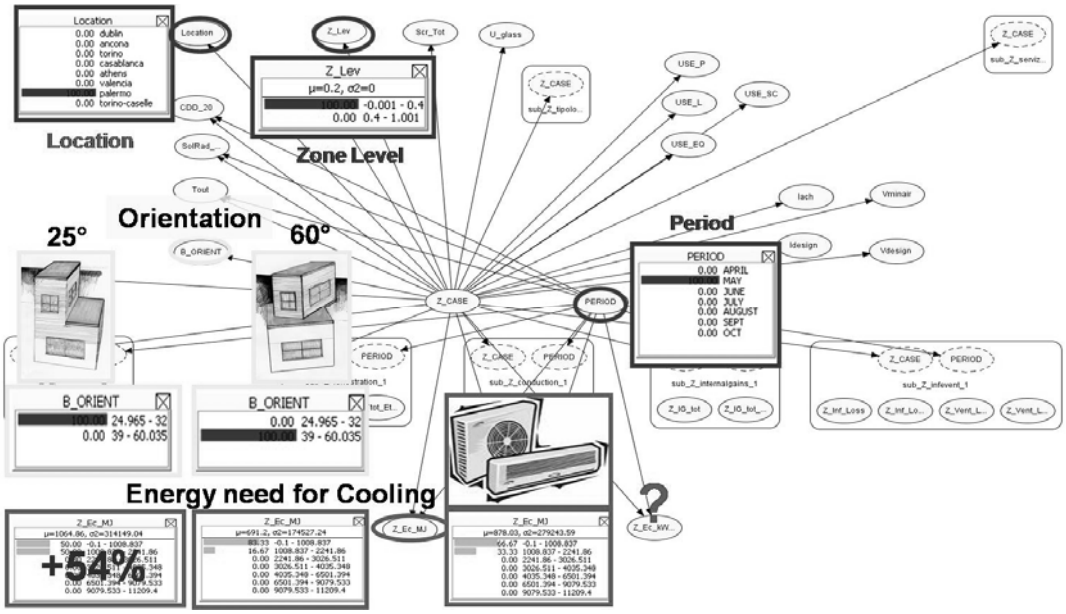

Figure 4. Scenario example: Observed nodes and different Probabilistic Distributions and Values of Ec for alternative states of the parameter "Orientation".

	ORIENTATION 25°		ORIENTATION 60°	
APRIL	Z_Ec_MJ μ=504.37, σ2=-5.82E-11 100.00 -0.1 - 1008.837 0.00 1008.837 - 2241.86 0.00 2241.86 - 3026.511 0.00 3026.511 - 4035.348 0.00 4035.348 - 6501.394 0.00 6501.394 - 9079.533 0.00 9079.533 - 11209.4	MeanV = 504 0%	Z_Ec_MJ μ=504.37, σ2=-5.82E-11 100.00 -0.1 - 1008.837 0.00 1008.837 - 2241.86 0.00 2241.86 - 3026.511 0.00 3026.511 - 4035.348 0.00 4035.348 - 6501.394 0.00 6501.394 - 9079.533 0.00 9079.533 - 11209.4	MeanV = 504 REF
MAY	Z_Ec_MJ μ=1064.86, σ2=314149.04 50.00 -0.1 - 1008.837 50.00 1008.837 - 2241.86 0.00 2241.86 - 3026.511 0.00 3026.511 - 4035.348 0.00 4035.348 - 6501.394 0.00 6501.394 - 9079.533 0.00 9079.533 - 11209.4	MeanV = 1064 +54%	Z_Ec_MJ μ=691.2, σ2=174527.24 83.33 -0.1 - 1008.837 16.67 1008.837 - 2241.86 0.00 2241.86 - 3026.511 0.00 3026.511 - 4035.348 0.00 4035.348 - 6501.394 0.00 6501.394 - 9079.533 0.00 9079.533 - 11209.4	MeanV = 691
JUNE	Z_Ec_MJ μ=2578.14, σ2=907809.74 0.00 -0.1 - 1008.837 50.00 1008.837 - 2241.86 0.00 2241.86 - 3026.511 50.00 3026.511 - 4035.348 0.00 4035.348 - 6501.394 0.00 6501.394 - 9079.533 0.00 9079.533 - 11209.4	MeanV = 2578 +45%	Z_Ec_MJ μ=1774.8, σ2=526348.39 16.67 -0.1 - 1008.837 50.00 1008.837 - 2241.86 33.33 2241.86 - 3026.511 0.00 3026.511 - 4035.348 0.00 4035.348 - 6501.394 0.00 6501.394 - 9079.533 0.00 9079.533 - 11209.4	MeanV = 1774
JULY	Z_Ec_MJ μ=3951.28, σ2=1.73E6 0.00 -0.1 - 1008.837 0.00 1008.837 - 2241.86 50.00 2241.86 - 3026.511 0.00 3026.511 - 4035.348 50.00 4035.348 - 6501.394 0.00 6501.394 - 9079.533 0.00 9079.533 - 11209.4	MeanV = 3951 +36%	Z_Ec_MJ μ=2914.42, σ2=493170 0.00 -0.1 - 1008.837 16.67 1008.837 - 2241.86 33.33 2241.86 - 3026.511 50.00 3026.511 - 4035.348 0.00 4035.348 - 6501.394 0.00 6501.394 - 9079.533 0.00 9079.533 - 11209.4	MeanV = 2914
AUGUST	Z_Ec_MJ μ=4399.65, σ2=754675.74 0.00 -0.1 - 1008.837 0.00 1008.837 - 2241.86 0.00 2241.86 - 3026.511 50.00 3026.511 - 4035.348 50.00 4035.348 - 6501.394 0.00 6501.394 - 9079.533 0.00 9079.533 - 11209.4	MeanV = 4399 +11%	Z_Ec_MJ μ=3951.28, σ2=1.73E6 0.00 -0.1 - 1008.837 0.00 1008.837 - 2241.86 50.00 2241.86 - 3026.511 0.00 3026.511 - 4035.348 50.00 4035.348 - 6501.394 0.00 6501.394 - 9079.533 0.00 9079.533 - 11209.4	MeanV = 3951
SEPTEMBER	Z_Ec_MJ μ=2129.77, σ2=254438.02 0.00 -0.1 - 1008.837 50.00 1008.837 - 2241.86 50.00 2241.86 - 3026.511 0.00 3026.511 - 4035.348 0.00 4035.348 - 6501.394 0.00 6501.394 - 9079.533 0.00 9079.533 - 11209.4	MeanV = 2129 +19%	Z_Ec_MJ μ=1793.49, σ2=141354.46 0.00 -0.1 - 1008.837 83.33 1008.837 - 2241.86 16.67 2241.86 - 3026.511 0.00 3026.511 - 4035.348 0.00 4035.348 - 6501.394 0.00 6501.394 - 9079.533 0.00 9079.533 - 11209.4	MeanV = 1793
OCTOBER	Z_Ec_MJ μ=878.03, σ2=279243.59 66.67 -0.1 - 1008.837 33.33 1008.837 - 2241.86 0.00 2241.86 - 3026.511 0.00 3026.511 - 4035.348 0.00 4035.348 - 6501.394 0.00 6501.394 - 9079.533 0.00 9079.533 - 11209.4	MeanV = 878 +27%	Z_Ec_MJ μ=691.2, σ2=174527.24 83.33 -0.1 - 1008.837 16.67 1008.837 - 2241.86 0.00 2241.86 - 3026.511 0.00 3026.511 - 4035.348 0.00 4035.348 - 6501.394 0.00 6501.394 - 9079.533 0.00 9079.533 - 11209.4	MeanV = 691

Figure 5. Scenario example: Comparison of alternative values of Energy need for cooling for alternative parameter configurations.

This kind of estimation is very useful, for example, for identifying the parameters having the biggest influence in each design solution. In this case, for instance, the Ec varies of 54% between the two cases. This means that the orientation parameter has a great impact in relation to the summer energetic consumption. Even if this estimation may be rather inaccurate in the early phases of the design process, the more the design is specified the more accurate estimation are available to the architect. Therefore the more the design proceeds the more the probabilistic CBD system adapts to the available information. Standard simulation software cannot produce any kind of result without having a complete definition of the model. Furthermore in few steps you can have a wide overview of the performances of alternative design solutions. Figure 5 shows the comparison of the states of two parameters (orientation and period). This frame can be reached with few clicks and it will be easily obtained through a more adequate software interface.

5 CONCLUSIONS

Decision support systems for preliminary design cannot make use of common analytical methods but require a synthetic approach to the problem. In this research, a new methodology is proposed, integrating case-based design paradigm and probabilistic modeling techniques which provide performance insight at different accuracy level on the basis of the available information. A prototype version of the system has been described pointing out the potential of this approach in preliminary design phases.

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The Requirements and Testing of Frost Durability of ETICS

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ABSTRACT: The frost durability of façade structures and materials is very important factor in durability issues especially in countries on cold weather region, such as Finland. Therefore the separate freeze-thaw tests of single material components and the full-scale rig tests with harsh weather conditions have been commonly conducted when developing new structure types or using new kind of materials in façades. External thermal insulation composite systems with rendering (ETICS) have been the one of the most used façade structures in Central Europe for decades, nowadays also in Finland when building new residential buildings or renovating old ones. The Guideline for European Technical Approval of External Thermal Insulation Composite Systems with Rendering (ETAG 004) covers a rather wide variety of tests to be used when assessing the fitness of system. However, it does not include any significant frost attack. Instead, frost durability requirements are presented in the form of absorption properties.

1 INTRODUCTION

Finnish weather conditions differ a great deal in contrast to e.g. Central Europe and thus they are very demanding considering building structures. One of the most considerable issues is freeze-thaw cycles which can occur all year round. The biggest problems with freeze-thaw cycles occur while at the same time ambient conditions are wet. That is common in Finland during autumn and spring time when the daytime temperature is slightly above 0 ^{o}C and by night below it. The same problems occur on warm winter days.

ETAG 004, European Technical Approval Guideline of Rendered External Thermal Insulation Composite Systems (2008), covers a rather wide variety of tests. However, it does not include any dealing with significant frost attack. Instead, frost durability requirements are presented in the form of absorption properties and it also instructs a method for testing hygrothermal behaviour. The latter test includes segregated heat-rain and heat-cold cycles for the wall structure and between those two steps the wall, in practice, dries. That is, however, not functional method in Finnish weather conditions where freeze-thaw cycles often include wet structures and moist ambient air caused by rain or melting snow.

As shown in the Figure 1 freeze–thaw cycles have occurred between 11 and 38 times (average 27) annually between 1961 and 2006 based on the data from the Meteorological Institute of Finland. The data includes every time when temperature has dropped below 0 °C not more than three days after raining. Thus the test methods suggested by ETAG 004 are not functional methods in Finnish weather conditions.

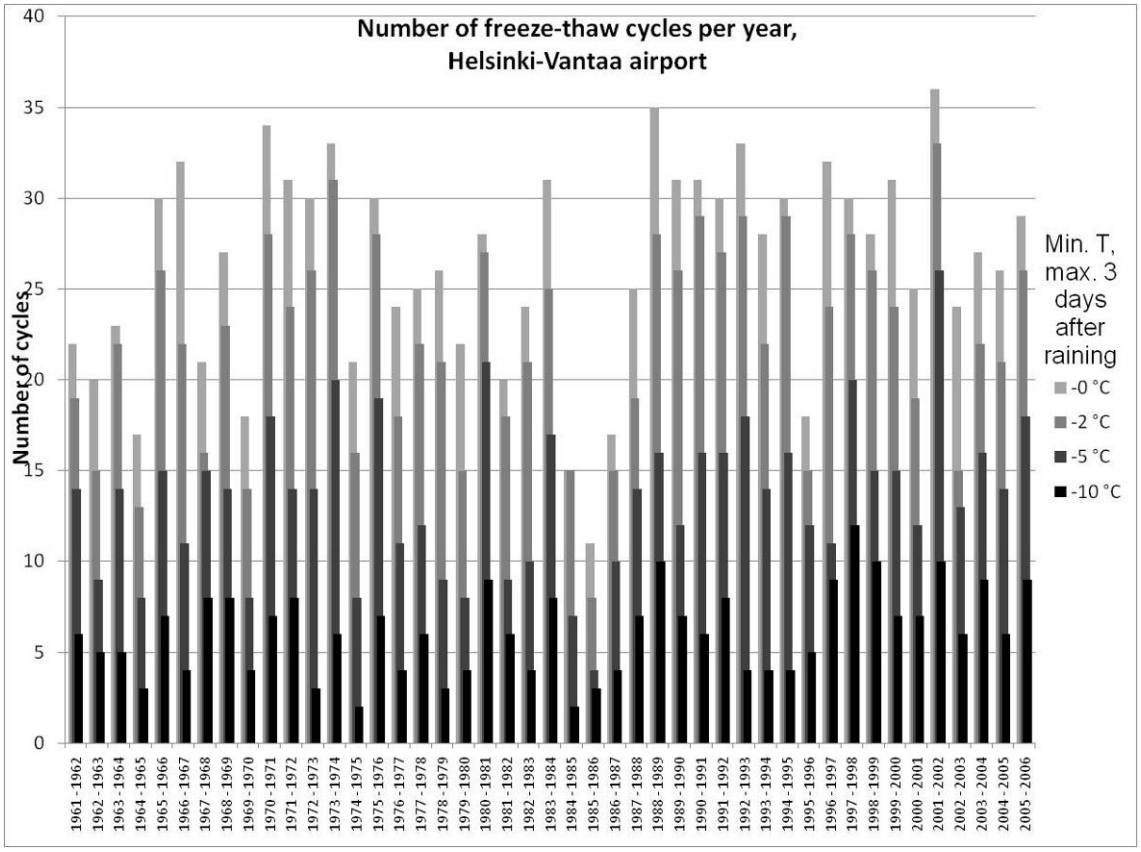

Figure 1. Annual freeze-thaw cycles in Finland between years 1961-2006. The annual data of freeze-thaw cycles contains data between September and April whereupon each bar in the chart is cited with two years.

During last decade most of ETICS systems in Finnish markets have been tested in a Structural Engineering laboratory of Tampere University of Technology with harsh weathering tests, where repeated 8 hour long cycles include freezing to -20°C temperature, fast heating to 60°C and wetting the façade surface with spraying. This 'standardized' Finnish test method includes 100 cycles and the judgment of the tested structure is based on occurred damages and strength tests before and after weathering. The new Finnish national instructions for ETICS will be published shortly. The instructions will involve the requirements of frost durability testing for rendering materials and full façade systems.

Quite often ETICS, especially imported systems, have already been tested according ETAG 004 requirements. However, in some cases the tested structures still have failed and major frost damages have occurred. This paper will present the new Finnish testing instructions and compilation of test results and examples of occurred failures mechanisms.

2 WEATHER TESTING

2.1 *Weather Testing according to ETAG 004*

ETAG 004 recommends testing the Hygrothermal Behaviour (§ 5.1.3.2.1) of external thermal insulation composite systems (ETICS) with rendering after selecting suitable coatings by the Water Absorption test (§ 5.1.3.1). The Hygrothermal Behaviour test is done for a test wall, referred here as a rig, which has a normal external rendered thermal insulation wall structure with a substructure, insulation material and rendering. The minimum dimensions of the rig are specified as 2.50 m wide and 2.00 m high, yet the total surface should be at least 6.00 m². (ETAG 004 2008)

The test includes two different cycles: heat–rain and heat–cold. The heat–rain cycle is repeated 80 times and after at least 48 hours of subsequent conditioning (10 – 25 °C; 50% RH) the

heat–cold cycle is repeated 5 times. In the heat–rain cycle the surface of the rig is subjected to a treatment which comprises the following phases:

- heating to 70 ± 5 °C (rise for 1 hour) and maintaining for 2 hours (total of 3 hours)
- spraying water (15 ± 5 °C) for 1 hour
- 2 hours of drainage

Following the heat–rain cycles and the subsequent conditioning, the heat–cold cycle comprises of the following phases:

- heating to 50 ± 5 °C (rise for 1 hour) and maintaining for 7 hours (total of 8 hours)
- cooling to - 20 ± 5 °C (fall for 2 hours) and maintaining for 14 hours (total of 16 hours)

Thus, the test lasts a minimum of 27 days. During the test observations must be done frequently, and any cracking, blistering or peeling of the surface should be recorded. (ETAG 2008)

As can be seen the heat–rain and heat–cold cycles are segregated and between them the rig dries. In Finland the weather conditions during autumn, winter and spring often include freeze-thaw cycles, sometimes even a few times a day. At the same time with freeze-thaw cycles the structures are often wet because of rain, snow or humidity, thus the wall structure is heavily subjected to frost weathering.

2.2 *Weather testing method in Finland*

Department of Civil Engineering at Tampere University of Technology (TUT) has developed a test which includes heavier stress cycles than the test suggested by ETAG 004. In the TUT test heat, rain and cold phases are merged, which is the main difference compared to the ETAG version.

The limit temperatures of the stress cycles are selected to cover normal temperature ranges in Finnish climate conditions: the sun warms surfaces of houses rarely over 65 °C and at the temperature of -20 °C, the smallest capillary pores in the plaster freeze (Pigeon & Pleau 1995). The stress cycles have three phases as shown in Figure 2:

- spraying water (15 ± 5 °C) for 1 hour
- cooling to - 20 ± 5 °C as fast as possible and maintaining, total 4 hours
- direct heating to 65 ± 5 °C as fast as possible and maintaining, total 3 hours

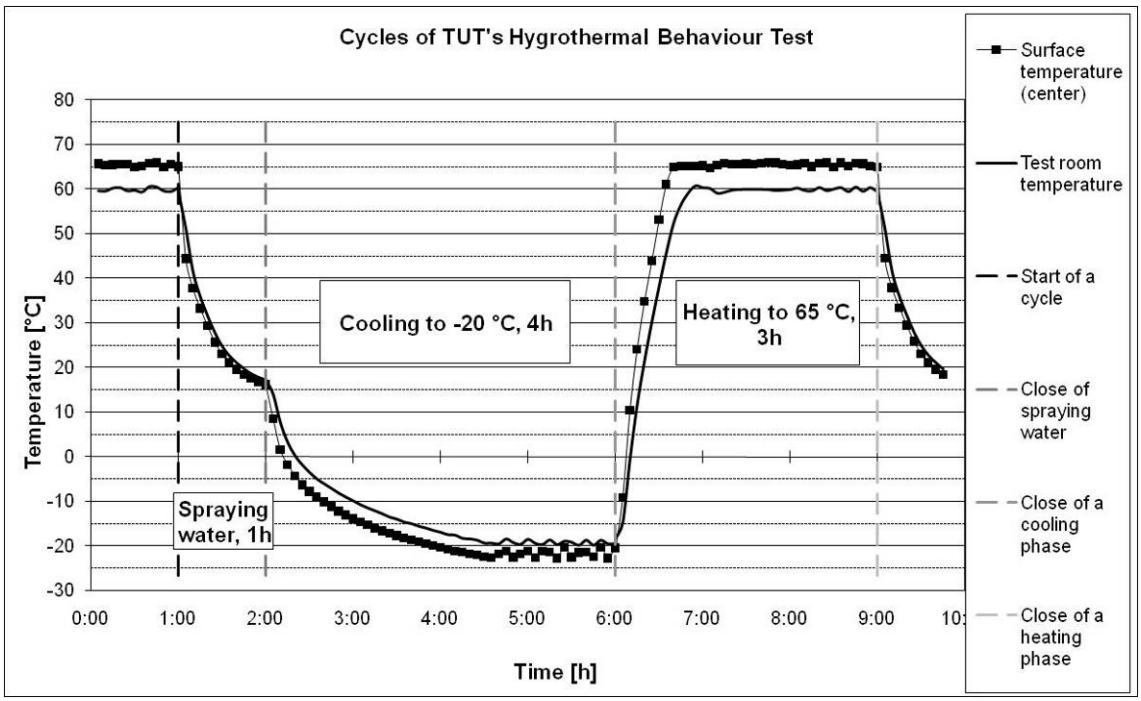

Figure 2. The chart demonstrates a progress of a cycle of TUT's Accelerated Weather Test.

The rendering of the rig is usually made by the manufacturer of the render product or other qualified worker so that the quality of the work is ensured. The external structure of the rig can also be bisected in the middle so that both sides have a different coating, e.g. different render products. If a fault situation is aspired to be studied, a self-imposed discontinuity, e.g. a horizontal crack, can be made on the coating. That should be done to be on the safe side because outcome of the rendering work is rarely perfect throughout a whole building. The discontinuity should be made at the bottom part of the rig, therefore the other parts will not sustain damages.

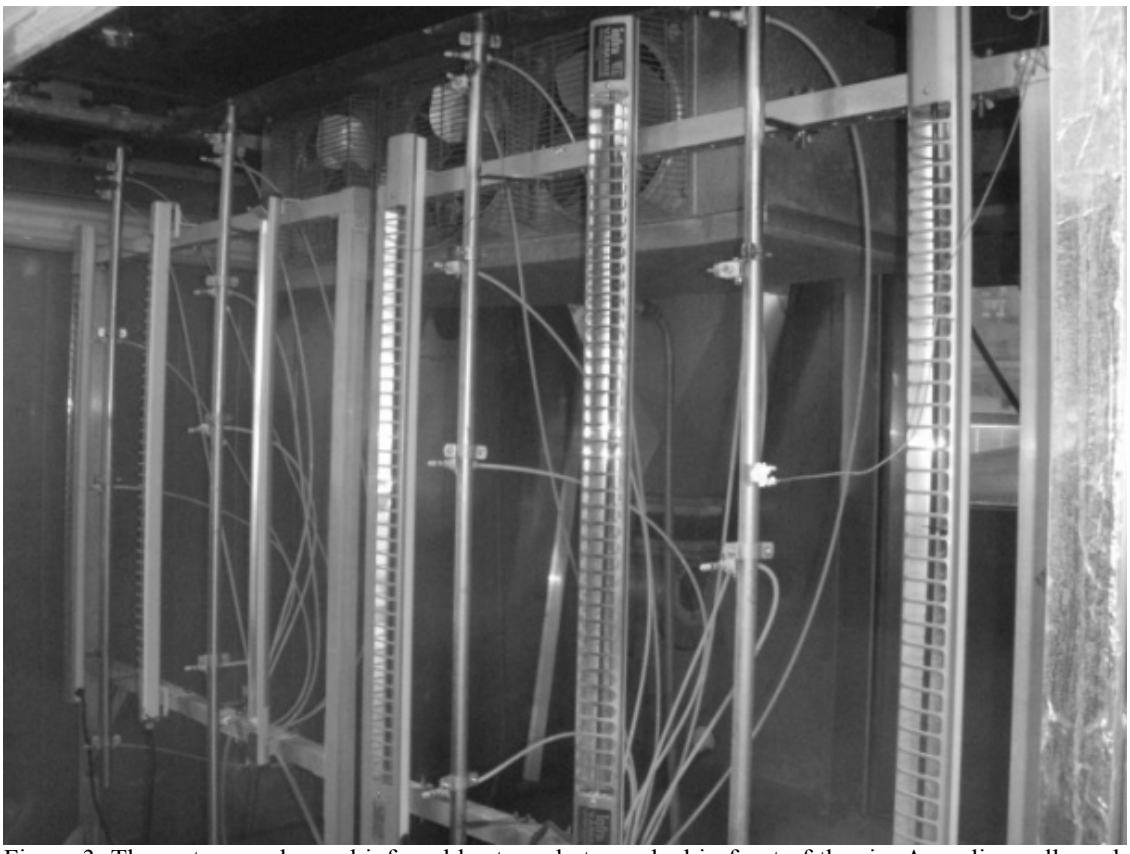

Figure 3. The water nozzles and infrared heaters photographed in front of the rig. A cooling cell can be seen hanging from the ceiling.

The test apparatus is 3 m wide, 6 m long and 2 m high box which has EPS insulation. The rig is positioned in the middle so that an outdoor condition and an indoor condition rooms are equal. Within 1 m from the rig are positioned 16 water nozzles and 6 infrared heaters as shown in Figure 3. They are directed so that the nozzles spray water all over the surface of the rig and the heaters could warm the surface as evenly as possible.

3 SURVEILLANCE DURING THE CYCLES AND FINAL TESTS

Observation methods and final testing of the test rig are basically the same as ETAG 004 (2008) suggests.

3.1 *Observation during the test*

The rig should be examined visually each working day and the progress of visual cracks should be recorded. The rendered surface can be inspected more thoroughly at least once a week e.g. by knocking the rendered surface with hard and light object avoiding to cause damages to find out if rendering has peeled.

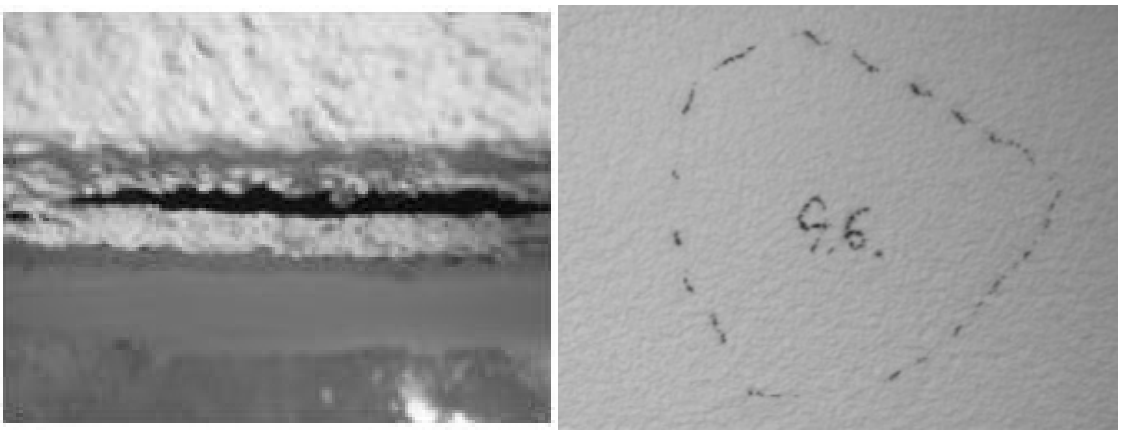

Figure 4. The damages on the rendered surface may vary between barely visible cracks and large scale blistering.

In Figure 4 the failure in the left picture was caused by insufficient work with reveal of a window which caused peeling of the rendering. On the right picture is shown blistering of rendering, diameter of 50 mm, outlined with marker. Blistering was caused by large-scale temperature deformation of an insulation material in contrast to rendering.

3.2 *Observations after the test*

As the test has come to an end the rig is left to dry for a week in normal room conditions. The rig may be studied more closely during drainage. E.g. an extent of frost weathering of the rendering may not always appear during the test as shown in Figure 5. After the drying, sections containing cracks or blistering can be removed to observe better water penetration i.e. penetration depth of cracks in rendering.

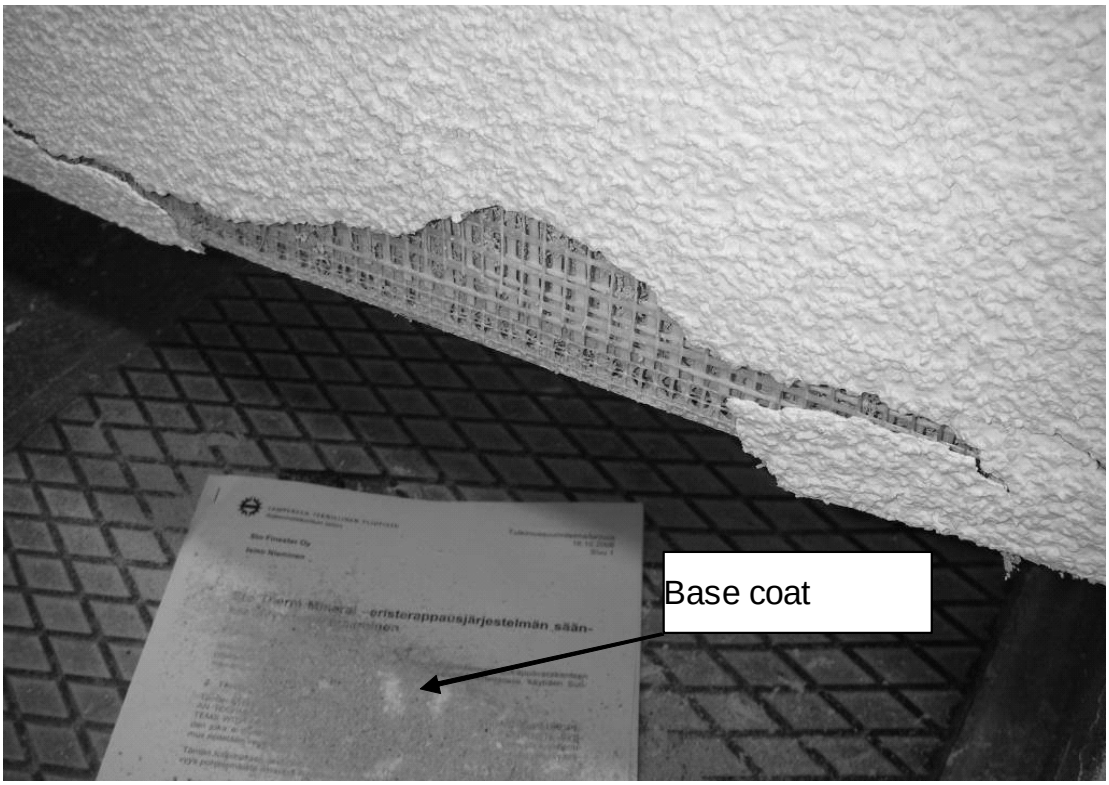

Figure 5. The base coat underneath the fairly good looking finishing coat had pulverized and fell down as the finishing coat was tapped with fingers.

3.3 *Final tests on the rig*

Final tests include bond strength test (§ 5.1.4.1. on ETAG 004) and impact resistance test (§ 5.1.3.3.1. on ETAG 004) (2008). For both tests it is recommended to have non-stressed comparison specimens which should have the same structure as the rig.

Bond strength test after the stress cycles determines the bond between a base coat and an insulation material. Number of tests is usually 6 per structure and test places should locate on undamaged area. However, if needed more tests can be made and locations vary e.g. near the self-imposed discontinuity cracks. Thus, the effect of water penetration in contrast to an undamaged surface can be determined.

Figure 6. On the left is shown the bond strength testing machine. The wooden tensile pieces are glued on the surface with two-component polyurethane glue. On the right is shown an example of an unsatisfactory result on impact resistance test.

The impact resistance is tested by hard body impact tests with a steel ball. The 3 and 10 joule impact tests are conducted for each structural variation (6 impacts / series / structure). The results of individual impacts are assessed visually on the basis of cracks appearing on the surface. In unclear cases a section of the thin rendering is removed and the backside is inspected for damage. The degree of the damage is divided in three categories I, II and III. Demands of each category are specified in ETAG 004 (2008).

4 EXPERIENCES

Experiences during the last 25 years of accelerated weather testing have shown that in Finnish climate conditions the heavy stress testing method is needed to assure frost resistance of ETICS. Often the system may have passed the requirements of ETAG 004 yet still have failed relatively fast on the real outdoor climate. Figures 7, 8 and 9 show typical failures that have occurred with ETICS in Finland.

Figure 7. Frost attack is probably the most common source for failure with ETICS in Finnish climate conditions.

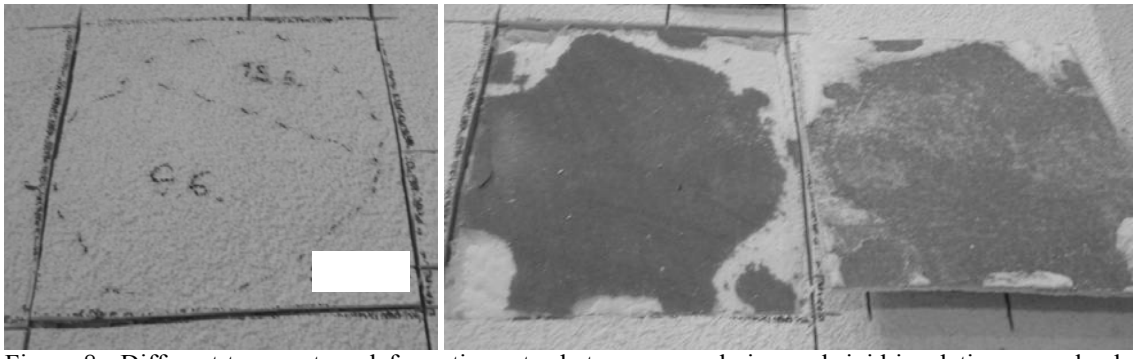

Figure 8. Different temperature deformation rates between a rendering and rigid insulation may also be critical for bond and thus cause blistering when temperature can vary annually between -30 – 65 °C. On the right is shown bond failure between primer and base coat under a blister.

Figure 9. Large scale frost damage and blistering on the wall of a three years old building with ETICS.

The accelerated weather testing method has given good results for render manufactures and it have shown that highly frost-resistant products can be made. However, a low quality of the work is one of the most important reasons for failures, e.g. the air-entrainment of the base coat. Some products have failed the test even if they have previously passed it because of failed air-entrainment.

Another notable risk factor can be jointing of other elements through the surface structure and window reveals which may pass water or moisture to insulation layer, thus exposing base coat to remarkable frost attack. Thus the frost durability requirements for rendering are increasingly high.

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Converting a conventional residential building into a sustainable one

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ABSTRACT: Sustainable design has become a major field of architecture, because of the uprising interest that the scientific community has shown in the environmental profile of buildings during the last decades.
The scope of this article is to examine different ways that contribute to the decrease of the buildings' energy needs for space heating and cooling, ventilation, lighting and electricity, as well as ways of decreasing water consumption. Passive solar systems, natural ventilation, photovoltaic panels, geothermal energy and use of rain water are included among the proposals.
The first part of the article aims to convert a residential building, located in northern Greece, into a green one, by alternating its architectural designs. The second part examines the influence that all these proposals have in the environmental profile of the building, by estimating the annual needs for space heating and cooling, ventilation, electricity and water consumption.

1 INTRODUCTION

The major scope of the article is to examine the influence that various techniques, targeting to "green building", have on the environmental profile of buildings, under the prism of the quantitative analysis.

Towards this way, the architectural designs of a conventional residential building, located in Polissitos, a village in northern Greece, have been selected. The designed building, which will be referred as "reference building", is a two-storey single-family residential building, with a total area of 160m^2, and other 85m^2 basement. The climate of the area is continental, with cold winters and cool summers, partly because of the strong north-east winds and the existence of the river Kossinthos.

The quantitative analysis includes the calculation of the heating and cooling energy demand, as well as calculation of the electricity consumption of the building. The heating energy needs are calculated according to the monthly method described in the European Standard EN13790, whereas the cooling energy calculation are based to the cooling degree day method, as it is described by Papakostas & Kyriakis. Both methods use mean monthly climate data and provide accurate results over a whole year's period. For the electricity calculations, a use scenario is adopted, in order to estimate the annual consumption.

The results show that the proposed alterations have significant influence on the energy demand of the reference building. The proposals aim to both decrease the energy consumption and substitute this energy by renewable energy sources.

2 REFERENCE BUILDING

2.1 *Orientation of the building*

A rectangular shape has been chosen for the reference building, with its main direction at the East-West axis, while the main zones (living room, kitchen, bedrooms) are placed in the two upper floors and the secondary zones (parking, central-boil room, pool) in the basement.

In terms of horizontal placement of spaces, functional zones were developed, with living room and bedrooms occupying the south side of the building, and auxiliary rooms (bathrooms, corridors, staircases, closets) occupying the north side. Finally, on the problematic, in terms of energy performance, west side of the building, two bathrooms and a kitchen have been placed.

Due to the prevailing northeast winds in the area, the roof has been designed to be curved and angled, sloping from south to north, in order both to halt the cold winds and enable the development of larger surfaces facing south, which increases the solar heat gains and enables the natural lighting of the interior.

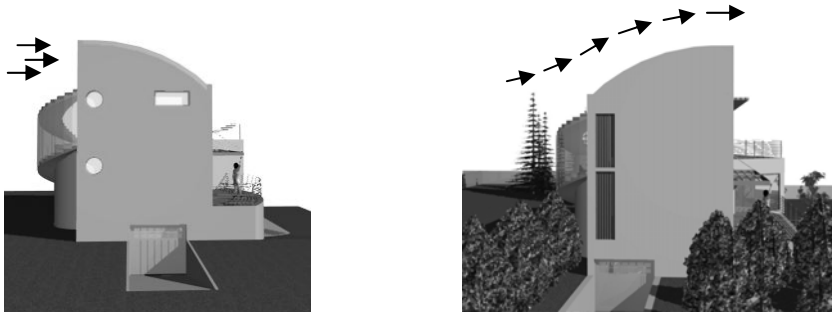

Figure 1 (a),(b). 3-D presentation of the roof before (a) and after (b) the alterations.

Finally, special attention has been paid to the selection of species and locations of plantings, so that they can positively influence the microclimate of the building. Specifically, in the north and northeast side of the building high evergreen trees have been placed, which operate as windbreaks; on the south side, low deciduous trees are proposed, in order to block the sunrays from breaking into the interior; on the west side low evergreen trees have been planted, which reduce the glare of the western areas during the afternoon. Moreover, grass has replaced concrete surfaces around the building, aiming to avoid overheating and discomfort during the summer months.

Figure 2. 3-D presentation of the plantation around the building.

2.2 *Passive solar systems*

The openings of the reference building have been selected in a way that they meet the requirements of the direct solar gain for space heating. Specifically, the majority of openings, covering a significant surface, have been placed mainly in the south facade, operating as solar collectors, whereas the openings' surface in the west and east is limited, with reflective solar

shades as well. Finally, in the north facade there are openings only in the outer shell of the glass staircase, just to enhance the natural ventilation of the building.

Concerning the indirect gain systems, a water wall (Figure 3) has been placed on the southwest side of the living room, with a discharging possibility during the summer period, in order to avoid overheating phenomena.

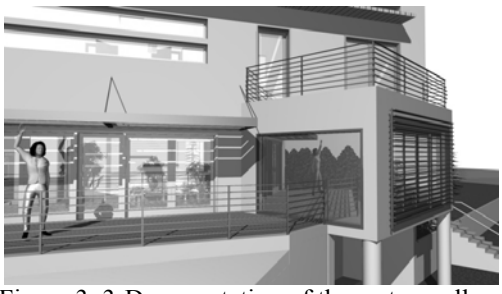

Figure 3. 3-D presentation of the water wall.

Finally, on the south side of the building, in front of the terrace with an inclination of 40°, an isolated thermosyphonic panel has been installed. This system, which is developed in the basement, is estimated to have positive contribution on warming the ground floor, via two vent holes formed in the south and north side of it.

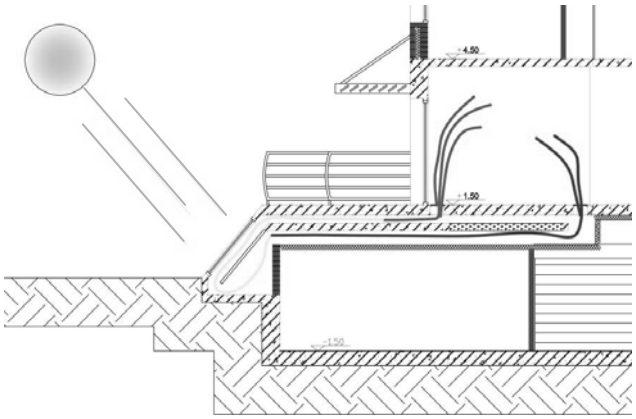

Figure 4. Schematic presentation of the function of the thermosyphonic panel.

2.3 *Passive cooling systems*

The cooling needs of a building during the summer period are very important for the Mediterranean climate. The easiest way is to control solar heat gains through canopies, blinds, glazing and special plantings. Thus, above the central southern windows located in the dining room, an horizontal roof has been fitted, whose length has been determined by the slope of the sunrays during the winter and summer months in this location. A smaller horizontal overhang has been fitted above the first floor's windows, leaving part of the solar radiation outside the building during the summer months. Furthermore, the bathrooms' windows on the west side and the living room's ones on the southeast side have been equipped with swivel mounted external blinds. Finally, the use of triple glazed low-emissivity (triple low-e) windows at all openings, in order to reduce heat loss in winter and solar gains in summer, should be noted.

Significant attention has been paid to the insulation of the building's envelope, aiming to reduce thermal transmission from the exterior to the interior in the summer period. Placement of a particularly thick (0.12m) insulation material can reduce the amount of heat which enters the building interior from the external environment through the building's envelope.

The part of the roof in the south facade is designed in a manner which enhances natural light to enter the building at a great depth, thus limiting the need for building's artificial lighting. This, combined with efficient bulbs and electric appliances, reduces the heat radiated from them which reduces the total internal heat gains of the building.

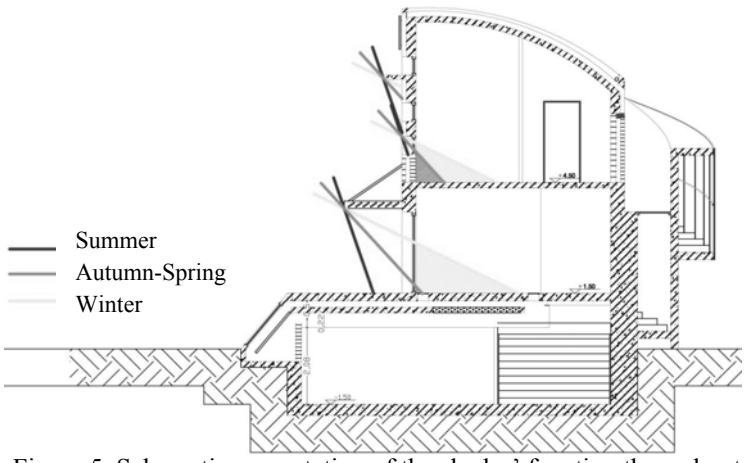

Figure 5. Schematic presentation of the shades' function throughout the year.

Regarding the building's ventilation, small windows have been placed in the glass shell of the north staircase, enhancing both horizontal and vertical natural ventilation.

Moreover, the existence of river Kossinthos near the building, as well as the pool's presence helps natural cooling via indirect and direct evaporation, respectively.

Finally, the first floor is in direct contact to the ground, which reduces the cooling load, as the ground temperature is approximately 14°C throughout the year.

2.4 *Photovoltaic panels*

In order to meet the domestic needs of electricity, the use of monocrystalline solar cells, which can yield 100Wp, is chosen. The reason of this choice is their efficiency, higher than that of polycrystalline. Specifically, the efficiency of monocrystalline solar cells is around 17%, compared to 13-15% of the polycrystalline. Solar cells are connected in series, forming a grid. It is estimated that in Northern Greece, monocrystalline solar cells with total area of 10m^2 can produce 1150kWh annually. Therefore, provided that the building's needs in electric energy are calculated at 3000kWh annually, the required surface of the photovoltaic panel is 26m^2. The solar cells are placed both in rotating louvers on the south roof of the building, and vertically on the south façade.

3 HEATING ENERGY CALCULATIONS

3.1 *Heating energy needs*

The calculation procedure of the heating energy requirements is proposed in the European standard EN13790. The monthly method described by this standard has been chosen. This method is based on the thermal balance of the building, taking into account both the heat losses and the heat gains.

The calculation procedure is briefly described in this article. Firstly, the overall heat transfer coefficient by transmission H is calculated. Then the heat losses for the particular month are derived by equation 1:

$$Q_l = H \cdot (\theta_{\text{int},set} - \theta_e)^+ \cdot t \tag{1}$$

where Q_l = total heat losses in the particular month; H = the overall heat transfer coefficient; $\theta_{\text{int},set}$ the set-point temperature for the particular month; θ_e the mean monthly temperature of the air and t = the duration of the month.

Then, the internal heat gains are calculated by equation 2:

$$Q_{\text{int}} = A \cdot \Phi_{\text{int}} \cdot t \tag{2}$$

where Q_{int} = the internal heat gains for the particular month; A = the total floor area of the build-

ing; Φ_{int} =the internal heat gains' flow, expressed in Watt; and t = the duration of the month.

The solar heat gains, symbolized as Q_s, are a function of the mean monthly solar irradiation and the total effective area of the openings and vary between the different orientations of the openings. The total heat gains are the sum of the internal and solar gains ($Q_g = Q_{int} + Q_s$).

The procedure continues with the calculation of the utilization factor, symbolized with n, which indicates the fraction of the heat gains that have a positive contribution in the heating needs. The utilization factor is a function of the heat gains to the heat losses ratio, the thermal capacity of the building and the overall heat transfer coefficient. The heating needs for the particular month are derived by the expression:

$$Q_h = Q_l - n \cdot Q_g \tag{3}$$

where Q_h = the total heating needs for the particular month; Q_l = the total heat losses; Q_g = the total heat gains; and n = the utilization factor.

The annual heating needs are the sum of the heating needs for every month. The U-values selected for the reference building vary between 0.21W/(m^2·K) and 0.25W/(m^2·K). The windows' U-value is 0.5W/(m^2·K). The overall heat transfer coefficient, except for the water wall, is calculated H=178.73W/K. The numeric results for the reference building are shown in Table 1.

Table 1. Heating energy needs per month

	Heat transmission coefficient	Heat losses	Heat gains			Utilization factor	Heating needs	
			Internal	Solar	Total			
	W/K	MJ	MJ	MJ	MJ	-	MJ	kWh/m^2
January	189.8	8030.1	1560.4	4367.2	5927.6	0.94	2453	4.17
February	192.0	6689.3	1409.4	4414.4	5823.8	0.89	1471	2.50
March	195.9	6243.5	1560.4	5441.3	7001.7	0.79	700	1.19
April	209.1	4010.3	1510.1	5434.3	6944.4	0.57	90	0.15
May	179.5	913.6	1560.4	3522.9	5083.3	0.18	0	0.00
June	179.5	-1163.3	1510.1	3252.2	4762.3	-0.24	0	0.00
July	179.5	-2452.2	1560.4	3581.1	5141.5	-0.48	0	0.00
August	179.5	-2259.9	1560.4	4030.0	5590.4	-0.40	0	0.00
September	179.5	≅0	1510.1	4262.2	5772.3	≅0	0	0.00
October	228.4	2935.8	1560.4	6358.3	7918.7	0.37	9	0.01
November	196.7	5099.3	1510.1	4504.6	6014.7	0.77	487	0.83
December	188.1	7203.3	1560.4	3308.4	4868.8	0.96	2541	4.31
Year							7750	13.16

3.2 *Geothermal energy*

A more efficient and environmentally friendly geothermal system has been selected, in order to meet the heating and cooling needs of the reference building, as well as the needs for domestic hot water. Specifically, a surface close-loop system has been selected.

The required area of the geothermal system is estimated to be 300m^2 and the excavations should be carried out in a depth of about 1.2 - 1.4m.

Finally, geothermal energy has been combined with underfloor heating systems, because it requires a lower temperature of the water that circulates into the pumps.

4 COOLING ENERGY CALCULATIONS

For the cooling energy calculations, a simple method based on the annual cooling degree days has been used (Papakostas & Kyriakis 2005). This method defines the set point temperature for cooling $\theta_{int,set}$ ($\theta_{int,set}$ is 20°C in this study) and derives the cooling degree days by the monthly average temperature of the external air, by equation 4:

$$CDD = \sum_{i=1}^{12} n_i \cdot (\theta_{e,i} - \theta_{\text{int},set})^+ \tag{4}$$

where *CDD*= the annual cooling degree days; n_i = the number of days of the month i; $\theta_{int,set}$ the set-point temperature for the particular month; θ_e the mean monthly temperature of the air and *t* = the duration of the month.

Finally the annual cooling energy needs are calculated by equation 5:

$$Q_C = 0.0864 \cdot CDD \cdot H \tag{5}$$

where Q_C = the annual cooling energy needs; *CDD* =the annual cooling degree days; and *H* = the overall heat transfer coefficient.

The results of the above analysis for the reference building are displayed in Table 2, which shows the mean monthly ambient temperature in the area. Only positive values of the cooling degree days and of the cooling energy needs are taken into account. Negative values are shown in Table 2, in order to give a whole idea of the calculation method. Nevertheless, negative values in a month mean that in this month no cooling is needed.

Table 2. Cooling energy needs per month

	Mean air temperature °C	Cooling degree days °C·days	Cooling energy needs MJ	kWh/m^2
January	4.2	-489.8	-7563.6	-12.84
February	5.6	-403.2	-6226.3	-10.57
March	8.1	-368.9	-5696.7	-9.67
April	12.6	-222.0	-3428.2	-5.82
May	18.1	-58.9	-909.6	-1.54
June	22.5	75.0	1158.2	1.97
July	25.1	158.1	2441.4	4.15
August	24.7	145.7	2249.9	3.82
September	19.9	-3.0	-4.63	-0.01
October	15.2	-148.8	-2297.8	-3.90
November	10.0	-300.0	-4632.7	-7.87
December	5.7	-443.3	-6845.6	-11.62
Year			5849.5	9.93

5 NATURAL LIGHTING

In order to achieve high levels of natural lighting in the building's interior, a series of measures, aiming at building's more appropriate insolation, have been included. In terms of orientation, most openings have been placed on the south façade, because in the northern hemisphere the south orientation receives the greatest amount of solar radiation throughout the year. The east and west orientation, always problematic, due to large amounts of solar energy received in the morning and afternoon respectively, has a limited number of openings, while in the north side the diffuse natural light enters the building through the glass staircase.

Light shelves and external reflective blinds have been applied for controlling the sunlight entering the building. A narrow shelf of lighting and reflective surface is placed on the south side, above the doors and windows, which enables the natural lighting to get into the interior. In the east and west façade's openings, rotating reflective blinds have been placed, as the angle of the incident solar radiation in these orientations varies continuously throughout the year.

Finally, the external glass staircase in the north façade could have significant heat loss during the heating period, fact that imposes the use of insulation. The solution is using transparent insulation. Specifically, aerogel, a transparent thermal insulation material, with low thermal transmission coefficient, varying between 0.004 and 0.04 W/(m·K), which minimizes heat loss due to transmission, has been used.

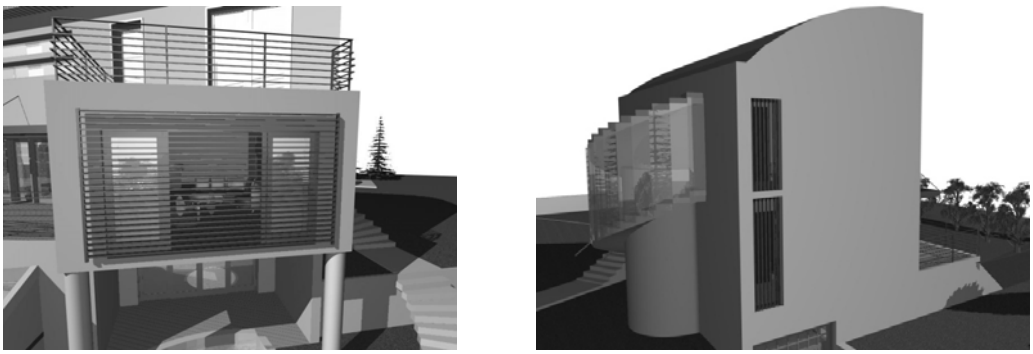

Figure 6 (a),(b). 3-D presentation of the swiveling blind in southeast (a) and west (b) façade.

6 ELECTRICITY

For the calculation of the electricity consumption of the reference building, a use scenario has been adopted. The power of the different electric appliances is multiplied with their estimated use duration, in order to derive the total energy consumed.

The results of the above analysis lead to an annual energy consumption of 2927.3kWh.

7 RAINWATER

The collection and reuse of rainwater -wherever possible- is substantial, when a whole environmental performance is considered. Rainwater can be used in the washing machine and dishwasher, in the toilet, in watering the garden, etc. It is generally estimated that the amount of rainwater used for these purposes is 50% of the building's total consumption of drinkable water.

The determination of the storage tank's capacity involves the following factors (Bikas 2000); the quantity of rainwater, the estimated consumption for the uses that can be substituted by rainwater, and the period of autonomy.

In order to take into consideration the various losses in the amount of rainwater incident on the surface of the capstone, a reducing coefficient, symbolized as ψ, is implied in the calculation procedure.

The annual available amount of rainwater, symbolized with V, yields by equation 6:

$$V = E \cdot \psi \cdot N \tag{6}$$

where: E = the horizontal projection of the collecting surfaces' area in m^2; ψ = dimensionless reducing coefficient; N = the average annual rainfall in mm p.a.

Provided that the autonomy period is estimated to be 30 days, the calculation procedure leads to the result that the available quantity of rainwater in November, the month with the largest rainfall, is $V=4.026m^3$. Therefore, a tank with capacity of $4.0m_3$ is adequate.

On the other hand, the needs of a four members family for water that can be substituted by rainwater are estimated to be V_{needs} = 50% * 4 (people) * 150 (l / day) * 30 (days) = $9000l=9.0m^3$. So, even in the month with the greater amount of rainfall, the needs surplus the capacity, so a rainwater storage system is needed.

8 SUMMARY

The presented article is an effort to examine the effects that different measures have on the environmental performance of a building. The design of the reference building has been modified, in order to be closer to a sustainable building. Passive solar systems, natural ventilation, photovoltaic panels, geothermal energy and use of rain water are included among the proposals. In figures 7(a), 7(b) and 8, general 3-D presentations of the building are shown.

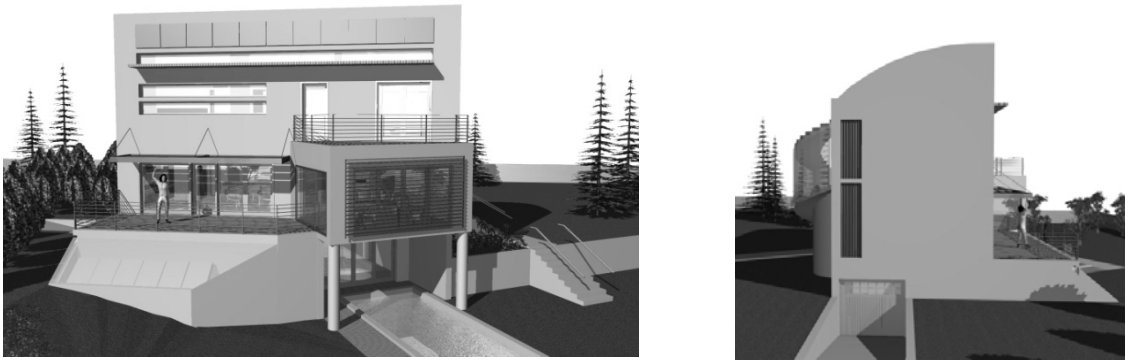

Figure 7 (a),(b). 3-D presentation of the south (a) and west (b) façade.

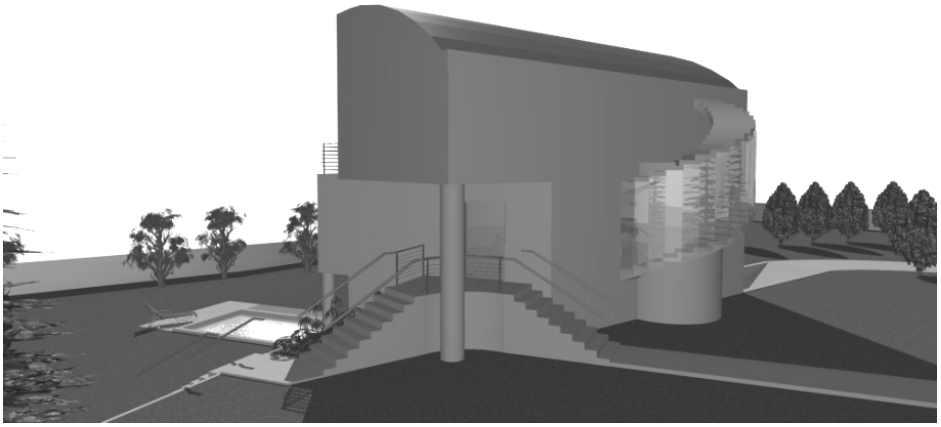

Figure 8. 3-D presentation of the northeast façade.

The results show that these proposals lead to a significant decrease of the energy consumption for heating and cooling, as well as decrease of the water and electricity consumption. Passive solar systems, combined with proper design of the building yield to annual heating energy needs of 13.16kWh/m^2 and annual cooling energy needs of 9.93kWh/m^2. In addition, the estimated annual electricity consumption is 2927.3kWh. Finally, via the collection and use of rainwater, 50% of the total water consumption is replaced by the collected and stored rainwater.

Conclusively, it can be stated that the contribution of the different measures taken towards the environmental enhancement of a building over its whole environmental performance is very important. The numeric results of this study show that the introduction of various passive solar systems, as well as the more proper design of the building, can significantly reduce the total energy consumption.

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From the Traditional Architecture, throughout the Formula, to the Design Guidelines: the Wind Tower Tradition.

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ABSTRACT: Wind tower technology belongs to the traditional architecture of the Middle East Countries. Indeed, in hot climate wind towers were traditionally used where, due to different reasons, the openings in the building envelope were not enough large to enable airflow coming inside the building.
Starting from the architectural and geometrical analysis of the traditional wind tower, the present work studies the relations between the climate contexts, the physical phenomena and the tower design features. The equilibrium equation of force was firstly used to define the tower functioning with regard to the tower characteristics and the wind speed and direction. The vertical baric gradient, the wind action and the buoyancy force were taken into account, considering also the comprehensive and localized energy losses. Two different analyses were carried out for extracting and uptake towers stressing the attention on opening and duct design. Finally, the influence of building traditional design on the tower functioning was pointed out, considering also the comfort needs in the indoor spaces.
The physical analysis allowed comprehending the traditional features of *malqaf* and *badgir* as, respectively, uptake and extracting tower. The results were summarised in some charts that allowed to pre-size a wind-tower system starting from the wind speed data and taking into account the indoor comfort air velocity.

1 INTRODUCTION

1.1 *Historical overview.*

Energy saving in buildings during the summer time is an important present-day goal in building design. Passive cooling strategies has always been used in hot climate and their study could be very important in today professional practise. For that reason the wind tower technology belonging to the Middle East Countries (especially in Egypt and Iran) has been analysed separating the bioclimatic aspects from the cultural needs. Indeed, in the Islamic world, indoor privacy provision is a very important issue in the architectonical design and windows are often screened for these reasons and for solar control needs. Hence natural ventilation by windows is nearly impossible; moreover, the high-density urban structure interacts with wind speed and direction and usually the air-velocity at street level is not sufficient to provide natural ventilation inside buildings. Then, the use of wind tower permits to provide natural ventilation in the indoor spaces without compromising the solar protection purposes and without compromising the privacy needs inside the building.
In spite of these common purposes, traditional wind towers were characterised by very different architectonical features in accordance with the specific geographical and climatic contexts. A

morphological-geographical classification is then introduced in the literature in the field of architecture and two main types of wind tower are distinguished:

- *badgir*, traditional wind tower belonging to Iran
- *malqaf*, traditional wind tower belonging to Egypt.

Compared to *malqaf* towers, *badgir* are characterised by high vertical development and by a higher thermal mass structure. Also openings and duct designs are very different. *Malqaf* upper-openings are orientated towards the prevailing winds and are characterized by sloping roof (20°- 40°). The openings are usually related to a single duct with a rectangular cross-section. Instead, considering no prevailing winds are recorded in Iran, the Badgir upper-openings are generally oriented in several directions. Each upper-openings is related to a duct that is consequently dived in several parts by inner longitudinal walls.

1.2 *Physical principals.*

In spite of their design, all wind towers are subjected to the same system of forces producing different status of pressure in the duct ends:

a- wind stress (ΔP_{WS});
b- pressure-gradient (ΔP_{PG});
c- buoyancy force (ΔP_{BF}).

Each force generate an upward or downward airflow inside the duct in accordance with the values of physical parameters involved in the phenomena, consequently their sum determine the functioning of the tower. Also the comprehensive and localized energy losses ($\Sigma P_{L,tot}$) influences the functioning of the tower and for that reason they are taken into account defining a net pressure drop inside the duct ($\Delta P_{tower,net}$). Than, a new classification of towers based on $\Delta P_{tower,net}$ value is introduced:

a- airflow uptake tower (wind catcher) $\Delta P_{tower,net} = \Delta P_{WS} + \Delta P_{PG} + \Delta P_{BF} - \Sigma P_{L,tot} > 0 \text{(Pa)}$

b- airflow extracting tower $\Delta P_{tower,net} = \Delta P_{WS} + \Delta P_{PG} + \Delta P_{BF} - \Sigma P_{L,tot} < 0 \text{(Pa)}$

At least the physical parameter values are influenced by the tower design features and by the climatic context in which towers are built. According to the literature in the field of architecture and to the following study, the geographical-morphological classification matches the functioning one: malqaf towers are essentially wind catcher while badgir towers are mainly airflow extracting systems. Some exceptions could be done for the badgir tower: indeed, some of them are designed to function both in uptake and extracting modes.

2 METHOD

2.1 *Analysed model.*

A general model derived from the traditional building and tower designs were used as study case (Fig.1). Six point are plotted in the scheme to identify the main control-sections in the tower system:

- point $A_{1,0}$ and $B_{2,0}$, that represent the external air conditions at the tower upper-opening and bottom-opening levels;
- point A_1 and B_2, that represent the internal air conditions at the ends of the duct;
- point $B_{2,1}$ and B_3 that represents the air conditions at the exit opening plan.

Downwards flows are assumed to be positive in the model analysis and the action of each force on the control sections were firstly considered separately and then resumed adding the energy losses to identify the functioning mode of traditional wind towers and the architectonical features influencing it. From a physical point of view, two study-cases are introduced: tower with upper-openings oriented towards the prevailing winds (case 1), tower with upper-opening oriented in the opposite direction of prevailing winds (case 2). The *malqaf* are represented by the first case-study, while *badgir* could fall both the two study-cases depending of their functioning and of their upper-opening design.

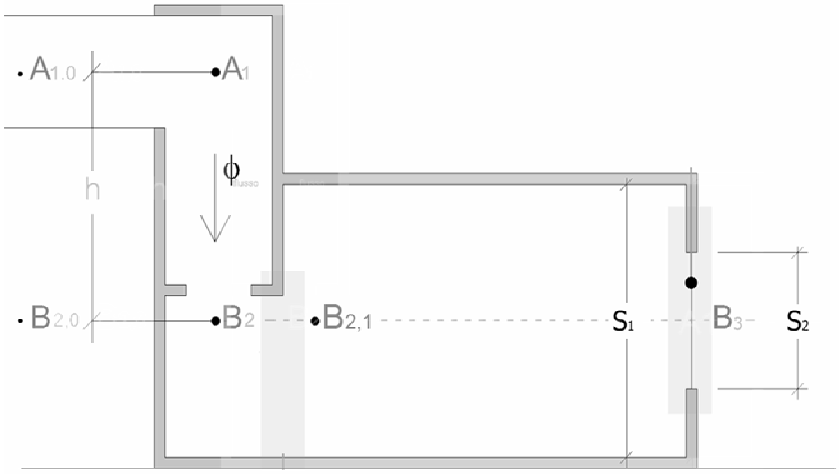

Figure 1. Analysed model

2.2 *Buoyancy force, wind stress and pressure-gradient force.*

The duct pressure drop driving the airflow is calculated by:

$$\Delta P_{tower} = \rho_m \frac{v_A^{\ 2} - v_B^{\ 2}}{2} + (P_A - P_B) + (\rho_A - \rho_B)hg - \sum P_{L,tot} \quad \text{(Pa)}$$

where ν_A and ν_B are the airflow velocity respectively at the duct inlet and outlet section; P_A and P_B are the pressure status due to the vertical pressure gradient; ρ_m, ρ_A and ρ_B are respectively the average air density and the air density at the inlet and outlet duct sections; *h* is the length of the duct and *g* represents the gravitational force. Finally, the $\Sigma P_{L,tot}$ represents the sum of the localized and comprehensive energy losses due to the duct and to the openings design.
The study is aimed to stress the relations between the physical parameters in the formula, the climatic conditions (wind speed, temperature) and the principal architectonical features (tower high, openings design) that influence the wind tower functioning. According to our results, ΔP_{WS} and ΔP_{PG} are more influent in the tower functioning than the ΔP_{BF}.

2.3 *Comfort needs.*

Taking into account $B_{2,1}$ and B_3 points, the model analysis permits to evaluate the indoor airflow velocity considering the ΔP_{PG} and ΔP_{BF} are null hence the two points are usually quite at the same high. Then the indoor airflow velocity is:

$$v_{indoor} = Cd\sqrt{\frac{2 \cdot |\Delta P_{indoor}|}{\rho}}$$

where Cd is the discharge coefficient and ΔP_{indoor} is the pressure difference between the two control section at point $B_{2,1}$ and B_3 in which only the wind stress is non zero values. No indoor energy losses are considered hence the flux preserves its direction and the tower width is put equal to the building width, as it happens in real traditional buildings. Finally, the coefficient Cd takes into account the energy losses due to the exit section at window plan considering the indoor space dimensions compared to the window ones (S_2/S_1).

Varying the indoor airflow velocity from 0,5 to 3,5 (according to comfort need), it is possible to evaluate the flow velocity at the tower down opening and consequently the net pressure drop inside the duct by:

$$v_{tower} = Cd\sqrt{\frac{2 \cdot \left|\Delta P_{tower,net}\right|}{\rho}} \quad \text{and consequently} \quad \Delta P_{tower,net} = \frac{\rho}{2}\left(\frac{v_{B2,0}^{\;2}}{Cd^2}\right)$$

where the coefficient Cd (discarge coefficient) is introduced to take into account the flux dimension changes after it exits the tower duct.

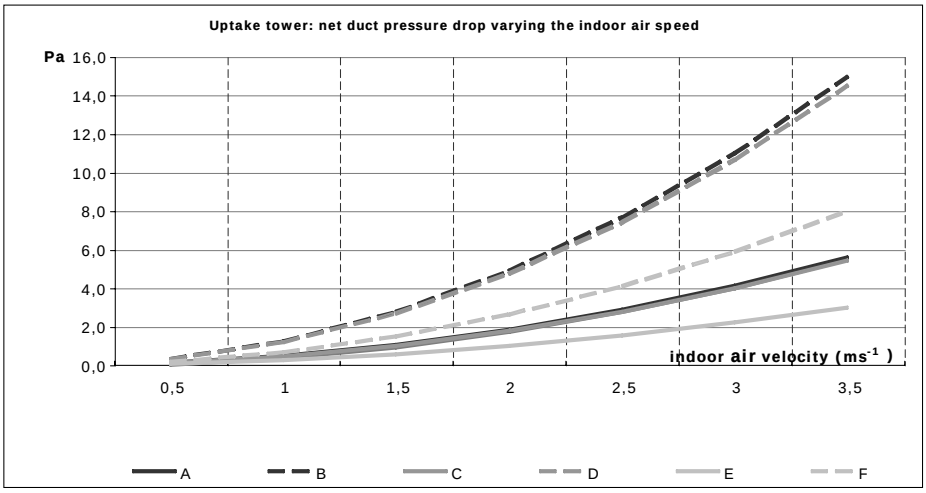

Figure 2. Duct pressure drop to assure comfortably airflow inside buildings varying the indoor airflow velocity. The dot lines represent tower with pipe restriction at the bottom openings section while the solid lines represents tower without any restrictions. Three different room setting were considered: $S_2/S_1 \rightarrow 0$ (lines A and B); S_2=0,5 S_1 (lines C and D); S_2= S_1 (lines E and F).

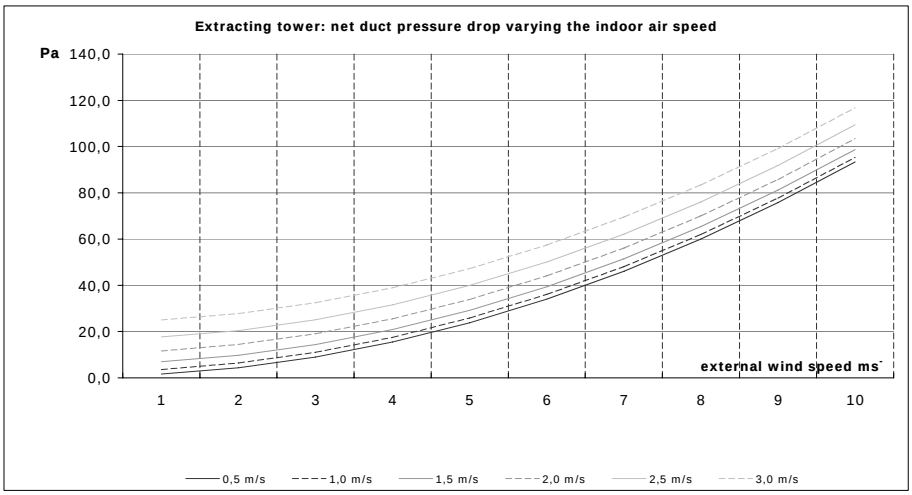

Figure 3. Duct pressure drop to assure comfortably airflow inside buildings, varying the external air speed

3 ANALYSIS

3.1 *Air-flow uptake tower: malqaf structure*

In *malqaf* tower, the upper-openings are oriented toward the prevailing wind and consequently the ΔP_{WS} is positive. Generally, the uptake functioning is possible only if the sum of ΔP_{PG} and of ΔP_{BF} is less then the ΔP_{WS} considering the pressure losses due to the openings design. In traditional architecture this leads to sloping roof design that reduces the energy losses in the inlet section allowing the airflow coming inside the duct. At the same time, the main force contrasting the uptake functioning ΔP_{PG} has to be minimized by means of architectural building design. Courtyards or double-high spaces are introduced to reduce the pressure status in point $B_{2,1}$ and to generate an airflow extraction system inside the building enhancing the tower functioning. Finally, the ΔP_{BF} value has a very low influence respect to the ΔP_{PG} and to the ΔP_{WS}. Moreover, it generates a positive flow if the temperature at the up-section of the duct is lower than the temperature at $B_{2,0}$. In other cases the air flow generated by the ΔP_{BF} is negative.
Some guidelines have been defined starting from this analysis. Figure 2 resumes the three actions in terms of Pascal driving airflow and allows choosing the tower height in accordance to the prevailing wind velocity. The pressure drop due to the upper-opening design is assessable by means of Figure 5 in which the different fitting type effects in terms of Pascal are plotted varying the wind speed.

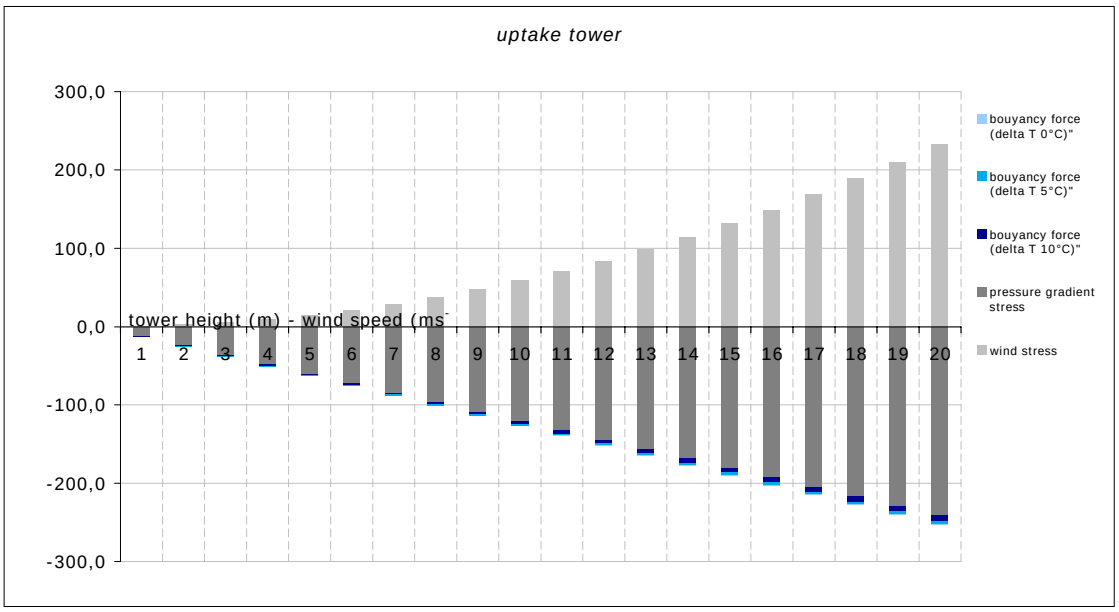

Figure 4. Pressure drop inside the duct varying wind speed and tower height.

3.2 *Airflow extracting tower: the badgir structure.*

A double duct connected to two opposite upper-openings characterizes the most common badgir structure. According to the analysis, the upwind duct generally doesn't work due to the 90° fitting opening design. Indeed the wind pressure in that section is always less than the pressure losses due to that localized phenomena (figure 3). The resulting phenomena is an eddy at the inlet section that prevents the air flow coming in or exiting through the upwind duct.
At the same time the wind action produces a pressure drop on the tower downwind opening section increasing the ΔP_{PG} effect (figure 4). Due to the impact with the tower outline, the wind generates an eddy at the downwind section reducing its own velocity: v_A is less than v_B and the wind effect in the downwind duct is a negative flow. The two most important forces acting in the system produce an up-flow: the tower works always in extracting mode.

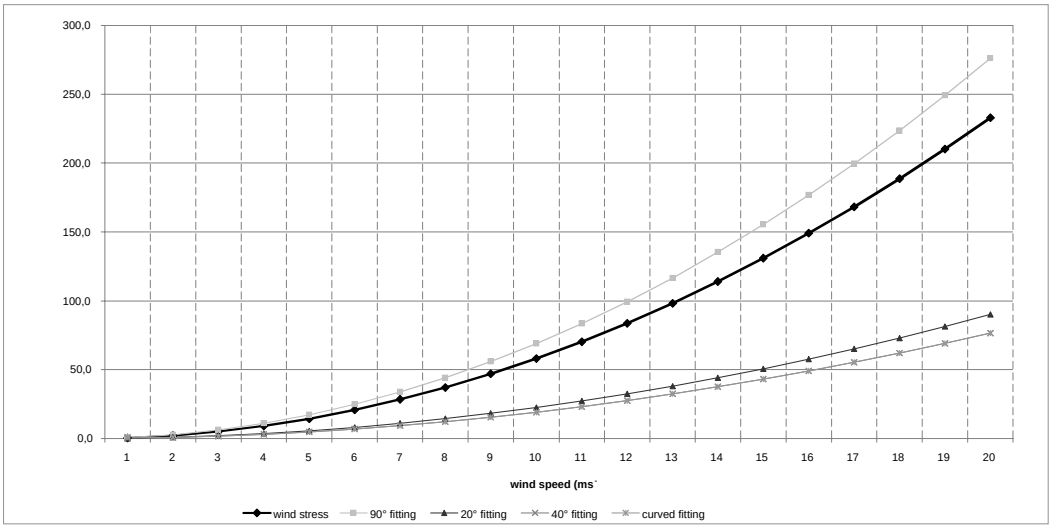

Figure 5. Energy losses due in wind direction change.

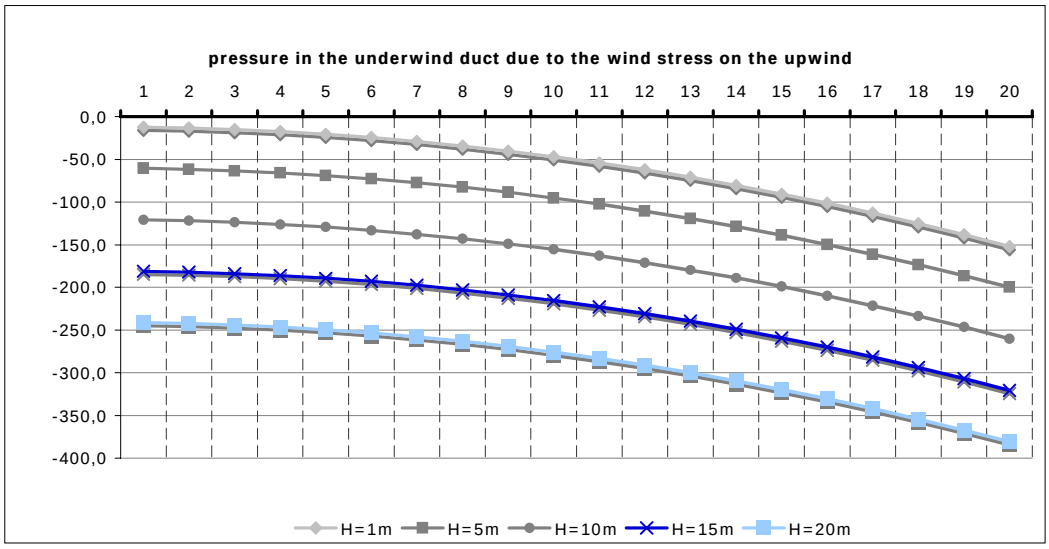

Figure 6. Pressure change in the upwind opening due to the wind stress in the underwind.

The ΔP_{BF} could be positive or negative according to the temperature difference between the outdoor (upper-opening section) temperature and the indoor (bottom-opening section). In hot dry climate where temperature falls down during the evening hours and where building are high mass construction, the ΔP_{BF} effects is positive during the day and negative during the night.
Some guidelines falls the analysis also for the extracting towers. Figure 7 resumes the effects of the three forces driving naturally airflow in accordance with the tower height (ΔP_{BF} and ΔP_{PG}) and the wind speed (ΔP_{WS}). Some considerations are needed to pre-size the system. The wind speed data refers to the undisturbed flow hence the input airflow speed is lower than the wind speed from national databases. At the same time the ΔP_{PG} must be increased according to the pressure value in figure 5. This figure shows the pressure drop at point $A_{1,0}$ due to the wind action in the upwind duct. Different trends are plotted according to different tower height and varying wind speed.

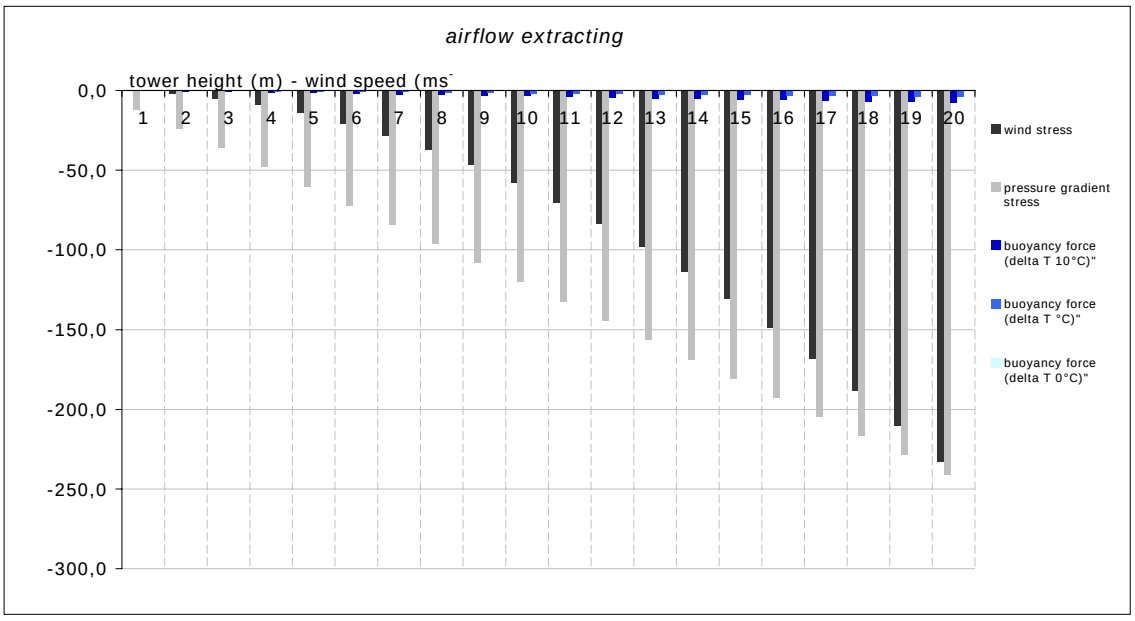

Figure 7. Pressure drop inside the duct varying wind speed and tower height.

4 DISCUSSION

Starting from the initial assumptions, the present work allows understanding the main mechanisms that influence wind tower design and functioning. The results can be used as a pre-sizing method, even if further analyses are needed from a comprehensive point of view. Research developments can regard the study of material influence and tower exposure to sunlight influence on the temperature trend inside the duct and, consequently, on the buoyancy actions. At the same time more complex building systems could be analyzed by means of CDF simulations to find out some relations between the indoor pressure status and the baric gradient stress.

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Evaluation of the impact of some Portuguese thermal regulation parameters on the buildings energy performance

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ABSTRACT: Due to the high energy consumption associated to the building sector, several legal documents with the aim of promoting energy efficiency have emerged in recent years. Some of these documents led to deep changes in the way that buildings are designed. The Portuguese thermal regulation for residential buildings (RCCTE) is a good example of that.
The main objective of this paper is to analyze the RCCTE with the purpose of identifying the parameters that most influence the energy performance of buildings and in what way they interfere with the achievement of their final energy label.

1 INTRODUCTION

During recent years it has become clear that emissions produced by fossil fuels, used to satisfy the globally growing energy needs, are causing dangerous climate changes on our planet. The consequences of global warming are alarming and possibly will become catastrophic. The production and use of energy are responsible for 94% of CO_2 emissions (Isolani, 2008), so the use of energy in a rational way is one of the paths to follow in order to minimize these problems.

The building sector is responsible for consuming approximately 40% of final energy in Europe. However, more than 50% of this consumption can be reduced through energy efficient measures (ADENE, 2009).

Aware of this situation, the European Commission has been promoting relevant measures to improve the energy performance of buildings. The European Directive nº2002/91/CE, Energy Performance Building Directive (EPBD), recently updated by 2010/31/EU (EPBD Recast), is an example of that. The EPBD was transposed into the Portuguese legislation through the review and subsequent adaptation of the thermal regulation constituted by three decrees (Decree-law no. 78/2006, Decree-law no. 79/2006 and Decree-law no. 80/2006).

The purpose of this paper is to select the most relevant parameters that interfere in the energy labelling calculation of residential buildings and evaluate which of them have the strongest impact and in what way they are related to their final energy rating achieved.

2 METODOLOGY

For residential buildings, some parameters were chosen and a parametric analysis was carried out based on a case study building in order to assess their influence on the building thermal performance. This case study is a four room detached single family house with a heated area of 271.57 m^2. It is located in Ponte de Lima (Northwest of Portugal) at an altitude of 74m and about 25km way from the Atlantic Ocean coast. According to the Portuguese legislation, the climatic region of this building is I2, V2 North (between the most severe, I3 V3, and the mildest, I1V1, climatic regions) and its thermal inertia is classified as strong. The case study building, that will be referred as the reference solution, verifies all the legislative thermal requirements and its energy label is B- (low thermal quality – is the minimum allowed for new buildings).

The parameters analysed were the following: i) the heat transfer coefficient (U) of walls and slabs belonging to the exterior and interior envelope, thermal bridges and windows; ii) the number of indoor air changes per hour; iii) the windows solar factor; iv) the shading factor (Fs) of vertical and horizontal windows; v) the external walls absorption factor (α); vi) the efficiency of Domestic Hot Water (DHW) preparation systems (ηa); vii) the contribution of solar systems to DHW preparation (Esolar); viii) the heating system efficiency (ηi) and; ix) the cooling system efficiency (ηv).

For each of the abovementioned parameters, alternative solutions to the conventional reference solutions were investigated. The selected alternative solutions include at least one high-performance solution, one low performance solution and two other different solutions. In any case, all the selected solutions are used and marketed in Portugal.

After selecting all the solutions to be simulated, the energy calculations were performed according to the Portuguese residential buildings regulation methodology. The influence of each parameter on the building final energy label achieved will be discussed and shown bellow.

3 RESULTS

The detailed analysis performed to the exterior walls heat transfer coefficient will be explained as an example. The results obtained for the other studied parameters will be only presented and discussed.

3.1 *Heat transfer coefficient*

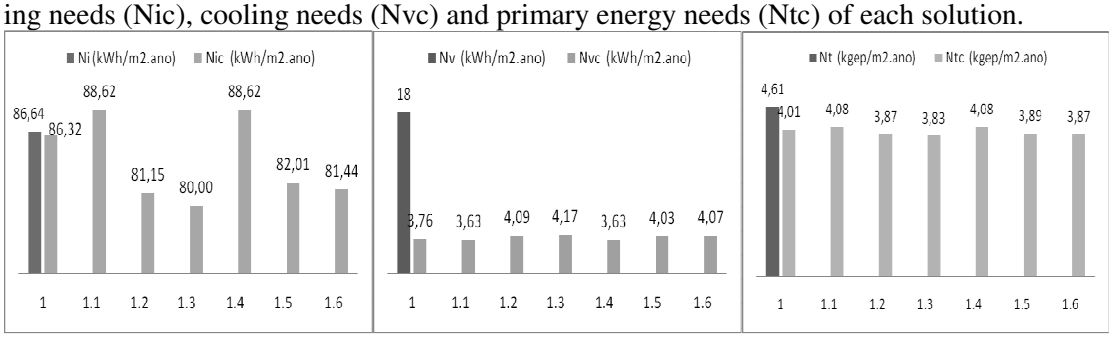
3.1.1 *Walls belonging to the exterior envelope*

The solutions presented in Table 1 were used to carry out the analysis of the influence of the heat transfer coefficient of walls belonging to the exterior envelope. Two types of construction solutions, double walls and External Thermal Insulation Composite Systems (ETICS), were studied. These two construction systems were chosen because they are the most current solutions used in Portugal nowadays.

Table 1. Solutions under study to analyze the exterior walls heat transfer coefficient influence.

Solution	U (W/m^2·ºC)
1 – Reference Solution: Double masonry wall 15+11(cm) with 4cm of extruded polystyrene (XPS)	0,50
1.1 - Double masonry wall 15+11(cm) with 3cm of XPS	0,58
1.2 - Double masonry wall 15+11 (cm) with 8cm of XPS	0,32
1.3 - Double masonry wall 22+22 (cm) with 8cm of XPS	0,28
1.4 – ETICS (15 cm) with 4cm XPS	0,58
1.5 - ETICS (15 cm) with 8cm XPS	0,35
1.6 - ETICS (22 cm) with 8cm XPS	0,33

The results obtained for the different exterior walls solutions are presented in Figure 1.
In this figure, the dark grey bar represents the maximum regulatory values for heating needs (Ni), cooling needs (Nv) and primary energy needs (Nt). The light grey bars represent the heating needs (Nic), cooling needs (Nvc) and primary energy needs (Ntc) of each solution.



a) b) c)

Figure 1. Obtained results for the analysed exterior walls solutions for exterior walls. a) Buildind heating needs (Nic). b) Building cooling needs (Nvc). c) Annual primary energy needs (Ntc).

Through the overall results obtained it was possible to verify that the solutions that have better performance in the heating season are those which have the worst performance in the cooling season.

It was also verified that with an increase in the insulation thickness, the influence on the element's U value decreases. At a certain point the increase in the insulation thickness has very limited influence on the element's U value and on the corresponding contribution to the overall heating needs (Nic value).

For the two construction solutions types studied (double masonry walls and ETICS), it was observed that both have similar performance although the double masonry walls have a slightly higher performance. The ETICS system can, however, be considered a viable alternative system to the double walls regarding the building thermal behaviour.

In Table 2 are presented the obtained results of the solutions with high and low heat transfer coefficients and the differences between both.

The Nac index represents the DHW energy needs for the building. However, this index isn't influenced by this parameter.

Table 2. Differences between solutions with high and low heat transfer coefficients (external walls analysis)

	Nic	Nvc (kWh/m^2·year)	Nac	Ntc (kgep/m^2·year)
Umin=0,28W/m^{2}ºC (Solution 1.3)	80,00	4,17	17,12	3,83
Umax=0,58W/m^{2}ºC (Solution 1.1)	88.62	3,63	17,12	4,08
Variation on energy needs	8.62	0,73	0,00	0,25

It can be observed that the exterior walls heat transfer coefficient has a relevant influence on the Nic value. The solutions with the higher and the lower values of U lead to a significant variation of the Nic value.

It was also verified that the influence of this parameters regarding summer comfort conditions is not negligible. The final energy label of the building is achieved from an index directly proportional to primary energy needs. Thus, as this parameter has a small influence as regards to primary energy needs, it has also a small influence on the final rating of the building.

3.1.2 *Walls belonging to the interior envelope*

The walls belonging to the interior envelope don´t have, in the reference solution, any influence regarding to energy indexes, since they all are in contact with a non-heated space where the coefficient τ is zero, which means that this non-heated space is at the same temperature as the building (20ºC). However, any modification on their constitution will have impact on the thermal inertia of the building. Because of this, four solutions were studied corresponding to different thicknesses of the brick used. Nevertheless, it was verified that the thermal inertia class did not change and so these elements have no influence on the final energy label of the studied building.

3.1.3 *Slabs*

The influence of the slabs heat transfer coefficient was studied taking into consideration the existing construction solution on the reference building. Four solutions were considered, three with different insulation thicknesses and one where the position of insulation was changed.

The results obtained with the different heat transfer coefficients considered are presented in Table 3. This table shows three different situations. Two correspond to floor slabs with different types of coating ($U_{(LI1)}$ e $U_{(LI2)}$) and one corresponds to a ceiling slab ($U_{(LS)}$).

Table 3. Differences between solutions with high and low heat transfer coefficients (slabs analysis)

	Nic	Nvc (kWh/m^2·year)	Nac	Ntc (kgep/m^2·year)
$U_{(LI1min)}$=0,20; $U_{(LI2min)}$=0,32 e $U_{(LSmin)}$=0,34 (Slab with 8cm of XPS)	76,37	3,76	17,12	3,72
$U_{(LI1max)}$=0.60; $U_{(LI2max)}$=0,58; $U_{(LSmax)}$=0,67 (Slab with 3cm of XPS)	92,25	3,76	17,12	4,18
Variation on energy needs	15,88	0,00	0,00	0,46

The results presented in Table 3 show how this parameter has a significant influence on heating demands and comfort conditions in the heating season.
However, these results may not be so expressive in other building types because these results are due to the large contact area of the ceiling slab with a non–heated space, which leads to substantial heat losses. This situation is not characteristic of many Portuguese buildings.

3.1.4 *Thermal bridges*

The heat transfer coefficient of the thermal bridges was analysed considering different thermal insulation thicknesses. Table 4 shows the solutions studied.

Table 4. Differences between solutions with high and low heat transfer coefficients (thermal bridges analysis)

	Nic	Nvc (kWh/m^2·year)	Nac	Ntc (kgep/m^2·year)
Umin=0,32W/m^{2}ºC (Plane thermal bridges with 8cm of XPS)	86,16	3,77	17,12	4,01
Umax=2,00W/m^{2}ºC (Plane thermal bridges without insulation)	86,86	3,73	17,12	4,03
Variation on energy needs	0,70	0,04	0,00	0,02

The values shown in the table show that the building energy needs are not significantly influenced by the thermal bridges heat transfer coefficients. This is because in the reference solution the thermal bridge area is small. Therefore, if other buildings have larger thermal bridge areas, these elements might have a bigger influence on their comfort conditions, especially when they are not treated.

3.1.5 *Glazing*

In this case different types of glass and window frames were analysed taking into account some windows solutions described on the official publication ITE50. Table 5 shows the solutions studied.

Table 5. Differences between solutions with high and low heat transfer coefficients (glazing)

	Nic	Nvc (kWh/m^2·year)	Nac	Ntc (kgep/m^2·year)
Umin=2 W/m^{2}ºC (Double glass, plastic window frames without thermal break)	81,91	4,32	17,12	3,89
Umax=4,1 W/m^{2}ºC (Simple glass, Metal window frames without thermal break)	90,33	3,31	17,12	4,12
Variation on energy needs	8,42	1,01	0,00	0,23

The building comfort conditions in both heating and cooling seasons are influenced by this parameter, as shown in Table 5.

3.2 *Number of indoor air changes per hour*

The study of the influence of the indoor air changes rate (Rph) was performed taking into consideration the existence, or not, of three items: window frames labelled by EN12207, air admission devices on the facade and mechanical ventilation.

Table 6. Diferences between solutions with high an low number of indoor air changes per hour

	Nic	Nvc (kWh/m^2·year)	Nac	Ntc (kgep/m^2·year)
Rph $_{min}$=0,66 (mechanical ventilation)	74,35	6,52	17,12	3,69
Rph $_{max}$=0,95 (Window frame without classification and without air admission devices on the facade)	86,32	3,76	17,12	4,01
Variation on energy needs	11,97	2,76	0,00	0,32

Observing the results in Table 6 it is possible to verify the significant influence this parameter has in both heating and cooling seasons. However, when regarding the energy labelling this influence is not so significant.

3.3 *Windows Solar factor*

The thermal regulation calculations include different solar factors both for cooling and heating seasons. The study for the summer solar factor consisted on the analysis of different kinds of glass and external solar protections. The winter solar factor was studied through the analysis of different types of internal solar protections.

3.3.1 *Summer Solar Factor (g_{Summer})*

Table 7. Diferences between solutions with high an low solar factor (glass type analysis)

	Nic	Nvc (kWh/m^2·year)	Nac	Ntc (kgep/m^2·year)
g_{Summer} min=0,43(Double glass – reflective, coloured in mass + clear glass (4mm+8mm)	86,32	2,69	17,12	4,00
g_{Summer} max=0,59 (Simple Glass - clear glass 4mm)	89,53	4,16	17,12	4,11
Variation on energy needs	3,21	1,47	0,00	0,11

The variation in the glass type has significantly influenced the cooling needs. As in the previous studies, the Ntc variation is low, meaning that the influence of the glass type on this index is small.

Table 8. Diferences between solutions with high an low solar factor (external protection analysis)

	Nic	Nvc (kWh/m^2·year)	Nac	Ntc (kgep/m^2·year)
g_{Summer} min=0,25 (External light wooden shutters and double clear glass)	86,39	1,43	17,12	3,99
g_{Summer} max=0,55 (Internal dark wooden shutters and double clear glass)	86,39	3,76	17,12	4,01
Variation on energy needs	0,00	2,33	0,00	0,02

The influence of external solar protection on Nvc value is even greater than the glass type influence. However, regarding to primary energy needs and to building energy label this influence is small.

3.3.2 *Winter solar factor (g_{Winter})*

As shown in Table 9, the interior solar protection has a little influence over the comfort conditions of heating season. However, as in many previous parameters the Ntc index is slightly influenced by these elements.

Table 9. Diferences between solutions with high an low winter solar factor

	Nic	Nvc (kWh/m^2·year)	Nac	Ntc (kgep/m^2·year)
g_{Winter} min= 0,30 (Light wooden shutters (opaque) with simple clear glass)	91,67	3,76	17,12	4,17
g_{Winter} max=0,70 (Very transparent light curtains and simple clear glass)	85,19	3,76	17,12	4,01
Variation on energy needs	6,48	0,00	0,00	0,16

3.4 *Shading factor*

The study of the influence of the shading factor was carried out by evaluating the effects of horizontal and vertical shading elements. To do so, several shading elements with different sizes were evaluated in the main building's orientations.

3.4.1 *Horizontal Shading (Fo)*

Table 10 shows that the horizontal shading devices influence on both Nic and Nvc indexes. However, this influence is greater when regarding to cooling needs. It was verified that the shading solutions which decrease the Nic index increase the Nvc index.

Table 10. Diferences between solutions with high an low α value (horizontal shading analysis)

	Nic	Nvc	Nac	Ntc
		(kWh/m^2·year)		(kgep/m^2·year)
Fo min (Without shading α=0º)	85,72	4,32	17,12	4,00
Fo max (All windows shaded with α=60º)	89,32	2,07	17,12	4,08
Variation on energy needs	3,60	2,25	0,00	0,08

Note: α is the angle between the plane of the glass and the line joining the glass midpoint to the edge of the horizontal shading device.

3.4.2 *Vertical shading (Ff)*

The vertical shading devices have little influence on both cooling and heating needs. When regarding to cooling needs, horizontal shading devices have higher influence than vertical shading devices (Table 10 and Table 11).

Table 11. Diferences between solutions with high and low α value (vertical shading analysis)

	Nic	Nvc	Nac	Ntc
		(kWh/m^2·year)		(kgep/m^2·year)
Ff min (Without shading, β=0º)	85,15	3,78	17,12	4,01
Ff max (All vain shadows with β=60º)	88,47	3,30	17,12	4,07
Variation on energy needs	2,32	0,48	0,00	0,06

Note: β is the angle between the plane of the glass and the line joining the glass midpoint to the edge of the vertical shading device.

3.5 *External walls absorption coefficient*

The influence of the external walls absorption coefficient (α) was evaluated through the analysis of three kinds of paint colours – light, medium and dark – as described in the regulation.

Table 12. Diferences between solutions with high an low α value

	Nic	Nvc	Nac	Ntc
		(kWh/m^2·year)		(kgep/m^2·year)
α min=0,4 (External walls with light colour finishing)	86,39	3,76	17,12	4,01
α max=0,8 (External walls with dark colour finishing)	86,39	5,05	17,12	4,02
Variation on energy needs	0,00	1,29	0,00	0,01

The comfort conditions in cooling season are considerably influenced by this parameter as shown in Table 12. Moreover, the Ntc index is once again slightly influenced by the variation of a parameter.

3.6 *DHW preparation systems efficiency*

To evaluate the influence of the DHW preparation systems efficiency (ηa), several equipments, with different efficiencies and fed by different fuels, were studied.
The study enabled to observe that the equipment with worse efficiency is the one that leads to the greater Nac index but it is not the one that leads to the higher primary energy needs. This fact is the reason why the results of the parametric study performed for this parameter are presented in two tables instead of one.

Table 13. Diferences between solutions with high an low ηa

	Nic	Nvc	Nac
		(kWh/m^2·year)	
ηa $_{min}$=0,65 (Gas boiler)	86,32	3,76	17,2
ηa $_{max}$=1,09 (Gas boiler)	86,32	3,76	6,21
Variation on energy needs	0,00	0,00	10,91

Table 14. Differences between solutions that lead to a high and a low Ntc

	Ntc
	(kgep/m^2·year)
Ntc $_{max}$ (Electric heater η=1)	4,76
Ntc $_{min}$ (Gas boiler, η=1,09)	3,07
Variation on primary energy needs	1,69

Through the results recorded in Table 13 and Table 14 the big influence of this parameter is clear both in Nac index and in primary energy needs.

3.7 *Contribution of solar systems to DHW preparation*

The contribution of solar systems to DHW preparation (Esolar) was assessed through different solar collectors' analysis. The analysed collectors were selected from the database of the official SOLTERM 5.0 software, being the ones with the best and the worst circulation systems and thermosiphon systems.

Table 15. Diferences between solutions with higher an lower Esolar

	Nic	Nvc	Nac	Ntc
		(kWh/m^2·year)		(kgep/m^2·year)
Esolar $_{min}$ = 0 (Without solar collectors)	86,39	3,75	27,02	4,86
Esolar $_{max}$ = 2153kWh (Collector "CPC Ao Sol" – forced circulation)	86,39	3,75	17,12	4,01
Variation on energy needs	0,00	0,00	9,90	0,85

The results in Table 15 proof the high influence of the solar collectors both on Nac index and on primary energy needs.

3.8 *Heating system efficiency*

The heating system efficiency (ηi) study was preformed through the analysis of several equipments with different efficiencies and fed by different fuels.

Table 16 – Diferences between solutions with high an low ηi

	Nic	Nvc	Nac	Ntc
		(kWh/m^2·year)		(kgep/m^2·year)
ηi max = 4,46 (Heat pump)	86,39	3,75	17,12	2,07
ηi min =1(Electrical resistance)	86,39	3,75	17,12	4,01
Variation on energy needs	0,00	0,00	0,00	1,94

The values recorded in Table 16 show that the heating system is one of the elements that most influences the primary energy needs and the final energy rating of the building.

3.9 *Cooling system efficiency*

To evaluate the cooling system efficiency (ηv) different air conditioning systems were considered.

Table 17. Diferences between solutions with high an low ηv

	Nic	Nvc	Nac	Ntc
		(kWh/m^2·year)		(kgep/m^2·year)
ηv Max (air conditioning systems with η=5.15)	86,32	3,76	17,12	4,01
ηv min (air conditioning systems with η=3)	86,32	3,76	17,12	4,00
Variation on energy needs	0,00	0,00	0,00	0,01

The results presented in Table 17 enable to confirm that cooling system efficiency has a small influence on Ntc index. This fact is due to the small value of the cooling needs and to the high efficiency of all studied systems. However, there were only studied the most common equipments in Portugal.

4 CONCLUSIONS

The carried out study allowed verifying that the parameters which have a greater influence on heating energy needs were: the external walls, the slabs and glazing heat transfer coefficients and the indoor air changes rate. However, the windows solar factor had also a relevant influence on these needs.

In what concerns cooling needs, the most influent parameters were: the windows solar factor, the indoor air changes rate and the shading factor (especially horizontal shading devices).

Only two of the studied parameters interfered in the DHW energy needs: the contribution of solar systems to DHW preparation and the DHW preparation systems efficiency.

When regarding to the primary energy needs, the most influent parameters were: the heating systems efficiency, the contribution of solar systems to DHW preparation and the DHW preparation systems efficiency. Due mainly to political reasons, translated in the regulation calculations, the parameters related with DHW preparation have a huge influence on the primary energy needs, in opposition to the cooling and heating needs provoked by the envelope. For this reason, the importance of parameters related with the envelope performance is low.

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New Performing Art Centers of the World and Sustainability Concept

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ABSTRACT: Today, sustainability is becoming one of the most important design criteria of architectural design, by the increase of the awareness degree of people about living in a sustainable environment, especially while designing a public building such as opera house, theatre house, concert hall, library etc. With this idea, in the paper, it is aimed to examine the most recent examples of performing art spaces from the point of view sustainable design. Also by examining these important examples it is aimed to emphasize the importance of whole building approach and to show that it is possible to design public spaces with interesting architecture and strict user demands while considering the sustainable design.

1 INTRODUCTION

Since it is discovered that World has limited sources that human beings need, sustainability is (must be) one of the most important criteria of life. This idea also indicated in the report of World Commission on Environment and Development (widely known as Brundtland Report) in 1987: "*…sustainable development, which implies meeting the needs of the present without compromising the ability of future generations to meet their own needs, should become a central guiding principle of the United Nations, Governments and private institutions, organizations and enterprises"* (United Nations, 1987)

Sustainable development concepts have been also applied to the design, construction, and operation of buildings, due to the fact that they cause many damages or changes in the environment. This issue was also underlined in 1993 by The Union Internationale des Architects/American Institute of Architects (UIA/AIA) in Declaration of Interdependence of World Congress of Architects; "If sustainable design principles are incorporated into building projects, benefits can include resource and energy efficiency, healthy buildings and materials, ecologically and socially sensitive land use, transportation efficiency, and strengthened local economies and communities" (Abraham et.al., 1996). For that reason it is very important to consider sustainability concept from the beginning of design phase to the material selection while designing any kind of building.

Performing art centers, which constitute the subject of this paper, are very important images of the urban context. It can be said that since beginning of theatre art in ancient times, theatres, opera houses and concert halls have been very important landmark for the city and indispensable part of cultural life. Many performing art centers, especially opera houses have been built since the beginning of the 21st century all around the World and they have been attracting many people. It can be said that many of them have been designed considering the sustainability concept or at least regional climatic specifications. These public buildings with thousands of visitors are expected to help disseminating the ecological concepts used in the buildings and emphasize the importance of sustainable design to a very wide range of people.

2 EVALUATION OF CASES FROM THE POINT OF VIEW SUSTAINABLE DESIGN

There are many descriptions and principles about sustainable/ecological/green architecture in literature. Although the main goal of architecture (to create a built environment in which people can feel comfortable) meet some of these principles, for creating a sustainable construction there are some more criteria. The three principles of sustainable design are listed basically as economy of resources, life cycle design, and humane design, which are believed that provide a broad awareness of the environment issues associated with architecture (Kim & Rigdon, 1998).

Buildings for performing arts like opera or theatre houses and concert halls usually as a result of quite long and detailed design and construction period due to the fact that they are important public spaces and usually landmarks within the urban context as mentioned before. Within such a cultural complex, quite complicated facilities have to be considered together and connected while dealing with the user demands and/or strict codes.

In this context, some of the most famous performing art centers are examined and it is seen that it is possible to consider sustainability while dealing with the other requirements. While selecting examples, it is aimed to choose centers that have been built in different regions of the World. One of the selected cases within the paper is Oslo Opera House which was completed in 2008. Second one is Royal Playhouse of Denmark and both of the buildings were already built as a part of a project named Eco-Culture. Another important opera house is the Margot and Bill Winspear Opera House which has been opened in 2009 in Dallas, USA. The building is a design of a world-famous architect Norman Foster. Another selected project considering the environment as the main design criteria is The Stavros Niarchos Foundation Cultural Center, which has been designed by Renzo Piano. In addition, only opera house of Arabian Peninsula is selected as a case, since it has been designed in Oman by using mostly the local materials and considering the climate of the region.

Figure 1. New opera house, Oslo – (exterior view of the building, photo from the construction period in 2007)

Figure 2. Royal playhouse, Copenhagen – exterior view of the building (The Royal Danish Theatre, 2008).

2.1 *New opera house, Oslo, Norway*

The new house of Oslo Opera (Figure 1) is designed by Norwegian firm Snohetta who won the 1st prize among the 240 entries of the international architectural competition for design of new National Opera House in 2000 (MacKeith, 2008). There are three stages in the new opera house; The Main Stage with approximately 1400 seats, secondary stage with approximately 440 seats and the third one with 200 seats. The sloped roof of the building is designed to create the sense of more accessible opera house (Snohetta, 2008). On the line between the sea and ground, construction of this monumental building which rises as a part of fjord completed in 2008. The result is quite distinctive and even it is thought that "the building brings to mind typological and urbanistic features of other, similar structures, from the grand staircase and sense of public areas of Charles Garnier's Paris Opera House (now Palais Garnier) in Paris (1875), to Jorn Utzon's iconic soaring forms and civic plazas of the Sydney Opera House (1963–73) in Australia" (MacKeith, 2008).

The building has been selected for demonstration of energy efficiency technologies/ solutions within a European Commission project shortly named as Eco-Culture. These technologies are listed as (European Commission- Eco-Culture Project, 2010);

- Demand controlled and energy efficient distribution of ventilation, including humidity control;
- Control strategies for glass facade, light, ventilation, heating and cooling to improve use of daylight and passive heating and cooling;
- A south facing glass facade with solar cells.

From the point of view architectural design, glazed facades of building have a nice contrast with the sloped massive surface of the roof. On the other hand, large glazed south facing facade in the foyer causes over-heating without shading. To solve this problem, a 400 m2 solar cell grid, which provides both shading and electricity integrated in façade. These solar cells are the most visible part of the energy system and help to introduce technology to a large audience. (European Commission- Eco-Culture Project, 2010)

2.2 *Royal playhouse, Copenhagen, Denmark*

In 2008 another important performing arts center was rising near the sea, but this time it was in Copenhagen; “The Royal Playhouse”(Figure 2). Its grand opening was on 16 February with the premiere of "Hamlet". The construction of the building had started in October 2004. The architect of the Playhouse is Arkitektfirmaet Lundgaard og Tranberg A/S. In total building area, building has three stages with capacities of 750, 200 and 100 seats as well as a foyer with restaurants and facilities of the backstage (Lundgaard & Tranberg Arkitekter A/S, 2008) (The Royal Danish Theatre, 2008).

Like Oslo opera, Royal Playhouse in Copenhagen has been built as a part of Eco-culture project which is considering mainly energy efficiency in cultural buildings. And demonstrated technologies within the Playhouse are listed as;

- Integrated 'climate belt' energy storage using thermo active slabs;
- Optimized heat pump and seawater cooling;
- Optimized and intelligent controlled ventilation system, including BeMS;
- Environmental friendly building materials - environmental friendly concrete ("green concrete").

Generally, the building has been designed as a building with low energy consumption. Again ventilation systems are very important part of energy savings. In the project, six different ventilation systems are used with very strict demands on acoustics and comfort level. The project is expected to improve the state-of-the-art by increasing the demand controlled part of the ventilation, by highly efficient heat recovery rate using regenerative heat recovery systems and by heat pumps with storage of surplus heat/cooling in the thermo active slabs. When possible, however, the building uses free cooling from the seawater, which is placed adjacent to the building (European Commission- Eco-Culture Project, 2010).

2.3 *Winspear opera house, Dallas, USA*

Opera house is designed as the focal point of new cultural complex of Dallas which also includes the Dee and Charles Wyly Theater, the Booker T Washington High School, the Morton H. Meyerson Symphony Center and in the future, the new City Performance Hall. The masterplan was designed by Foster + Partners and OMA with Michel Desvigne (Foster and Partners, 2009).

With the designer(Foster and Partner)’s words “The new Winspear Opera House in Dallas redefines the essence of an opera house for the twenty first century, breaking down barriers to make opera more accessible for a wider audience”. Organizationally, the building creates a transparent, publicly welcoming series of spaces, which wrap around the rich red glass drum of the 2,200-seat horseshoe shaped auditorium (Figure 3-4). The transparent façade also make the shiny red skin of the main auditorium visible from outside as an exhibition object. During the design process it is aimed that the building will be attractive even for the non-opera going public, with a restaurant and café that is publicly accessible throughout the day (Foster and Partners, 2009).

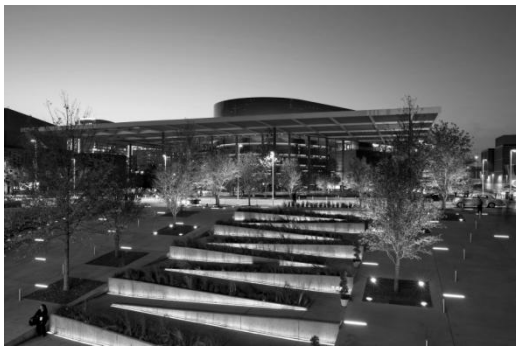

Figure 3. Winspear opera house, Dallas – Exterior view of building and recreation area in front of the opera (Foster and Partners, 2009).

Figure 4. Winspear opera house, view of canopy which helps to obtain cool, shaded microclimate (Foster and Partners, 2009).

Punctuated with indigenous trees, the canopy provides a cool, shaded microclimate to the public areas beneath. Vertical sliding glass panels moving the full length of the east façade allow the building with its cafe and restaurant to be fully opened up, further enhancing the transitional inside-outside nature of the space (Foster and Partners, 2009).

2.4 *Royal opera house, Muscat, Oman*

A select group of international design firms were invited by the Royal Court Affairs of the Sultanate of Oman to compete for the design of the project in 2003 and after a number of competitive stages, WATG won the international design competition (Wimberly Allison Tong & Goo, 2007). In designer's words; the challenge was to design a unique and distinctive upscale venue for a 1,000-seat concert hall in a new urban district which could also be used for musical, theatrical and operatic productions. Construction period has been started in 2007 and the building is planned to open at the end of 2010 (Kola, 2009).

According to the project director of Royal Opera House "The design is a blend of traditional Omani architecture with a contemporary touch (Figure 5). External facade will be cladded with Omani desert rose stone, while the interior decor will be unique with a touch of traditional Arabic design ... the stage will be extremely flexible, able to accommodate symphony concerts, recitals, chamber music, as well as fully staged productions of opera, dance, musicals and other aspects of more popular entertainment." Nearly 50 percent of building area is left for landscaping for gardens (Kola, 2009). Flexibility of the stage is achieved by designing the concert hall's shell as a mobile structure that can be detached to allow an adjustable proscenium to drop into place to create a traditional theatre format. The building design has evolved with these large moving structures to create a unique adaptable volume, which gives the venue unparalleled natural acoustic potential. (Wimberly Allison Tong & Goo, 2010).

Figure 5. Royal opera house, Muscat – Simulation of exterior view of building (Wimberly Allison Tong & Goo, 2010).

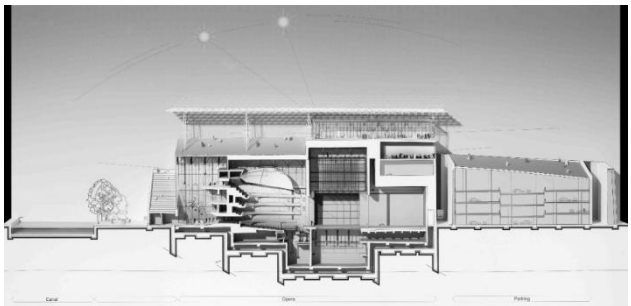

Figure 6. Stavros Niarchos Foundation Cultural Center, Athrns – Longitudinal Section of building (Pesavento & Piano, 2010).

2.5 *The Stavros Niarchos Foundation cultural center, Athens, Greece*

The Stavros Niarchos Foundation Cultural Center is intended to be a cultural meeting point for Athens with two main facilities; national opera house and national library. The place of the complex was a harbor in ancient times, although it does not have direct relationship with the sea. Renzo Piano's design aims to recreate the visual and physical relationship between the sea and the cultural complex by digging a canal that will run along the pedestrian axis and past opera and library. Also, visual connection with sea will be strengthening by using an artificial hill which slopes downward to the park (Pesavento & Piano, 2010) (Ozler, 2009).

On this, Piano says: "The Cultural Center's proximity to water, and the natural warm breezes and light of Athens were particularly inspiring during the design process. It was immediately clear that we must take advantage of all these elements to ultimately design a zero emissions building that expresses movement and energy". In addition to integrating with the environmental and climatic conditions, the roof of the center consists in a series of interconnected photovoltaic cell panels which will cover the structure's needs, taking advantage of the pure "green" solar and wind energy, in a similar way to the California Academy of Science (Basulto, 2009).

3 CONCLUSIONS

According to Jason F. McLennan from BNIM Architects (McLennan & Berkebile, 2009); "*…The buildings of the future may not look like flowers but they certainly will not resemble the buildings of today. A new architecture is emerging as an expression of climate and culture while being shaped by technologies that are bio-mimetic in nature. ... Communities in desert regions will be designed to maximize the ability to collect water, and like the plants of the desert retain and conserve that water. In colder climates the focus will shift to retaining heat and capturing the available sunlight. From region to region the focus will change but environmental performance will be constant. ... Exemplary buildings and communities will be restorative, pedagogical and inspirational Living Buildings.*"

And these living buildings will:

- harvest all its own water and energy needs on site
- be adapted specifically to site, and climate and built primarily will local materials
- operate pollution free and generate no wastes that aren't useful for some other process in the building or immediate environment
- promote the health and well being of all inhabitants–consistent with being an ecosystem
- be comprised of integrated systems that maximize efficiency and comfort
- be beautiful and inspire us to dream (McLennan & Berkebile, 2009).

In this context, when the selected cases are considered it will not be wrong to say that they can meet most of the criteria listed above. All the buildings are quite inspiring ones and landmarks that attracting or supposed to attract thousands of people. At the same time, they help to sustainable urban development of surrounding sites. For example, Oslo Opera House is intended to be the first step of the urban transformation of the harbor area while it is aimed to recreate the connection with the sea like in ancient times in the design Stavros Niarchos Cultural Center.

Although it is quite a hard job and a complicated process to make a building self-contained one, it is seen that use of nearby natural elements like sea-water and local plants or by integration of more technological solutions like solar canopies, shading elements, PV ventilation cells, intelligent ventilation systems can help to reduce the energy demands of buildings. And all these elements can be successfully integrated in or become one of main elements of architectural design.

Another criterion for designing a sustainable building is understanding of place; be adapted specifically to site and climate and built primarily with local materials. In Muscat, it is quite distinctive that a fully equipped European style opera house can be built by following the principals of traditional Oman architecture. Winspear Opera is also one of the most successful examples of understanding of place by creating not only an elegant space for opera performance but also creating new outdoor spaces for visitors to gather and relax with a solar canopy that meets the climate of Dallas. Also, the success of integration with the topographic conditions of

site is quite distinctive in the design of Stavros Niarchos Foundation Cultural Center. From the point of view understanding place, Oslo Opera house and Royal Playhouse of Copenhagen are both very important examples of building near the sea.

Clearly, all the buildings are results of hard and collaborative work of experts from different fields such as architects, systems consultants, and engineers. In addition to giving us the chance of experiencing the magical atmosphere of Opera/Drama/Music, they are inspiring us to think about sustainability of our future.

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Monitoring of a close-to-zero energy building

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ABSTRACT: In the recent five years close-to-zero energy houses have appeared also in Eastern Europe. Currently there are some dozens of buildings in Hungary, five of them are qualified passive houses. The qualification of five other buildings are under progress. The paper presents an ongoing monitoring in a close-to-zero energy house near Budapest.
The monitoring started in 2009 summer, thus the data of two summer seasons and one heating season are already available. The purpose of the monitoring is testing the close-to zero energy concept in continental climate. In Hungary extreme outdoor minimum temperatures below -20 ^{o}C and maximum temperatures above 38 ^{o}C can occur. The monitored building was built with polystyrene cells filled with cast concrete. Although this kind of construction is heavy, the concrete does not take part in the daily heat storage processes, because it is "packed" into the polystyrene. Therefore the summer performance was expected to be risky. As a consequence the building was equipped with a ground heat exchanger with liquid heat transfer medium and the HRV ventilation was operated during summer.
The test results are positive: the peak indoor temperatures did not exceed 26 ^{o}C indoors (without active cooling) and in winter the heating energy consumption stayed below 17 kWh/m^{2}a. Since the construction of the building in 2009 several heat supply alternatives as well as heat recovery units have been installed and tested: simple electric radiators, high efficient electric radiators, air heating with heat pump, recuperative and regenerative heat recovery units.
The frequent modification of the systems provided an opportunity to compare the different solutions with the monitoring. Low cost solutions applied in the building are also described in the paper. With a wise management and smart compromises the building owner could keep the construction costs under 750 euros/m^2 that is equivalent to a standard building construction in the country.

1 THE SUNFLOWER BUILDING AND THE MONITORING CONCEPT

The Sunflower house is located near Budapest. The two-storey, 145m^2 house was built with polystyrene cells filled with concrete on site. The heating is provided by heat recovery ventilation. The air is pre-heated by an indirect ground heat exchanger.

An online monitoring was installed and the data collection started on 3 August 2008 and is still running. 10 mobile data loggers are located in different rooms of the house and one data logger is positioned outside. All data loggers measure air temperature, some measure relative humidity and/or surface temperature of building finishes. Additionally the loggers in the large rooms measure illuminance [Lux] in order to follow the user's behaviour in relation with the application of shading devices. In the near future the ventilation system will be equipped with sensors and after the installation of the solar collectors, their performance will be monitored as well.

Figure 1. Winter and summer view of the Sunflower house.

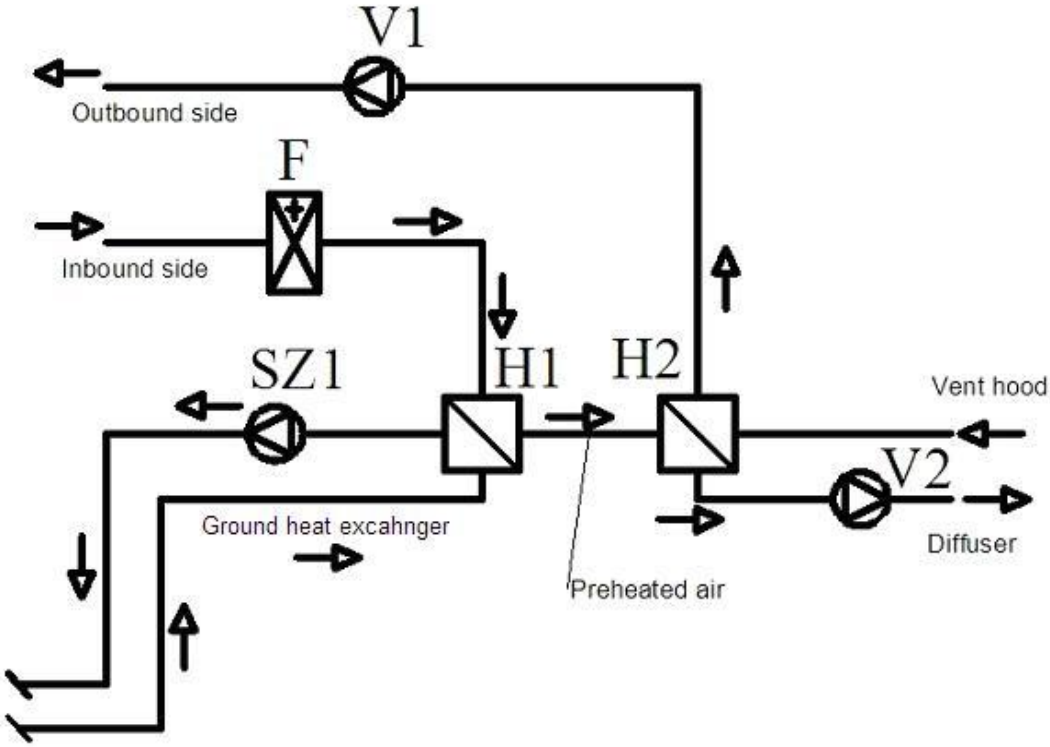

Figure 2. Scheme of the ventilation system of the Sunflower house.

Table 1. Overview of the operation of the different systems.

		Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
Heating	Electric radiators												
	Heat pump												
	ADAX												
DHW	Electric boiler												
	Heat pump												
Ventilation	HRV												
	GHE												
Rainwater	Collection syst.												
Sewage	Depletion biolog.												

2 THE BUILDING SERVICE SYSTEM AND ITS MONITORING

The heating is provided partly by a Helios heat recovery ventilation (HRV) system. The air is pre-heated by an indirect ground heat exchanger (GHE). The ventilation concept is presented in Figure 2.

The remaining heat was covered by three different ways during the heating season. The owner wanted to test different heating options. In the beginning the house was heated only with two ordinary electric radiators. Later it was substituted by a standard quality air-heat pump with heat extraction from the outside air. In February and March high efficiency ADAX radiators were introduced as a parallel heat source beside the heat pump. As an emergency solution, a small 2 kW bio-ethanol fireplace is also installed, but it hasn't been used. In the near future, probably new heating methods will be installed and tested.

In the beginning DHW was produced by an ordinary electric boiler, but after installing the air heat pump it has taken the role of DHW production.

3 THERMAL COMFORT DURING THE YEAR

Figure 3 clearly proves that most of the time of the year the indoor air temperature was between 20 °C and 24 °C and it never dropped under 19 °C, which is the evidence of high level of comfort. It is not our objective to go more into details of the comfort results, because of length restrictions, but the topic will be further disseminated in the near future.

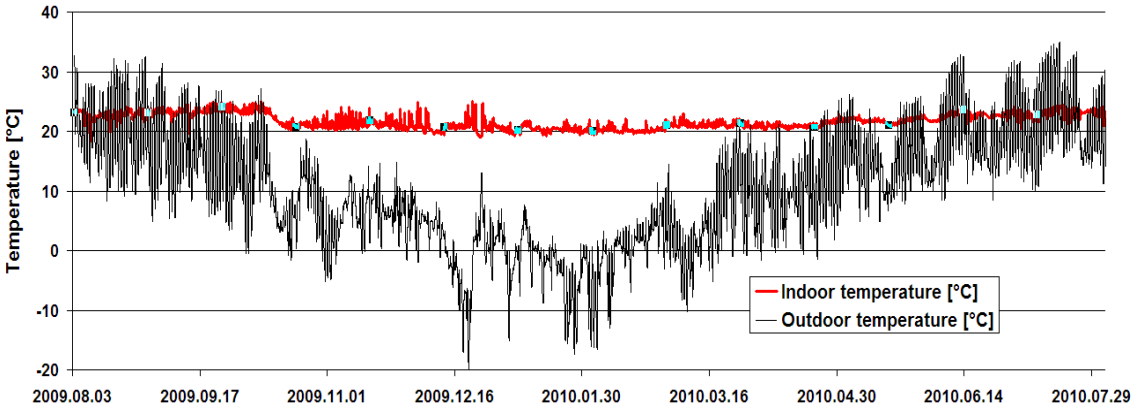

Figure 3. Development of the indoor and outdoor temperatures (03.08.2009-02.08.2010).

4 ANALYSIS OF THE ANNUAL ENERGY CONSUMPTION IN THE SUNFLOWER HOUSE

4.1 *Heating period and heating degree days*

The heating energy consumption of the Sunflower house was higher than it would have been in an average year of the last 18 years (1991-2008) period at the meteorological station of Budapest where the reference data were registered [Figure 4]. The winter of 2009-2010 was significantly colder than the average monthly mean outdoor temperature of 1991-2008. In addition, the site of the building has a particular cold microclimate, the building lays in a valley under a forest.

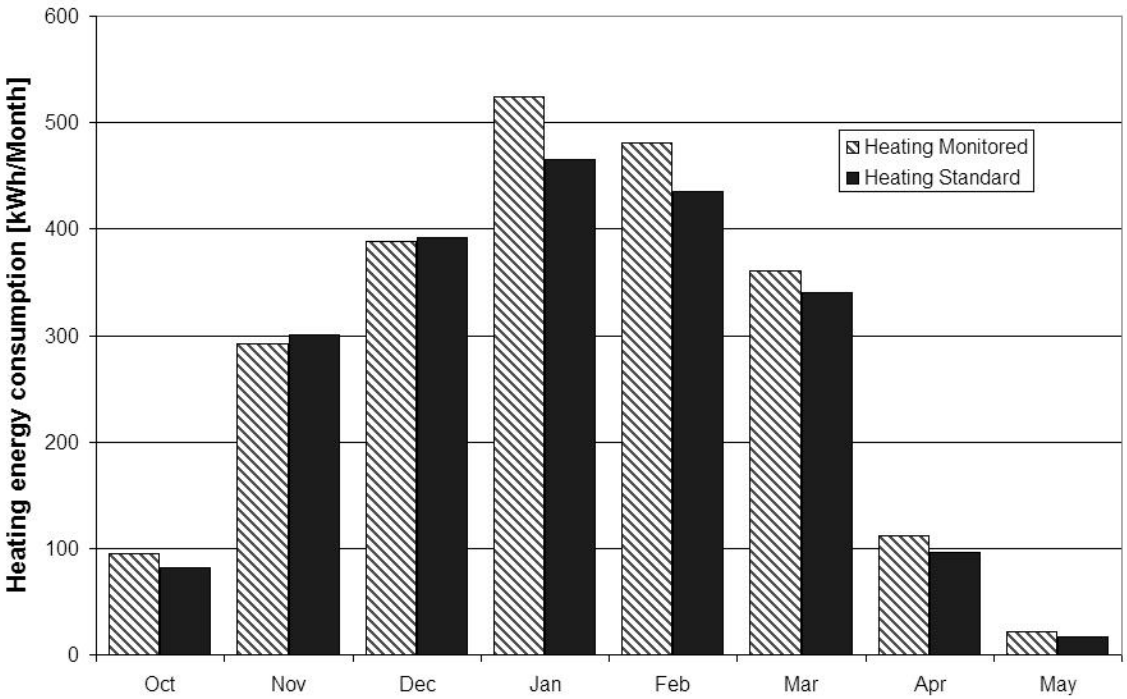

Figure 4. Comparison of the monitored and standard heating period of the Sunflower house (Reference base: Average monthly mean outdoor temperature of 1991-2008).

As the ratio of the average degree days (1991-2008) to the monitored heating degree days is 2998 / 3222= 93%, the below presented heating consumptions should be decreased with 7% to obtain the normalised consumption.

Table 2. Comparison of the monitored and monthly mean outdoor temperatures and heating degree days.

	Monthly Main Outdoor Temperature Monitored	Monthly Main Outdoor Temperature Average	Heating period Monitored Days/Month	Heating period 10ys Average Days/Month	Heating degree days Monitored	Heating degree days 18ys Average
Oct	9,71	11,52	15	15	154	127
Nov	6,03	5,59	30	30	419	432
Dec	0,68	0,48	31	31	599	605
Jan	-2,45	0,28	31	31	696	611
Feb	-0,11	2,00	28	28	563	504
Mar	5,29	6,25	31	31	456	426
Apr	10,11	11,86	30	30	297	244
May	15,24	16,80	**8**	**15**	38	48
			204 Days/Heating period	**211** Days/Heating period	**3222** Days°C	**2998** Days°C

4.2 *Energy consumption of different building units*

Basically the energy consumption contains two main parts. The HVAC+DHW include the heating system, the ventilation system and the domestic hot water system. The domestic usage includes the consumption of the household appliances and the lighting.

The annual energy consumption of the domestic uses is about the 40% of the total energy demand of the Sunflower house.

This is an impressive value in the light of the complex and complicated installation system. Figure 5 and table 3 present the yearly energy consumption structure. The total energy con-

sumption dedicated to heating is the sum of the energy consumption of the three heating types and a part of the energy consumption of the ventilation system as heat recovery covers a significant share of the heat demand. Without heat recovery the conventional heating energy consumption was much higher, but heat recovery needs electric energy for the ventilators therefore it must be taken into account in the balance and dedicated to the heating.

Summing up the energy consumption of only the heating systems the result is 15,71 kWh/m2a. If it is normalised for an average year (1991-2008) the 14,61 kWh/ m2a fulfilling the first passive house requirement (heating energy consumption must be under 15 kWh/ m2a), but it is higher than the calculated value with PHPP (11 kWh/m2a). A probable reason for the difference is described in chapter 4.4.

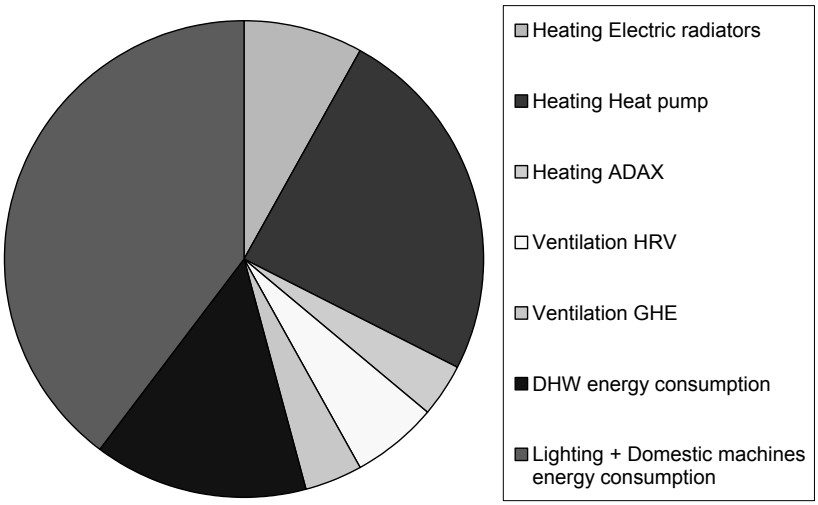

Figure 5. Structure of the consumed electric energy during the one-year period (Heating ADAX: efficient electric radiators, KWL: ventilators in the air-to-air heat recovery units, GHE: circulating pump in the loop of the ground heat exchanger).

Regarding the total primary energy consumption the building fulfils the passive house requirements again. The measured value is 108,7 kWh/m^{2}a, whilst the requirement is 120 kWh/m^{2}a. The PHPP calculation gave 73 kWh/m^{2}a for this value, but it didn't consider any modifications in the heating systems.

4.3 *Comparison of the heating systems*

As *Table 3* and Figure 6 show the different heating systems consumed different amount energy, but they operated in different periods as well, therefore their comparison is possible only with regards to the weather conditions of their operation periods. Table 4 presents the energy consumption of each heating type and the corresponding monthly heating degree days. The last coloumn shows the ration between the consumption and the degree days. If we assume that the heating energy consumption is influenced mainly by the degree days, the higher figures mean lower efficiency. The result is clear: the months when the heat pump operation was dominant the energy consumption was higher. The poor efficiency can be explained by the fact that it is an air heat-pump extracting heat from outside air, which is not recommended in cold period, when the COP figure of such units is very low. In addition the heat pump is probably not a high-efficiency product, as COP-outdoor temperature diagram was not available in the technical description of the product.

Table 3. Structure of the consumed energy during the one-year period (Heating ADAX: efficient electric radiators, HRV: ventilators in the air-to-air heat recovery units, GHE: circulating pump in the loop of the ground heat exchanger). All energy use is electric energy.

		Sum kWh/(m^{2}year)
Heating	Electric radiators	3,53
Heating	Heat pump	10,61
Heating	ADAX	1,57
Ventilation	HRV	2,56
Ventilation	GHE	1,67
DHW	energy consumption	6,27
Lighting + Domestic use	energy consumption	17,27
Total in final energy		**43,48**
Total in primary energy		**108,7**

With other words the figures show that it is not recommended to invest in a poor efficiency air-heat pump extracting heat from outdoor air instead of normal electric radiators. Certainly, there are other heat pump types that are much more efficient and are successfully used in passive houses.

It also has to be mentioned that energy consumption depends also on the solar gains that are lower in winter (when the heat pump was dominating) than in the beginning and in the end of the heating season. This fact would modify the numerical values of calculated the system efficiencies that we did neglected in the above considerations.

4.4 *Performance of the ventilation system*

Basically the ventilation energy consumption can be devided into two parts:

- Energy consumption of the ventilator machine [HRV] in the air-to-air heat exchanger
- Energy consumption of the pump in the ground heat exchanger [GHE]

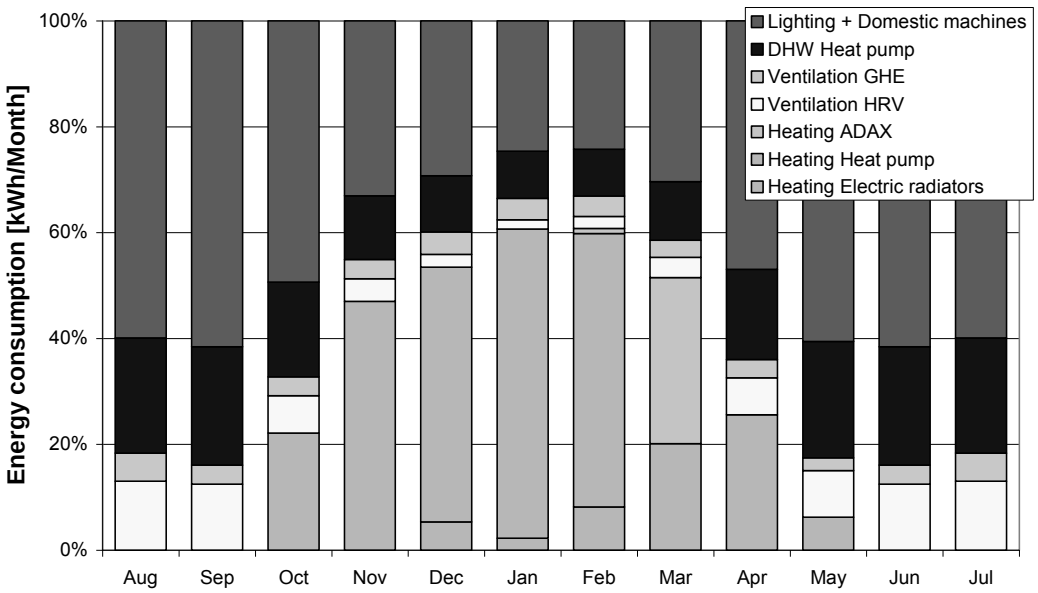

Figure 6. Energy consumption in the Sunflower house with a focus on the applied heating systems.

Table 4. Energy consumption of different heating types and the corresponding monthly heating degree days.

	Heating	Heating	Heating	Heating	Monitored Heating	Heating
	Electric radiators	Heat pump	ADAX	Summa	degree days	consumption/ degree days
	kWh/month	kWh/month	kWh/month	kWh/month	Days°C	kWh/(Days°C)
Oct	95	0	0	95	154	0,61
Nov	293	0	0	293	419	0,69
Dec	39	350	0	389	599	0,64
Jan	20	505	0	524	696	0,75
Feb	65	409	8	481	563	**0,85**
Mar	0	141	220	361	456	0,79
Apr	0	112	0	112	297	0,37
May	0	22	0	22	38	0,57

Seasonally the significance of the energy consumption of the energy using units changes. In winter, the pump of the GHE requires more energy and in summer the ventilators of the HRV-system, because of the different needs. The development of the energy consumption of the ventilator machine follows the changes of the outdoor temperature. The users keep the appliances under control. The HRV is set at a higher airflow level in summer. That is confirmed by the electrical data loggers. The figure shows that the GHE operates also in transition periods when cooling and heating were needed. Ground heat exchanger operates under 5°C, when it is used as a heating machine. If the outside temperature is higher than 20°C, it operates as an cooling machine.

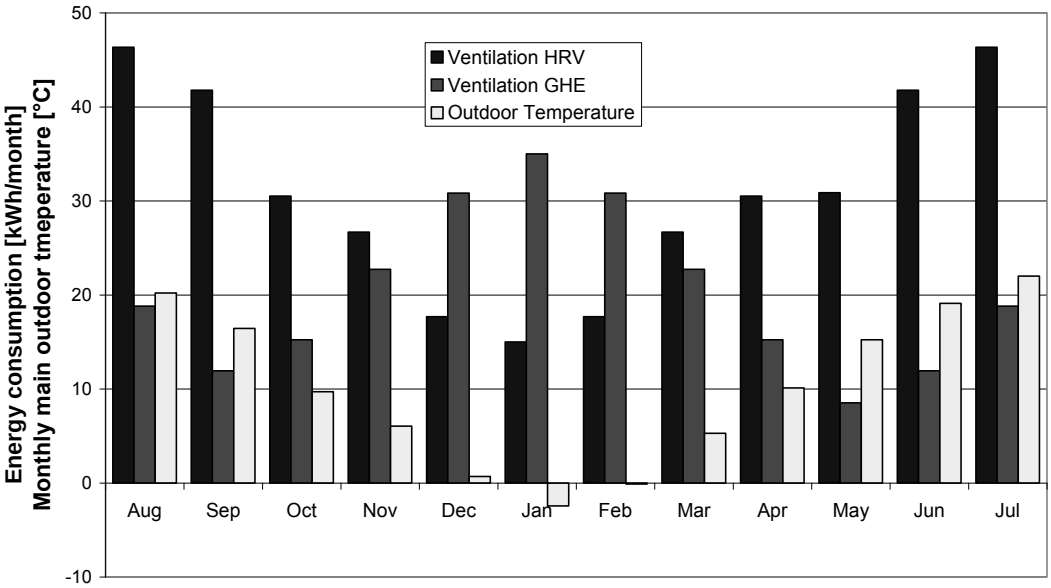

Figure 7. Energy consumption of the HRV and the GHE systems.

5 INVESTMENT COSTS

With a wise management and smart compromises the building owner could keep the construction costs under 750 euros/m^2 that is equivalent to a standard building construction in the country.

The precise grand total investment cost of the Sunflower house is 103 386 €. The two-storey, 145m^2 size building's specific cost is an excellent 713 €/m^2. This value does not contain the land price of the building.

The figures cover all construction costs including not only the energy related costs, but also the cost of the holding structures, surface finishing and sanitary equipments, etc. In Table 5 the "building envelope" covers all costs other than the costs of the heating system and DHW-system.

The tables show that the cost of the passive house HVAC system is only 7,5% of the grand total investment cost.

Table 5. Total and specific investment cost of the Sunflower house.

	Investment costs	Specific investment costs
	€	€/m2
Envelope	95 651	660
HVAC + DHW	7 735	53
Total	103 386	713

6 CONCLUSION

The one-year long monitoring of the Sunflower house proved that the thermal comfort level is of high standard all over the year, even in hot and cold continental circumstances. In addition the building fulfils the passive-house requirements not only in theory, but also in the practice. However, an important negative element was detected that should be avoided in the future: the air heat pump extracting heat from the outside air. If actions were taken to solve this problem, the performance of the building could be even better.

With a conscious financial management and fullness market condition the building owners can keep the investment costs on an equivalent level to standard building construction in the country.

The monitoring will be continued in the future. It is expected that further developments will be made in the installation system and the building envelope by the owner and the monitoring will follow the influence of any modifications.

ACKNOWLEDGEMENT

The publication is supported by the TÁMOP 4.2.1/B-09/1/KONV-2010-0007 project. The project is co-financed by the European Union and the European Social Fund. Authors would like to say thank to István Keszthelyi and the Kamleithner Kft. for providing the monitoring equipment (Kimo instruments), to József Feiler, the owner of the Sunflower house.

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Sustainability Assessment of a Multistorey Steel Structure Located in a Seismic Area

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ABSTRACT: The case of an existing steel structure is analysed, located in a relatively central area of the city of Arad, Romania and made of steel built-up welded elements. The building has been practically abandoned after its partial erection (1993), for a period of about 14 years, with an extremely unfavourable impact on the environment and site architecture. As the roofing and the cladding of the building could not be completed, the exposed steel elements have suffered quite severe influence of climatic factors, typical to an inner continental area (snow, rain, wind, moisture, temperature variations) causing considerable damage to the steel surface. The new owner required to retrofit and restore the damage structure for modern office building purposes. Sustainable design principles were in view when planning the described restoration and their application, as well as their degree of implementing, is briefly discussed in relation with practically available technologies. Furthermore, the analysed practical case is helping to understand the necessity of a "whole building approach" and to try to apply it in further design activity.

1 INTRODUCTION

The reality of the construction market is often offering quite interesting cases, as the one presented in the paper, i.e. an existing building located in the city of Arad (close to the western border of Romania). The steel structure of the building was erected in 1993, in two distinct phases: one initial phase consisting into ground floor plus two floors, followed by a second phase consisting into a supplementary third floor, linked by bolted hinged connections to the top of the previous zone. Prefabricated 19 cm thick concrete hollow strips were used to build the floor decking, however, without succeeding to cover completely the required surface and with practically no connection to the underneath steel beams except the simple support. The initial idea was to build the roofing using tiles on steel skeleton, further on renounced to and replaced by the third floor steel structure, with terrace roof of prefabricated concrete decking. Probably out of economic reasons, the building could not be finished and was abandoned for 14 years in this partially finished phase, without proper roofing and practically with no cladding. This caused an exposure of the steel structure (protected only with a layer of primer) and to the concrete of the prefabricated strips, to climatic factors characteristic to an inner continental area (wind, rain, snow, or quite severe temperature variations) causing metal corrosion. As the site was located near one of the most important transport arteries of the city, quite near to the road, the intense heavy traffic caused vibrations which gradually shifted the simple supported concrete strips and caused some of them to fall down inside the building. All that, combined with an incomplete and improper wind bracing, suggested an insecure and really dangerous location, in degradation, which needed quick intervention.

Furthermore, the prefabricated concrete strips (which were not connected to the metal beam underneath) continued to represent a danger by threatening to fall down again and thereby cause fatal accidents under the continued action of vibrations induced by traffic.

The ground floor of the abandoned construction was in fact a storing room for all kind of debris and garbage (typical to such situations) and extremely harmful to environment, especially in the middle of a large city (see Fig. 1).

Figure 1. Typical aspect of abandoned building: adverse environment impact.

Confronted with this situation, the new owner of the building has decided to reuse and retrofit the old steel and concrete structure, in view of creating a modern multistorey building of offices with glazing working as cladding. In order to maximize the space for offices, it was decided to build the new staircase and elevator structure outside the reconstructed building, in form of a tower of masonry and reinforced concrete (materials imposed by fire protection reasons) with links at every level to the corresponding story. The separate staircase would have to be located in the backyard of the building. All these requirements have led to a specific design procedure, characteristic to building restoration and consequently tightly linked to sustainable design principles as further-on described.

2 SUSTAINABILITY APPROACH PRINCIPLES. RESTORATION DESIGN

Modern society is intensely looking nowadays at sustainable development, trying to implement its four basic concepts (i.e. environmental, economic, social and cultural) into the new investments of any kind. To achieve that, it is of paramount importance to perform sustainable design in the planning phase, which means to comply with the following basic principles, explained and detailed in (WBDG, 2010) following US experience:

- Optimize site potential;
- Optimize energy use;
- Protect and conserve water;
- Enhance indoor environmental quality (IEQ);
- Use environmentally preferable products;
- Optimize operational and maintenance practices.

Respecting all these requirements in real design situations is not easy at all and the obtained results are often a matter of compromise (as for example in the investigated case).

Among mentioned sustainability requirements, the evaluation conducted by the authors is strongly related to the first point, i.e. the optimization of site/existing structure potential. This generally means the creation of sustainable buildings which have minimum impact on local ecosystem, based on proper site selection (as far as location, orientation and landscaping are concerned). The existing construction experience has shown that it is more sustainable to renovate an existing building than to tear it down and construct a new one. In other words, it is highly advisable to consider reuse and retrofit of available existing buildings before deciding to build new. From this point of view, the decision taken by the owner of the analysed structure (together with the architect and structural engineer) of restoring the partially erected frame, is fully complying with sustainability requirements.

Actually, structural restoration is performed either on monumental / historic buildings or on ordinary buildings, as the analysed building (Panelis, 2009). The structural restoration performed on ordinary buildings has the aim of repairing and strengthening these to keep them in use at a specified safety level. The reanalysis and redesign process of the existing structure implies a certain level of intervention, aiming to preserve the original structural system with proper strengthening of its weak elements, if necessary.

The next paragraph is briefly presenting some of the procedure steps, as applied by the design team in the restoration process.

3 RESISTANCE AND STABILITY CHECKING OF THE EXISTING STRUCTURE

The analysed steel structure layout is schematically presented in Figure 2 (as the initial project was available to the restoration team). As evident from the layout dimensions, the span values 5.50 m + 1.80 m +5.50 m adopted by the initial designer are not entirely suitable and correspond more to concrete than to steel structures. Also, quite small bay values were adopted (i.e. 3 × 3.30 m + 4.20 m).

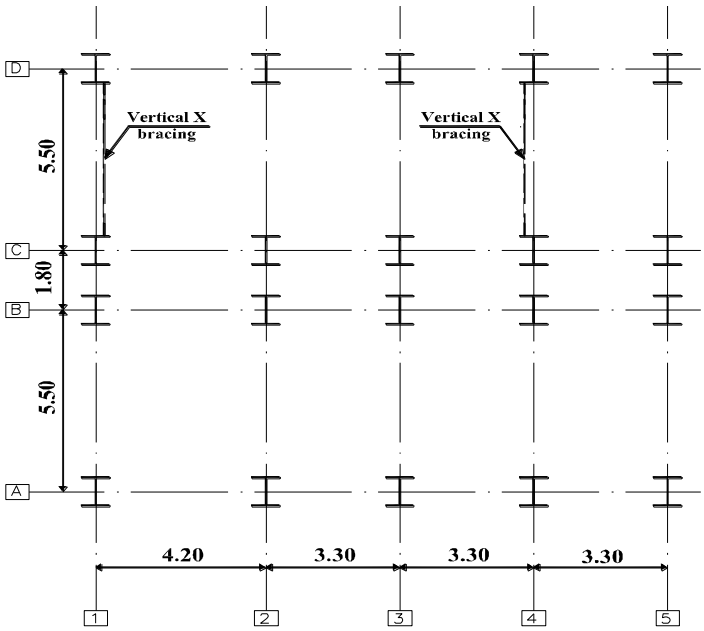

Figure 2. The initial steel structure layout – schematic presentation.

In order to evaluate the existing structure and its capacity to resist loading, the first structural analysis was performed on this initial configuration, with transverse vertical wind bracing in first and the fourth transverse axes and without vertical bracing on the longitudinal direction (sway frame). The hinged connection of the 3rd floor structure to the rest of the building was plenty contributing to increase the deformability of the structure. Another important aspect related to the existing steel structure refers to the vertical bracing system as the existing bracing system was also incomplete, living a sway frame on the longitudinal direction.

Some results of the FEM analysis in SAP2000 Nonlinear are quite relevant. The first eigen periods of the existing structure (i.e. T_1=1.068 sec) indicates an excessive deformability of the structure on the longitudinal direction (no bracing system provided on that direction). The longitudinal beams and the ground floor columns resistance is exceeded under the load combinations including longitudinal earthquake. The lateral sway at the top of the structure was found of 138 mm > H/200. This made the initial structure totally unacceptable and clearly indicated the necessity of structural measures by the designer. A certain number of other bracing configurations were therefore analysed in order to find the optimum one.

In the end of the study, the optimal bracing configuration has been chosen, and is presented in Figure 3. The architect / client requirement of free space in the front façade at ground floor

level (no bracings!) has been considered in this choice, together with a reversed position of the lateral bracing at ground floor between axes A and B required by street circulation reasons. It is however interesting to notice the obtained eigen periods for the chosen bracing configuration (T_1=0.625 sec), which show a much stiffer structure than the initial configuration with closer values, sign of quasi uniform rigidity on all directions as per seismic codes provisions.

Figure 3. Chosen bracing configurations.

As well known, the structural ductility is basically related to the employed steel grade which in this case is S235 and provides the required stress-strain diagram plateau and required ratio between ultimate strain and yield strain for ductile behaviour. The columns and beams cross-section made of built-up steel plates were found to be of class 1 according to EN1993-1-1 and P100-2006 (Romanian code) classification. Upper observations allow for the adoption in the earthquake analysis of the seismic behaviour factor q=5 characteristic to a ductile steel structure. This dissipation level was very important to reduce column base reactions and thus to avoid exceeding of foundations capacity under the new structural configuration. After choosing the optimum structural configuration and performing a FEM structural analysis, a maximum level of solicitation of 35-40% (compared to member resistance capacity) was found for the whole structure. Therefore, the decision was taken not to take supplementary measures for over strength in the beam-to-column connections of the new structure.

4 DISCUSSIONS ON STRUCTURAL RESTORATION PROCEDURE

As a positive start for the restoration procedure, the new owner of the building did not request any major modification in the metal structure geometry and only asked for a multistorey office building having glazing as cladding and an outer staircase located in the backyard. The inner partition walls would be of gypsum board on light metal structure, bringing no significant supplementary dead load. The cladding would be glazed, much lighter than the initially planned masonry cladding. The performed structure analysis on the existing building, as previously presented, results in a number of intervention techniques aiming to consolidate and adapt the structure to the new requirements and simultaneously provide a satisfactory level of safety. In the frame of restoration theory, such techniques divide into reversible and irreversible techniques.

In the particular case under study, after performing the described steps of the restoration design process, a number of technical consolidation measures resulted, i.e.:

- dismantling of the existing prefabricated concrete hollow strips;
- rust cleaning of the steel structure on site by blasting;
- application of a special primer, to repair corrosion protection;
- performing of all required mechanical operation;

- cut down of the existing steel bracing;
- installation of the new bracing system according to the performed structural study;
- lay down of the concrete hollow strips;
- supplementary reinforced concrete layer, cast on site upon prefabricated strips at each level, to provide better horizontal diaphragm effect;
- on site casting of a new reinforced concrete plate, over the 3rd storey, using a lost formwork of steel corrugated sheet.

The described intervention techniques are all included in the category of irreversible ones, as the restored building is an ordinary building and considering the environment requirements plus (last but not least) the financial acceptance by the client.

5 SUSTAINABILITY ASSESSMENT OF THE RESTORED BUILDING

As previously mentioned, when considering the existing sustainability requirements and trying to apply them in practical situations (as the analysed one) the project team was confronted with many obstacles of economical, technological or social nature often leading to compromise.

On this line of interest, the authors have checked the design and erection phases of the analysed construction, trying to emphasize those aspects where the sustainability requirements have been followed and where not. These observations have been gathered in Table 1 where, cells in grey indicate respected requirements, while cells in white indicate not applicable requirements or requirements which could not be respected owing to technological or economic reasons.

Table 1. Synthesis of sustainable design principles

1) Optimize site potential	4) Enhance Indoor Environmental Quality (IEQ)	5) Use environmentally preferable products
Proper site: location	Facilitate quality IEQ through good design, construction and O&M practices	Renovate existing facilities, products and equipment
Proper site: orientation	Value aesthetic decisions	Evaluate environmental preferability using life cycle assessment (LCA) tools
Proper site: landscaping	Provide thermal comfort	Maximize the recycled content of all new materials
Reuse and retrofit of existing building	Supply adequate levels of ventilation and outside air	Specify materials harvested on a sustained yield basis (as timber)
2) Optimize energy use	Prevent airborne bacteria, mould and other fungi	Encourage the use of recyclable assemblies and products
Reduce heating, cooling and lighting loads through climate – responsive design and conservative practices	Limit spread of pathogens	Limit construction debris
Employ renewable or high-efficiency energy sources	Avoid use of materials high in pollutants (paints, coatings, sealants, adhesives)	Eliminate the use of materials that pollute or are toxic during their manufacture, use or reuse.
Specify efficient HVAC and lighting systems	Assure acoustic privacy and comfort	Give preference to locally produced materials with low embodied energy content
Optimize building performance and system control strategies	Control disturbing odours through contaminant isolation (smoking) and product selection	6) Optimize operational and maintenance practices
Monitor project performance	Create a high-performance luminous environment	Preventive maintenance (training staff for sustainability)
Employ effective solar shading devices	Be aware of exposure to electric and magnetic fields	Environmentally preferred cleaning products
	Balance IEQ strategies with security requirements	Reduce waste through source-reduction and recycling

Table 1 was built on the purpose to obtain a general view on the implementation level of sustainable design principles. Some of these could be implemented at a reasonable level through design, material supply policy and available manufacturing / construction technology. On the other side lie those principles which could not be respected from various reasons and thereby show clear directions for some improvement measures in the future. A discussion is presented on the following, trying to evaluate the percentage degrees of fulfilling for some of the mentioned topics as a tentative index for the sustainability of the resulting construction.

5.1 *Optimizing site potential*

Optimizing site potential in our particular case was partially possible by complying with the requirement of a proper site location for an office building, i.e. a central area of the city. The existing construction experience has shown that it is more sustainable to renovate an existing building than to tear it down and construct a new one. Furthermore, the new construction was replacing an abandoned steel structure, already obsolete in that zone and with adverse environment impact. The new investment reused main part of the former steel structure (see Fig. 3), and performed a retrofit (including required structural measures) as recommended. The site orientation and landscaping were practically imposed by the existing building and therefore do not apply. To conclude, with 2 of 4 requirements satisfied, one might consider this topic 50% fulfilled.

5.2 *Optimization of the energy use*

The optimization of energy use is tightly related to the optimization of thermal insulation, as a highly efficient measure of passive nature. Actually, the envelope opaque elements of the cladding where designed and built as a multilayer system made of outer polyurethane sandwich panels 100 mm thick, plus inner layer of 150 mm mineral wool cased on the inside face with gypsum board (indoor finishing). Thus, an efficient system resulted, both for heating and for cooling seasons, reducing energy losses. Also, solar shading devices (blinds) were provided as an energy efficiency measure during summertime. Unfortunately, using solar energy to maximize passive solar potential was not in view of the investor, nor monitoring building energy performance. Other criteria belonging to this topic were not met by technological reasons and provision of “classic” energy supplying solutions. Per total with 2 requirements met from a total of 6, this topic may be considered 33% fulfilled, showing the necessity for a lot of improving measures in the future as the use of renewable of high efficiency energy sources (for example sun energy), specification of efficient HVAC and lighting systems, observing and predicting non-renewable energy and predicting electrical peak demand, etc.

5.3 *Enhancing indoor environmental quality (IEQ)*

Enhancing indoor environmental quality implies first of all a good design procedure, with such decisions and solutions meant to improve inside conditions of the building, followed by subsequent construction and finally by suitable operation and maintenance (O&M) practices. Ease of cleaning and maintenance of inner spacing was in view together with indoor air quality by an adequate level of ventilation, based on operable windows for natural ventilation under occupant control. Value of aesthetic decisions implies provision of such windows that afford buildings occupants views outside but do not negatively impact the visual and acoustic comfort of the work environment. In the office zones, the openings were designed by the architects with sufficient dimensions to maximize the use of daylight when required, and also provided with shading devices (internal blinds) as protection against excessive radiation (see Fig. 4).

As for the glazing systems (including sealing systems) they were solved in the “classic” way by economic reasons, with no special thermal properties of glass or built-in measures for sun radiation control. That would be a drawback of the envelope solution in its glazing part. Also, some materials high in pollutants could not be avoided, as for example paints (intumescent type) or foam sealants, as part of the “usual” constructional detailing. Considering the fact that indoor space was devoted to office / IT activities, disturbing odours may come only from smoking. Therefore, smoking places were imposed on outside, separated from the inner space by

suitable sealed doors in order to prevent contamination. Together with proper natural ventilation, these measures actually provide a proper indoor air quality in a simple and direct manner.

Figure 4. Building location near traffic lanes (tram line visible).

However, the relation of the sealing / natural ventilation systems with existing HVAC (heating, mechanical ventilation and air conditioning) systems of the building is always a problem, with possible negative impact on buildings' overall energy performance. The Romanian continental climate with extreme cold in winter and very hot summer seasons is strongly putting at test any of such systems and always making the provision of a required indoor climate rather difficult. Another indoor quality requirement would be the awareness of electrical and magnetic fields (if existing). Owing to the imposed position of the old structure (very close to street traffic lanes and tram electric lines), a considerable influence of electro-magnetic field is to suspect. This position drawback has a negative influence also on indoor environment quality (purity of air and difficulty of ventilation, vibrations due to traffic, outer noise transmission, etc.) which fully confirms the difficulty of simultaneously complying with all sustainability and environmental criteria and shows the practical necessity of compromise.

In the end, looking at the whole topic, a number of 6 reasonably achieved criteria are found from a total of 12, leading to a 50% degree of fulfilling sustainable design requirements. As in previous cases, the important criteria for the researcher are those which could not be respected (i.e. avoiding the use of materials high in pollutants, dynamic integration of HVAC system which always depends on technological evolution, use of more efficient glazing systems from thermal point of view, preventing airborne bacteria and fungi generated inside air conditioning systems, etc.) Being aware of all these drawbacks shows very clearly the necessary corrections in the future and measures to take in favour of a sound and sustainable indoor environment.

5.4 Use of environmentally preferable products

The requirement to use environmentally preferable products was achieved, first of all, by the renovation of the existing steel structure. This procedure is highly recommended in order to serve the principles of sustainable design. The renovation procedure also provided an entirely new glazed envelope for the building. Owing to the high rate of recyclability of steel, this helps a lot to maximize the recycled content of the new materials as required. In the same recyclable category may be included the steel secondary structure of cladding inner layer or of the partition walls. Of course, owing to the limits of present technological level, some of the envelope materials are less recyclable, i.e. plastic vapour barrier, gypsum board, the PVC hydro-insulating membrane at roofing level, etc. Anyway, the detailing by which modern cladding and

roofing are built, make them easy to dismount and separate as recyclable assemblies or product (which is also required in sustainable design). No life cycle assessment (LCA) was done jet by the design team in order to evaluate the environmental preferability of employed materials. Actually, during design period (2006) the LCA concept was not very familiar in Romania, at the level of professional designers, as it gradually becomes nowadays. Another mention would concern the recommended preference to the designer for locally produced materials with low embodied energy content: such materials were not included owing to the adopted constructional concept, typical to "classic" multistorey structures. Consequently, of a total of 8 criteria, a number of 4 could be achieved at a reasonable level, which would show a fulfilling degree of 50% for the sustainability concept concerning environment friendly materials. Again, this shows a large number of measures to be taken in the field and aspects to improve.

5.4 *Optimize operational and maintenance (O & M) practices*

No matter how sustainable a building may have been in its design and construction, it can remain in this state only if it is operated responsibly and maintained properly. Therefore, maintenance is of paramount importance for any building. However, the so called "preventive maintenance" (meaning to train building occupants, facilities managers and maintenance staff in sustainable design principles and methods) is still in its early age in Romania. Also, the use of automated monitors and controls for energy, water, waste, temperature, moisture and ventilation is only partially performed. Bio-degradable and non-toxic cleaning products and supplies are increasingly used together with waste reduction by source-reduction and especially recycling. With one criterion of 3 achieved, this sustainability concept is 33% fulfilled, leaving a lot of necessary measures and procedures to be implemented.

6 CONCLUDING REMARKS

An existing steel structure, abandoned in a partial erection state and damaged by climatic loadings, with adverse impact on environment, was analysed in order to evaluate its resistance capacity and to identify the required consolidation measures. The design team has followed a reconstruction procedure, considering (as much as possible) the principles of sustainable building and environment integration. However, by analysing the whole design and construction procedure in the light of sustainable design principles, with an approximate overall rate of fulfilling less than 50%, the authors (as structural engineers, i.e. part of the design team mainly concerned with resistance and stability issues) have observed at what level the building is tributary to old ways to do things and have emphasized a number of directions to enhance sustainability. This clearly demonstrates the necessity of the "whole building approach" performed by complex and interacting multi-specialty design teams, the only capable to fulfil sustainable design criteria and respond to modern codes and regulations requirements.

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A new approach to energetic requalification of existing buildings

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ABSTRACT: The impact of the planning decisions on moisture content and on behaviour of the building components have to be taken into consideration when there are attempts to upgrade the thermal performance of existing building to save energy. In this paper insulation systems and technologies are analysed and energetic problems and performances are identified in order to propose a critical evaluation of the possibilities of intervention. Special attention is paid to moisture and condensation problems occurring as a consequence of retrofitting interventions. In this research an innovative simulation method is used to perform realistic and detailed simulation of the hygrothermal behaviour based on EN 15026:2008. The method allows evaluating the real potential of interior thermal insulation on existing building components under natural conditions.

1 INTRODUCTION

In the policies to reduce consumptions and emissions due to residential buildings, the energetic improvement represents an important potential in the European background, particularly in the Italian one: buildings constructed before the 70s represent in fact, in Italy, over 65% of the property, with consumptions that nowadays can not be considered acceptable in the EU panorama.

As in Italy constructions absorb almost 45% of the domestic energy demand, it is possible to foresee important feedbacks in terms of energy saving if a methodical intervention on existing buildings is implemented.

While in new constructions good energetic performance can be guaranteed by present rules, methods and innovative materials, the possibilities of interventions in restoration are often limited by the complexity of the problems. The designer has often to face the difficulty to find a feasible and viable solution because of the historical constraints, structural situation and regulations in force.

A good knowledge of technical features of existing building resources is necessary to improve their energetic performances. For this purpose, a complete analysis of the problem should consist in:

- Investigation of the present building structures;
- Identification of energetic problems and performances;
- Critical evaluation of the intervention potential;
- Research of the possibilities of application of materials and technologies;
- Control of moisture transport, surface condensation end mould growth.

Special attention has to be paid to moisture and condensation problems likely to occur in the retrofitting interventions. A detailed simulation of the hygrothermal behaviour is necessary in order to propose a critical evaluation of the real possibilities of intervention, especially when interior thermal insulation systems are applied.

2 CONDITION ASSESSMENT OF EXISTING BUILDINGS

Within existing residential buildings, a significant sample of external walls has been selected to analyse the constructive elements which are usually interested by heat loss.

The standard UNI/TS 11300 part 1 appendix B contains the Abacus of masonries in existing buildings in Italy. Basing on this document, different typologies have been identified, such as stonework (made by calcareous materials, available in the whole national territory), tuff-work (popular in the southern part of Italy), brickwork, concrete wall.

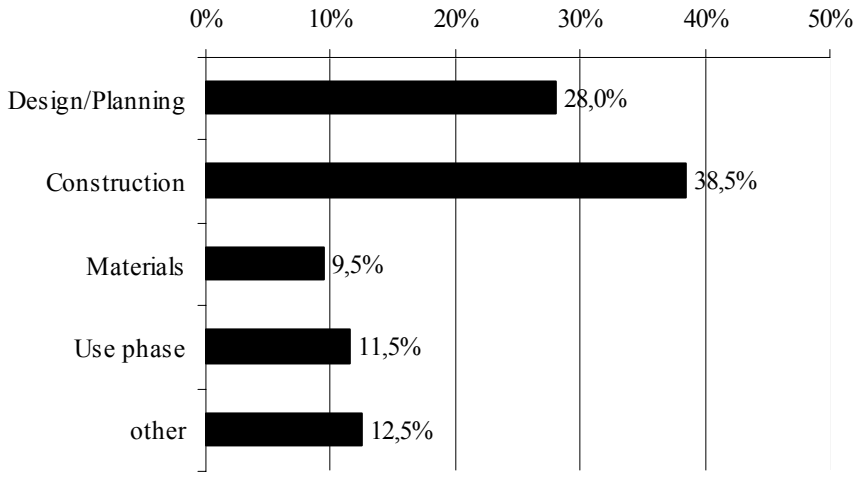

Figure 1. Causes of deterioration in buildings.

2.1 *Factors of deterioration in building*

The factors of deterioration in constructions are environmental conditions, acting on building components and leading to functional, structural and esthetical decay of the structure. Damages in buildings are likely to be caused by mistakes occurring during the planning, construction or use phase which can give origin to circumstances leading to deterioration.

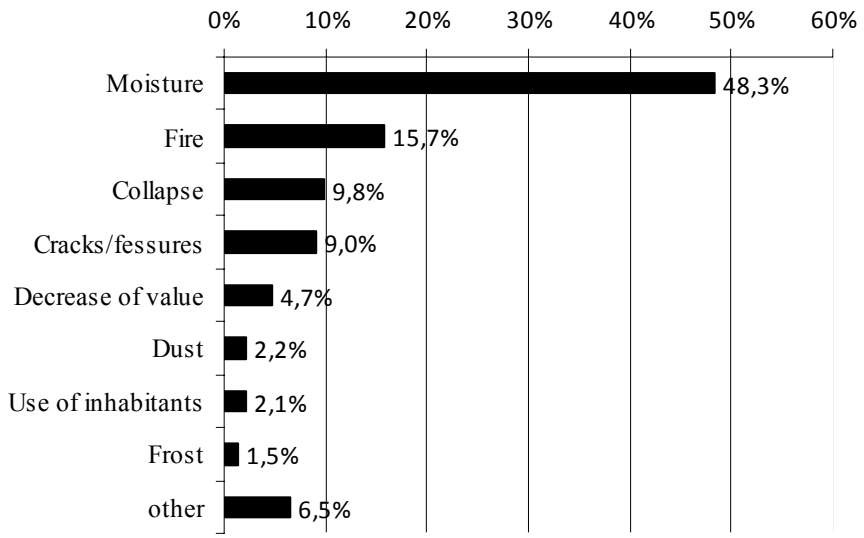

Figure 2. Deterioration factors in buildings.

The first official Austrian report on damages in buildings („*1. Österreichisches Bauschadensbericht – Zusammenfassung*") particularly underlines that a major number of errors (38, 5%) occurs during the construction phase, due to mistakes in assembling, installing and executing the intervention. Planning mistakes represent the second origin of deterioration of structures, corresponding to 20% of the observed cases.

The Hannover Building Research Institute (Institut für Bauforschung e.V. Hannover) has published a report dealing with the factors of deterioration. Among 275 existing buildings, 48% of damages had occurred as a consequence of moisture (Figure 2).

It has to be taken into consideration that different kinds of moisture damages are likely to occur in constructions: water entering due to failing waterproofing, wrong material choice, thermal bridges, superficial condensation, interstitial condensation, mould growth, capillary action.

3 HYGROTHERMAL EVALUATION IN BUILDINGS

3.1 *Thermal evaluation*

DPR 59/09 is the Italian law containing limits and requirements that have to be respected in buildings when a requalification intervention is carried out.

Table 1. Thermal transmittance of external walls

Climate Zone	U limit
	W/m^2K
A	0,62
B	0,48
C	0,40
D	0,36
E	0,34
F	0,33

In this research nine different typologies of external walls has been analysed to evaluate their thermal performances.

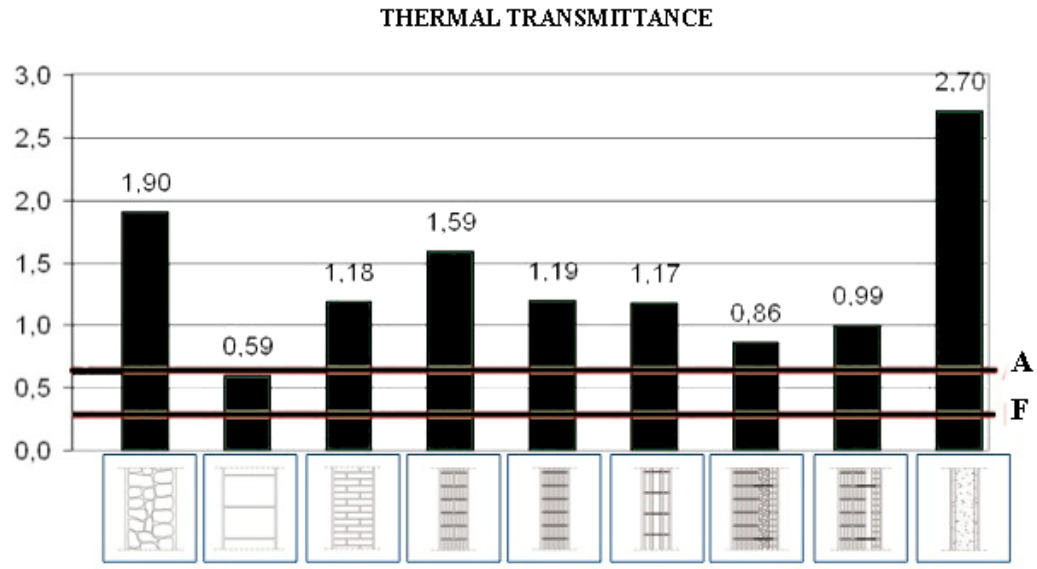

Figure 3. Thermal transmittance values.

In case of complete or partial renovation of a building element the following evaluations have to be considered:
- Thermal transmittance of external walls has to be smaller than the values in Table 1;
- Surface condensation should not take place;
- Interstitial condensation must be limited to the quantity which can evaporate;
- Heat store capacity of external walls has to be checked in all sites where mean monthly value of solar irradiancy on horizontal plane during most irradiated month is greater than 290 W/m^2. The surface mass of external walls must be higher than 230 kg/m^2 or, as an alternative, the dynamic thermal transmittance has to be smaller than 0,12 W/m^{2}K.

3.2 *Interstitial condensation evaluation*

The examination of interstitial condensation is usually performed considering the amount of condensed water developing in the building material due to vapour diffusion phenomena in the construction element. The standard UNI EN ISO 13788:2003 considers a simplified model, the so called Glaser method. In 1958 Helmut Glaser developed a basic, steady state graphic methodology which allows evaluating the water vapour diffusion and the condensation potential without computational instruments.

Nowadays this basic method is still widely used, but it presents some critical points, particularly when we deal with requalification of existing constructions. For the energetic refurbishment of an external wall with interior insulation system, the Glaser method doesn't allow to reach a high level of energy efficiency of the building. Indeed for an insulation thickness higher than 6-8 cm, the verification is not fulfilled and the planner has to take into consideration other possibilities.

Table 2: Comparison between UNI EN ISO 13788:2003 and UNI EN 15026:2008

	Model	Climatic data	Moisture transport	Condensation period	Evaporation period
UNI EN ISO 13788:2003	Steady state model Glaser	local medium data	diffusion	12 monthly calculations	12 monthly calculations
UNI EN 15026:2008	Instationary model	real measured climatic data	diffusion and capillarity	365 days x 24 hours	365 days x 24 hours

Among the different existing solutions the designer can decide either to decrease the thickness of the insulation, or to use a vapour barrier. If the first solution isn't viable due to the low level of thermal transmittance, the second one can be even a worst alternative, because of the existing difficulties in properly installing such a technical solution. If the vapour barrier is not perfectly installed, very serious damages are likely to occur, leading to rapid deterioration of the building element as a consequence of convection of humid air through the crevices in the vapour barrier.

In the last few years a new evaluation model has been introduced in order to examine the interstitial condensation in building elements. Beyond the vapour diffusion, this model considers other mechanism of moisture transport in the materials, such as superficial diffusion and capillary transport. In addition the model considers the dependence of the distribution of temperature and moisture in time and space and the real boundary and initial condition of the element, like initial moisture content, rain and solar radiation. This dynamic simulation model is described by means of the standard UNI EN 15026:2008.

4 MOISTURE TRANSPORT IN BUILDING ELEMENTS

4.1 *Water vapour diffusion*

The main transport processes in materials are vapour diffusion and liquid capillarity. The direction of these ways of moisture transport can be different. While vapour diffuses from the warm face of the material to the cold one, the liquid transport takes place from the humid to the dry side of the construction element. The diffusion flow can be described by means of the following equation:

$$g_v = -\frac{\delta_0}{\mu} \cdot \nabla p$$

where p is the air vapour pressure, δ_0 the vapour diffusion coefficient in quiet air ($\delta_0 = 2 \times 10^{-10}$ kg/msPa) and μ the water vapour diffusion resistance of the building material.

The equation shows that air vapour pressure gradient is the triggering potential moving the vapour molecules through the building element in dependence on the permeability property of the material.

During winter in standard conditions in buildings, the water vapour pressure is higher on the interior side and the vapour diffuses outwards. The interstitial condensation due to this transport process is described in the standard UNI EN ISO 13788:2003.

4.2 *Capillary transport*

When in a hygroscopic material a certain degree of relative humidity is reached (around 60%), a further transport process takes place on the surface of the pores, the liquid diffusion. An additional process occurring when the ultrahygroscopic field is exceeded and the pores are filled with water, is the liquid capillary conduction. This moisture transport is caused by the surface capillary forces on the meniscus of the condensed water in the material pores and moves from the humid to the dry material. It can be described by the following equation:

$$g_w = -D_w(\varphi) \cdot \nabla \varphi$$

where $D_w(\varphi)$ is the liquid transport coefficient, dependent on the relative humidity φ in the material.

If the directions of vapour diffusion and capillary conduction are opposite, the effect of the capillarity can produce a positive consequence on the interstitial condensation. The water condensing at the interface between existing wall and interior insulation can be conducted away by the absorption tensions in the pores.

This is a very important fact to be taken into consideration when dealing with evaluation of interstitial condensation, because it means that the amount of condensed water at the interface estimated by the UNI EN ISO 13788:2003 could be overestimated.

The standard UNI EN 15026:2008 describes all these transport processes by means of a dynamic model which can be used to determine the amount of water content in the construction element at each time step of the simulation.

5 ASSESSMENT OF THE INTERVENTIONS

In this analysis the results of the evaluation processed by means of UNI EN ISO 13788:2003 and UNI EN 15026:2008 were compared, in order to understand differences, similarities and applicability limits of the two assessment methodologies.

In renovations of building elements, different interventions have been supposed: internal thermal insulation, external thermal insulation and thermal insulation in cavity walls.

The thickness of thermal insulation that has to be applied is established by the limit of thermal transmittance coefficient U that has to be reached and depends on the heat conductivity λ of the insulation material.

When the insulation material is applied on the colder side of the wall, the solution is called external wall insulation system (EWIS). This intervention determines not only energy saving, but also provides a good protection to existing wall, it increases internal comfort and it reduces the risk of mould growth.

Internal wall insulation system consists in installing a layer of insulation material on the warmer side of the wall. This intervention is often used in case of refurbishment in historical buildings, but presents some disadvantages. The correct solution of thermal bridges usually represents a hard design challenge because of the complexity of the structural situation. Furthermore it is difficult to properly execute the air tightness of the building envelope and this increases the risk of interstitial condensation between insulation material and the existing wall.

5.1 *Boundary conditions*

The hygrometric evaluations were performed by means of two simulation programs: Dämmwerk 2005, for the steady state method and WUFI (Wärme und Feuchte Instationär) of the Fraunhofer-Instituts für Bauphysik for the instationary simulation.
For the steady state calculation the internal condition of the building were set to T_i = 20 ° C and interior relative humidity φ_i for the use category 3, in accordance with EN ISO 13788:2003.
The dynamic simulation was performed using the hourly climatic data of the town of Bolzano, including temperature, relative humidity, solar radiation, rain. The daily mean internal air temperature and humidity was set for normal occupancy conditions in accordance with Annex A of the standard UNI EN 15026:2008.

5.2 *Results and evaluations*

The results of fifty-seven different cases were taken into account and calculated in order to compare the methods described in the standards.

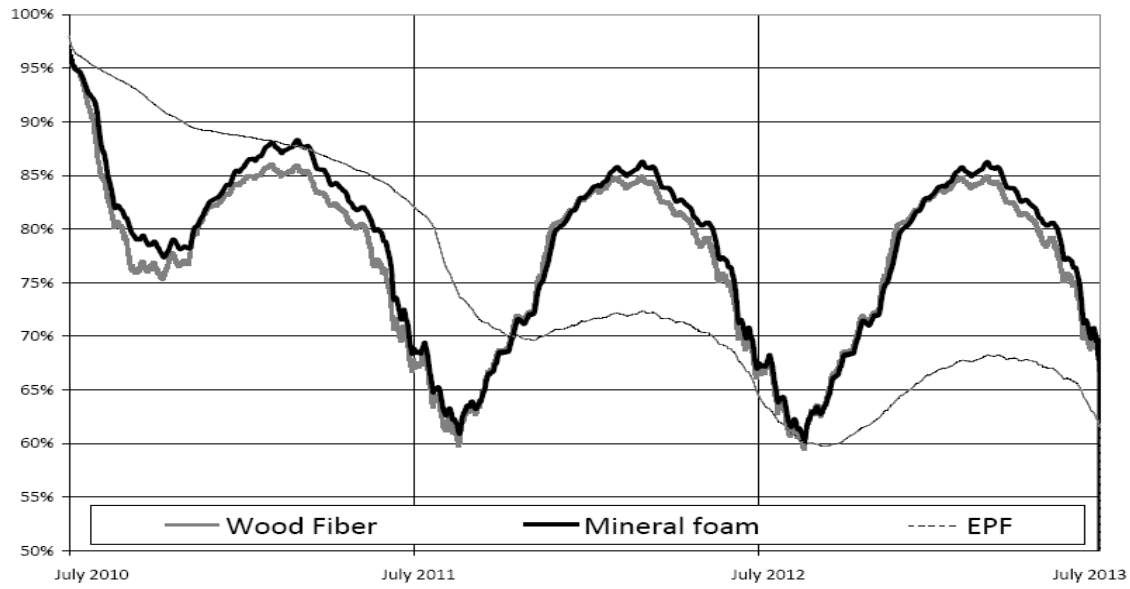

Figure 4. Comparison of different internal insulation materials.

Figure 4 represents the comparison of the relative humidity profile of three different insulation materials at the interface of an existing wall during the next three years after

installation of 10 cm of internal insulation system. The materials taken into consideration are wood fibre, mineral foam and expanded polystyrene foam (EPF).

It was observed that the requalification intervention carried out installing the internal wall insulation system couldn't fulfil the conditions of the UNI EN ISO 13788:2003. Simulating the intervention by means of the Glaser method, the amount of condensed water at the interface between existing substrate of the wall and applied insulating material was greater than 500 g/m^2.

On the contrary the evaluation of the same insulation solution performed by means of the instationary simulation method had a different output. In the profile of

it is possible to observe that in all the cases the amount of moisture in the material decreases after installing the system and that no condensed water takes place at the interface.

It is interesting to observe the different behaviour of the insulation materials. Wood fibre and mineral foam are hygroscopic materials with high permeability to vapour diffusion and have a very high variability in water content during winter and summer, because they immediately react to the changed boundary temperature and humidity conditions. The material in expanded polystyrene foam has a much smoother trend because the higher permeability resistance of the EPF acts as a vapour retarder on the vapour diffusion. During winter, when the vapour flow moves outwards a smaller amount of vapour reaches the wall surface, while during summer the vapour flow towards the interior side of the building is retarded and the wall has a lower capacity to dry up.

6 CONCLUSIONS

The national Italian law obliges to carry out hygrothermal evaluations and controls when a building intervention is planned. Until now the evaluation of interstitial condensation in building elements has been carried out by means of the Glaser method, a model described by the standard UNI EN ISO 13788:2003 and considering just the water vapour diffusion transport. This model doesn't take into consideration neither the liquid capillary conduction, nor the absorption capacity of hygroscopic materials, nor the real climatic conditions. This standard is widely diffused on national level, but it seems to overrate the amount of water condensation, especially when an interior insulation system solution is applied.

Recently an advanced evaluation model was introduced, based on the standard UNI EN 15026:2008. This dynamic simulation method proved to be suitable to correctly evaluate the moisture transport processes in building material.

By means of the dynamic simulation methodology it was established that the Glaser method overestimates the amount of water condensation when an internal wall insulation system is designed for upgrading existing solid external walls. It was determined that in this case interstitial condensation due to vapour diffusion doesn't represent a risk of deterioration of the thermally requalified building element. On the other hand, risks of damages are very likely to occur when thermal bridges are not accurately solved and when the air tightness of the building envelope is not properly executed. In this case interstitial condensation due to moist air convection and superficial mould growth has a high probability to cause structural, functional and esthetical deterioration of the building.

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Renovation of façades: environmental and energy issues

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ABSTRACT: This study verified two office buildings in the metropolitan area of the city of São Paulo, Brazil. Both of them have the same plate and number of stories, but one is oriented north-south, whilst the other is east-west. The main façades are all glazed without any kind of sun protection. Considering that glazed facades are responsible for solar heat gain and penetration of sunlight on people, work plan and equipment, the application of this study was undertaken in order to obtain the design of a system of sun protection and check its meaning in terms of reducing heat load and its possible effects in the energy consumption of air conditioning system. Different solutions were checked and compared, including brise-soleil, film and screens. To perform simulations of thermal energy was used annual weather data on hourly basis. Existing data based on its reliability and proximity to the place of study were considered: SWERA from station of Congonhas Airport, in the city of Sao Paulo. First, it was determined the need for masking the sky, for each of the façades involved in order to preserve the maximum possible visibility to the outside and natural light, determining the dimensions of the brise-soleils. The next studies aim to check the penetration of direct solar radiation in the openings of different façades, respectively for the case of winter and summer. The goal was to compare the penetration of sunlight to the current situation and the situation with the use of the proposed systems of brise-soleils. For the quantification of natural lighting system was considered the availability of daylight in the order of 20,000 lux on the frequency of 67% of daylight hours of the year in São Paulo. To calculate the Daylight Factor, it was considered the celestial component, the component of the external reflection and internal reflection component, being the sum of these weighted by frame and maintenance and the light transmission of glazing. Thermal energy simulations, based on the annual climate, were performed to compare the reduction in heat load and energy consumption by the system of air conditioning for the different interventions in the buildings.

1 INTRODUCTION

This study verified two office buildings in the metropolitan are of the city of São Paulo, Brazil. Both of them have the same plate and number of stories, but one is oriented north-south, whilst the other is east-west. The main façades are all glazed without any kind of solar protection. Considering that glazed façades are responsible for solar heat gain and penetration of direct sun radiation on people, work plan and equipment, this study was performed in order to obtain the design of a system of sun protection and its check in terms of reducing heat load and its possible effects in the energy consumption of air conditioning system. Different solutions were checked and compared, including film coated, screen and brise-soleil.

In order to perform simulations of thermal energy, it was used an annual weather database on hourly basis. Given the lack of specific data to the place where the buildings are under study, it was considered the availability of existing data, focusing on its reliability and proximity to place of study. Thus, the database project Solar and Wind Energy Assessment Resource (SWERA, 2004) was chosen to be used. The database refers to the meteorological station of Congonhas (WMO Sta-

tion 837800, IAG-USP, 2007), S23°37',W46°39',GMT-3.0,803M above sea level, standard atmospheric pressure of 92043Pa. Data were collected from 1973 to 2002, having been treated statistically to the creation of one year from the months typically representative of climatic conditions of the period.

2 SOLAR ANALYSIS

2.1 *Solar protection*

In the solar analysis, firstly, it was determined the need for masking the sky, for each of the façades involved, in order to take advantage of daylighting and preserve the maximum possible visibility to the outside, determining the dimensions of the brise-soleils.

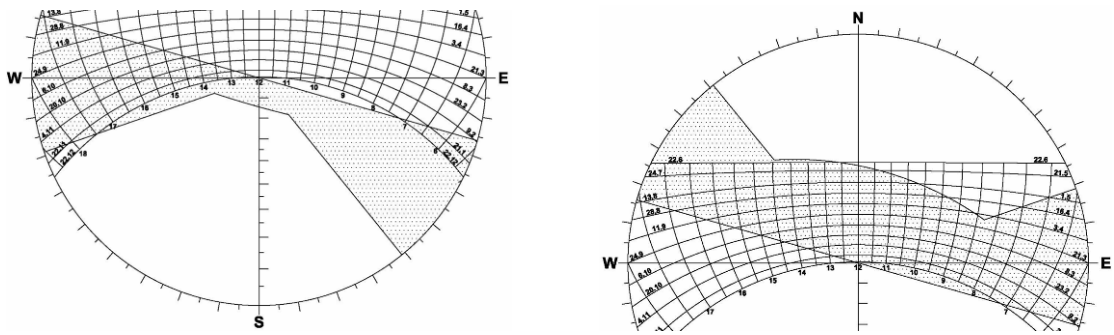

Figure 1. Solar mask provided by brise-soleil for the south façade (azimuth 196°) and north façade (16°).

As can be seen from Figure 1, the mask proposed for the south façade allows the penetration of sun in the summer solstice after 18:30. Considering the conditions of the surroundings (other buildings), a considerable part of the building will not even receive this incidence. Moreover, that time is outside the period of occupation provided by the client (Monday to Friday, from 8:00 to 18:00). In geometric terms, we have then an angle $\beta = 55$ ° (angle of vertical brise protection in relation to the normal of the facade) and about an angle $\alpha = 75°$ (angle of protection of the brise horizontal to the horizon). In fact, the solution of brise-soleil in the south façade, as will be seen, needs no horizontal plates, only one grid for each floor, which serves as the "closure" to the vertical brise and allows the maintenance of the façade. As can still be seen from Figure 1, the mask proposed for the north facade allows the entrance of the solar rays especially during the fall and winter. In the limit of the winter solstice (22/06), the penetration of direct solar radiation is from 6:45 until 12:30. In the months before and after (from early April until mid-September) the period that receives direct solar radiation decreases, to the extent that it penetrates only a small slit for a moment at 8:20. In geometric terms, it has remained the same angle $\beta = 55°$ (angle of vertical brise protection in relation to the normal of the facade) in order to standardize the two solutions brises in the north and south facades, also using the same solution grid to maintain the facades. However, due to higher solar incidence, it was determined an angle $\alpha = 75°$ (angle of protection of the horizontal brise to the horizon). Thus, in the south façade vertical brises are enough for solar protection, whilst in the north facade horizontal brises are also required.

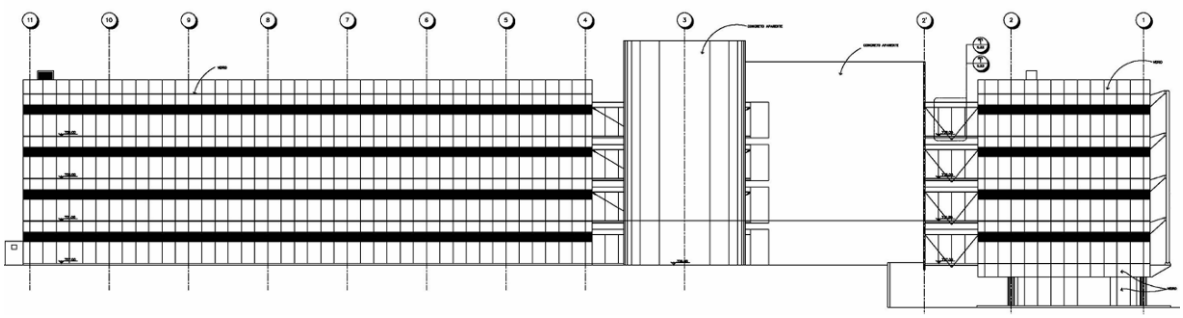

Figure 2. Elevation of North Façades, with Horizontal Brise-Soleil (black stripes) and Vertical-Brise Soleil (thin vertical lines).

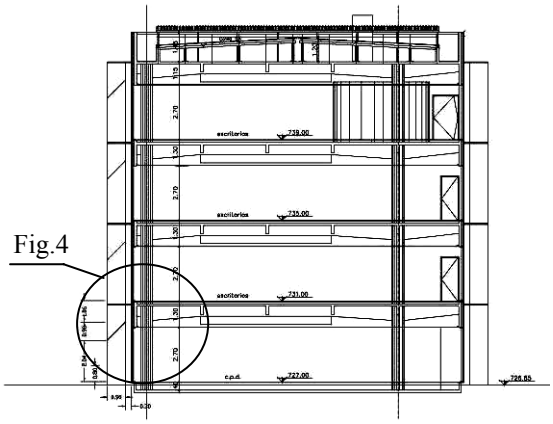

Figure 3. Section with the brise-soleil solution.

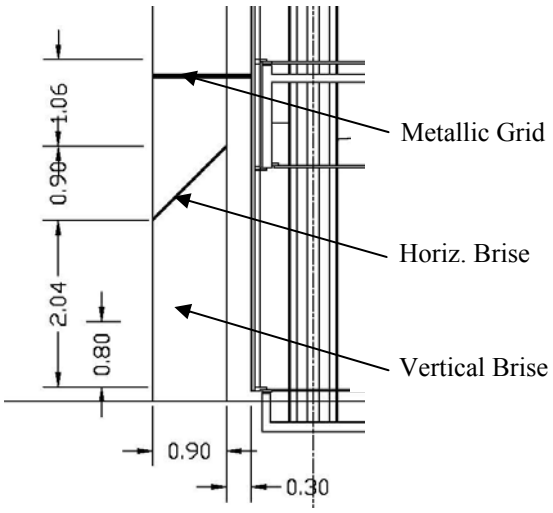

Figure 4. Detail with the brise-soleil (North Façade).

2.2 *Solar penetration*

The next studies aim to check the penetration of direct solar radiation in the openings of different façades, respectively for the case of winter and summer. The goal was to compare the penetration of direct sun penetration to the current situation and the situation with the use of the proposed systems of brise-soleils. Figure 5 and 6 show the results.

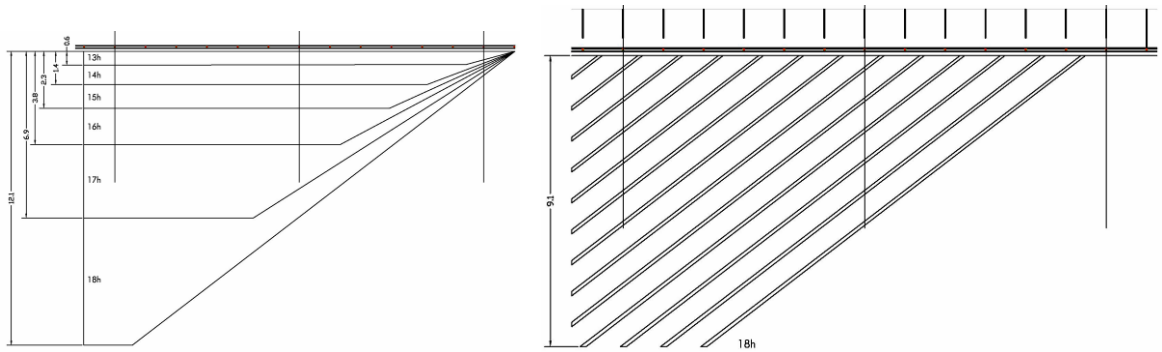

Figure 5. Solar penetration in the summer (South Façade) without brise-soleil (from 13h to 18h) and with brise soleil (only at 18h).

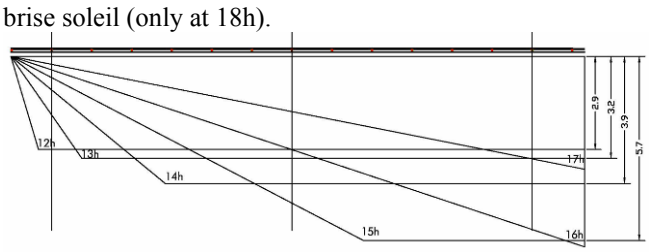

Figure 6. Solar penetration in the winter (North Façade) without brise-soleil (from 13h to 17h). With brise soleil there is no solar penetration in this period.

3 DAYLIGHTING ANALYSIS

3.1 *Daylighting assessment*

For the quantification of daylighting system, it was considered the availability of daylight in the order of 20,000 lux for the frequency of occurrence of 67% of daylight hours of the year in the city of São Paulo. To calculate the Daylight Factor (DF), it was considered the celestial component, the ex-

ternal and internal reflection components, being the sum of these components weighted by frame, maintenance and the light transmission of glazing coefficients (Alucci, 2007). It were studied the following spots (see Table 1) to determine the values of sky component and availability of daylight.

Table 1. Results of Daylight Factor and iluminance in different spots of the two studied buildings

	North Façade (2m from façade)		North and South Façades (8,2m from façades)		South Façade (2m from façade)	
Building A	DF	Ep	DF	Ep	DF	Ep
Actual	5,7%	1140 lx	3,3%	660 lx	-	-
Film	3,8%	760 lx	2,2%	440 lx	-	-
Screen	3,0%	600 lx	1,7%	340 lx	-	-
Brise-Soleil	2,8%	560 lx	2,0%	400 lx	-	-
Building B						
Actual	5,2%	1040 lx	1,6%	320 lx	4,7%	940 lx
Film	3,5%	700 lx	1,1%	220 lx	3,1%	620 lx
Screen	2,6%	520 lx	0,8%	160 lx	2,3%	460 lx
Brise-Soleil	1,5%	300 lx	1,1%	220 lx	1,9%	380 lx

As it can be seen, in building A, the three solutions provide sufficient daylight, for office activities, considering the NBR 5413 (1992), which recommends values between 300 and 700 lx, and one may note that the three solutions satisfactorily meet this criterion in situations of the studied sky conditions. With respect to Building B, the three solutions also comply with that in the facades, with values between 300 and 700 lx. Note that the dimensioning of horizontal plates in the previous topic was done exactly based on meeting the criterion of 300 lx in this situation. Regarding the situation of the inner situation in building B, it should be noted that the results have been between 160 and 220 lx. They appear quite favourable, since, although not sufficient for the practice of labour activities, they are sufficient for general lighting or for lighting for circulation. Finally, we emphasize once again that the adoption of the value of 20,000 lx refers to a situation of overcast or partly cloudy and when there is sun exposure, the availability of daylight will be up to five times greater than that shown in the results. Thus, it is considered that the intensity and distribution of solutions of daylighting proposals are appropriate, but may reach values much higher than necessary on a clear day. Thus, the brises solution proved to be more advantageous to minimize the situations of glare by blocking the direct solar radiation, as shown earlier in this article.

3.2 *Exterior visual access*

Among the three solutions in verification, the application of film coated is the one that least affects the visibility of the exterior, just causing some changes in terms of tone colours. The use of the screen remains visible outside, but its quality is impaired, reducing, for example, recognition of details of the external environment. The option for brise soleil also significantly alter the external visibility, but in a different manner. The visibility is reduced vertically by the lower horizontal edge of the plates (which is above the eye level of people), while the presence of vertical elements segments the visual as a whole. These consequences can be seen in the drawings presented earlier in this article, when considering the solutions proposed for the brise soleil.

4 THERMAL ENERGY ANALYSIS

4.1 *Thermal Loads*

Thermal energy simulations, based on the annual climate database, aimed to compare the reduction in heat load, and thus energy consumption by the system of artificial air conditioning, for different interventions in the buildings (Table 2).

The internal heat sources considered were: A) Occupation: According to data supplied by the client, Building A has capacity for 362 people and Building B to 370 people. Thus, considering the activity of office, which has metabolic rate of 130W, in which 65W are sensible heat and 65W are latent heat, it was calculated the internal heat load factor, resulting in the 7W/m^2 for sensible heat and 7W/m^2 for latent heat. B) Equipment: Specific data regarding the thermal loads of equipment were provided only to a lab of the 4th floor of Building A. Thus, for the generalization to other environments, it was assumed that each user has a computer, with an estimated load of 120W, resulting in 13W/m^2 sensible heat. C) Lighting: considering all the fixtures, lamps and their powers, it resulted in 13.5 W/m^2; considering all the lighting system, ie, the power of the lamps, plus their control

equipment used in conjunction (ballast, ignitor, transformer, etc), it resulted in 21W/m^2. Once finalized the computer simulations, considering all the hygrothermal trades of energy balance, Table 3 show the thermal loads to be removed respectively from Building A and B, considering the system of artificial air conditioning operating in a way to provide environmental conditions with air temperature at 24°C, relative humidity 50%, Monday to Friday, from 8h to 18h, with a total of 2.600 conditioning hours per year (approximately 60% of daylight hours of the year).

Table 2. Material properties used for the annual hourly basis thermal energy simulations.

Components: façades, ceilings, and pavements	Thermal conductibility λ (W/mºC)	Density d (kg/m^3)	Specific heat c(J/kgºC)	Global Heat transmission U (W/mºC)	Solar absorption α	Emissivity ε
Exposed concrete	1,65	2200	1005	3,196 (↔)	0,65	0,90
Structured concrete	1,75	2400	1005	3,226 (↔)	-	-
Corrugated metal roof	43	7800	500	4,759 (↓) 7,137 (↑)	0,53	0,25
Epoxy	0,31	1381	1600	0,391 (↓) 0,413 (↑)	0,60	0,90
Concrete	1,28	2000	1005		-	-
Air layer	-	-	-		-	-
Glassfiber	0,04	64	754		-	-
Veil of white glass	-	-	-		0,40	0,90
Carpet	0,06	186	1360	0,384 (↓) 0,405 (↑)	0,60	0,90
Felt	0,04	150	754		-	-
Concrete	1,28	2000	1005		-	-
Air layer	-	-	-		-	-
Glassfiber	0,04	64	754		-	-
Veil of white glass	-	-	-		0,40	0,90

4.2 *Energy Savings*

In order to verify the savings in the consumption of air conditioning it is required the coefficient of performance (COP) of air conditioning system and the pricing adopted by the energy supplier. According to available data, the value of the contract price is R$0.256/kWh. (1R$=0.54US$= 0.37 EURO, in Nov 10th 2010). The HVAC in Buildings A and B is composed of a central chilled water of 360 TRs, supplied by 4 refrigeration units (chillers) with air condensers and scroll type compressors. The expansion system is indirect, by cold water and fancoils, with no cooling towers. The chillers are Trane, model CGAD090-90TR. The cold water at 5°C is pumped to the buildings for bombs with spin control to keep the pressure at 6 kg/cm². Each floor has two fancoils, except the ground floor of Building A and the 1st floor of Building B that have only one each. Adjustment of temperature environments is done by controlling the volume of air blown by flow control valve installed in the distribution pipeline. The return air is full of the liner, or without ducts to the fancoil. Considering the description provided by the client, it was adopted the coefficient of performance of the system COP = 3.0.Considering an area of 3500m^2 per building, the values, presented before in this article, can be applied to forecast electricity consumption for artificial lighting system and equipment, considering the period from 8 to 18h from Monday to Friday throughout the year. Tables 3, 4 and 5 present the results.

Table 3. Thermal loads to be removed monthly by the HVAC system in Bulding A and Building B and respective reductions according to the adopted solutions (film coated, screen and brise-soleil).

	Building A (MWh)				Building B (MWh)			
	actual	film	screen	brise	actual	film	screen	brise
Jan	97,0	96,0	95,5	95,0	94,9	88,6	85,3	83,4
Feb	125,2	123,9	123,2	122,2	122,7	114,5	110,2	107,2
Mar	93,7	92,4	91,7	90,5	93,9	87,1	83,6	79,7
Apr	76,8	75,4	74,6	73,3	80,1	73,3	69,7	65,6
May	64,9	63,6	62,8	61,6	68,7	62,6	59,3	55,7
Jun	54,6	53,1	52,2	51,0	59,8	53,3	49,9	45,8
Jul	52,8	51,3	50,5	49,1	57,1	50,8	47,5	43,2
Aug	63,6	62,2	61,5	60,2	65,3	59,2	56,0	51,7
Sep	58,0	57,1	56,6	55,8	57,8	52,7	50,1	47,6
Oct	76,9	76,1	75,6	75,0	74,7	69,3	66,5	64,7
Nov	79,8	79,1	78,7	78,3	77,7	72,4	69,7	68,2
Dec	85,2	84,3	83,9	83,4	83,6	77,6	74,5	72,9
Year	928	914	906	895	936	861	822	785
Reduction	-	1,5%	2,3%	3,6%	-	8,0%	12,2%	16,1%

Table 4. Annual Energy Costs and Savings for Building A (1R$=0.56US$=0.39EURO, in Dec 15th 2009).

	Actual	%	Film	%	Screen	%	Brise	%
HVAC	R$ 79.226	33,3	R$ 78.020	33,0	R$ 77.381	32,8	R$ 76.403	32,5
Lighting	R$ 97.844	41,2	R$ 97.844	41,4	R$ 97.844	41,5	R$ 97.844	41,7
Equipments	R$ 60.570	25,5	R$ 60.570	25,6	R$ 60.570	25,7	R$ 60.570	25,8
TOTAL	R$ 237.640		R$ 236.434		R$ 235.795		R$ 234.817	
Reduction	-		0,5%		0,8%		1,2%	
Savings			R$ 1.205		R$ 1.845		R$ 2.823	

Table 5. Annual Energy Costs and Savings for Building B (1R$=0.56US$=0.39EURO, in Dec 15th 2009).

	Actual	%	Film	%	Screen	%	Brise	%
HVAC	R$ 79.894	33,5	R$ 73.508	31,7	R$ 70.181	30,7	R$ 67.038	29,7
Lighting	R$ 97.844	41,1	R$ 97.844	42,2	R$ 97.844	42,8	R$ 97.844	43,4
Equipments	R$ 60.570	25,4	R$ 60.570	26,1	R$ 60.570	26,5	R$ 60.570	26,9
TOTAL	R$ 238.308		R$ 231.922		R$ 228.595		R$ 225.452	
Reduction	-		2,7%		4,1%		5,4%	
Savings			R$ 6.386		R$ 9.714		R$ 12.856	

4.3 *Thermal comfort analysis*

For the evaluation of thermal comfort, ASHRAE 55 (2004) was used. Thus, considering the climate-controlled environments, PMV model was applied, which considers the air temperature, relative humidity, air velocity, mean radiant temperature, user activity and type of clothing. Considering the studies that were conducted, the following variables were considered for verification of thermal comfort: air temperature = 24°C (kept constant by the system of artificial air conditioning); Relative humidity = 50% (kept constant by the system of artificial air conditioning); Air velocity <0.2 m/s (at the user level, given the conditions of system); metabolic rate = 1.3 Met (rate of metabolic heat on the daily activities of office); clothing insulation = 0.5 clo (summer clothing: pants and social shirt). Therefore, it remains to determine the mean radiant temperature to see if the conditions are, or not, providing comfort. These values were obtained by the thermal energy simulations performed.

As a result, the curves of mean radiant temperature for the first and fourth floor of each building proved to have lowest and highest values, whilst the results of the second and third floors are intermediate to the previous curves. Thus, the results are going to be considered in terms of the extreme cases. For the given conditions was calculated the operative temperature, which, for the typical situation in question, was estimated from average of the mean air temperature and mean radiant temperature, as recommended by the standard. Performing the procedures prescribed by the standard, it is observed that for the conditions listed above, the operative temperature which provides comfort conditions (percentage of people dissatisfied with the environment in general, considering the criteria of less than 10%) is ≤ 27.2ºC (represented by the strong black line in graphics of operative temperature). Figure 7 and 8 present the final results of thermal comfort in terms of operative temperature, comparing the current situation with the three solutions tested for the case of Buildings A and B.

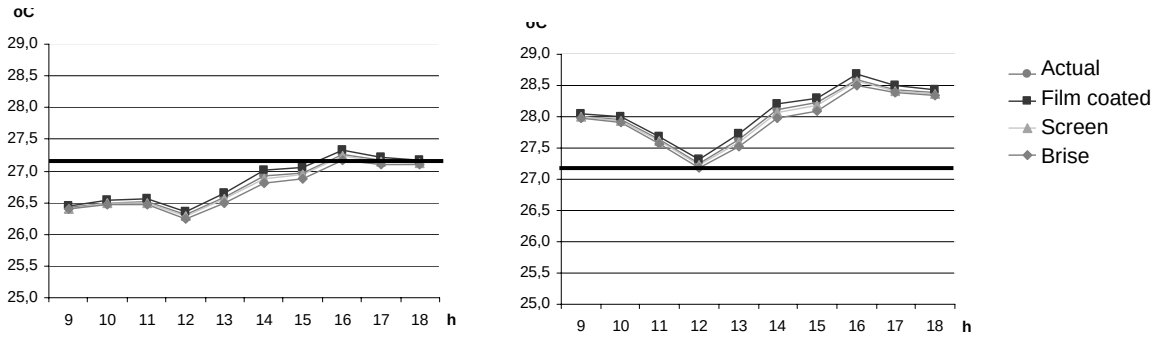

Figure 7. Operative Temperatures for Floors 1 and 4 of Building A.

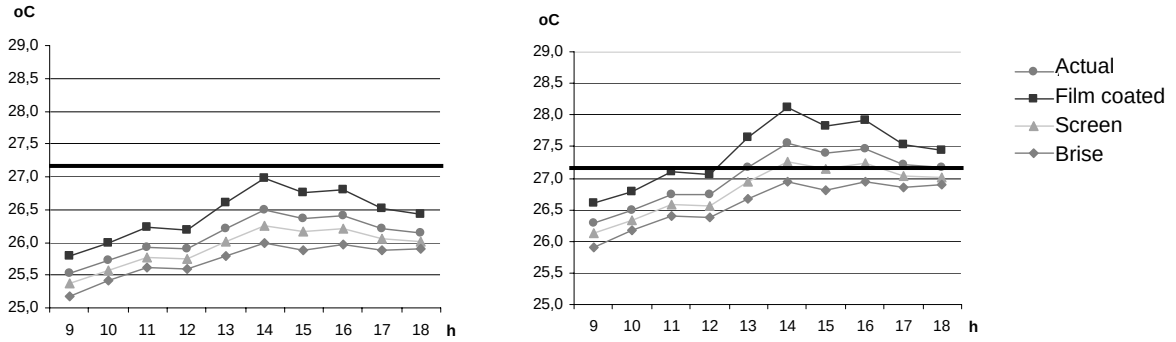

Figure 8. Operative Temperatures for Floors 1 and 4 of Building B.

5 DISCUSSION

Considering the proposed solutions, and the energy saving provided, one may also see the different impacts in terms of thermal comfort considering the maintenance of the initial 24ºC and 50% rh. These parameters could be reconsidered, but for now, the discussion is going to analyze the solutions is term of operative temperature. As can be seen in the graphs of operative temperature of Building A, the use of different solutions of solar protection does not involve significantly the results, with variations of only ±0.1ºC. This result is the verification for a hot summer day, and there is no occurrence of direct solar radiation on the north facade of Block A, for which solutions were studied. With respect to Building B, the operative temperature charts showed the most disparate results between the various solutions. This is because the glazed facades of north and south make the most significant for the rest of the building and mainly due to the different performance obtained with regard to blocking the direct solar radiation on the south facade, since it is a summer day. Looking at the chart to the first floor, the current situation and all the proposed solutions provide a level of comfort. However, one must emphasize that the solution of film coated presents performance well below the current situation, without it. Considering the situation of peak at 14h, the current situation presents operative temperature of 26.5ºC while the adoption of the film coated increase operative temperature to 27.0ºC. Throughout the day, on average, the adoption of the film coated increases by 0.3ºC the average operative temperature. As for the situation on the fourth floor, as argued for Building B it also becomes more critical. In this case the graph shows very different results for different solutions, indicating that the current situation is outside the comfort zone from 14h to 16h. The use of film coated takes the operative temperature from 27.6ºC up to 28.1ºC. The consequence is that from 13h to 18h it is outside the comfort zone. Since the solution of the screen provides comfortable conditions virtually throughout the day (only at 14h it has a peak operative temperature of 27.3ºC). Finally, the brise soleil solution presents itself as the most favourable, providing all day comfort conditions, with a maximum operating temperature of 27ºC, within the comfort zone.

6 SUMMARY

Table 6 presents a synthesis of the results found considering the solar and daylighting analysis, exterior visibility, energy saving and thermal comfort for different solutions (film coated, screen and brise-soleil) for the façades of the two different studied buildings. Considering the results presented, the solutions found to the first building (facing mainly North and South) show results with small reductions in energy consumption for air conditioning, respectively 1.5%, 2.3% and 3.6% for solutions with film coated, screen and brise-soleil, whereas estimates total energy reduction in respectively of 0.5%, 0.8% and 1.2%. When considering the results for the second building (facing mainly East and West), the results show more significant reductions in energy consumptions for air conditioning: 8.0%, 12.2% and 16.1%, estimating total energy reduction for respectively of 2.7%, 4.1% and 5.4%. Considering the results presented, the film coated solution provided an excessive daylight penetration, although does not alter the exterior visibility. On the other hand, it provides very low to low energy savings, worse thermal comfort conditions than the actual ones. The screen solution provides satisfactory illuminance levels and reasonable homogeneity, but with some alterations in the exterior visibility. Energy savings can be very low to considerable ones, providing better thermal comfort conditions than the actual ones.

Table 6. Final results for solar, daylighting, exterior visibility, energy saving and thermal comfort (R$=0.54US$=0.37EURO, in Nov 10th 2010).

	Film	Screen	Brise-Soleil
Solutions	Prestige Line Model P70 Brand 3M	Generic (to be produced) Luminuous transmission and solar transmission: 50%	According to drawings presented in this article
Daylighting	Satisfactory to excessive Reasonable homogeneity Façade: North, Centre, South Bldg.A: 760, 440, - lx Bldg.B: 700, 220, 620 lx	Satisfactory Reasonable homogeneity Façade: North, Centre, South Bldg.A: 600, 340, - lx Bldg.B: 520, 160, 460 lx	Satisfactory Adequated homogeneity Façade: North, Centre, South BlocoA: 560, 400, - lx BlocoB: 300, 220, 380 lx
Exterior Visibility	Practically no alteration	Alteration in quality	Alteration in quantity
Energy Saving	Bldg.A: Very Low Bldg.B: Low HVAC Energy Saving Bl.A: 1,5% Bl.B: 8,0% Total Energy Saving Bl.A: 0,5% Bl.B: 2,7% Annual Financial Saving Bl.A:R$1.205 Bl.B:R$6.386	Bldg.A: Very Low Bldg.B: Considerable HVAC Energy Saving Bl.A: 2,3% Bl.B: 12,2% Total Energy Saving Bl.A: 0,8% Bl.B: 4,1% Annual Saving Bl.A:R$1.845 Bl.B:R$9.714	Bldg.A: Very Low Bldg.B: Considerable HVAC Energy Saving Bl.A: 3,6% Bl.B: 16,1% Total Energy Saving Bl.A: 1,2% Bl.B: 5,4% Annual Financial Saving Bl.A:R$2.823 Bl.B:R$12.856
Thermal Comfort	Worse than actual (heating of glasses due to greater solar absorption of the film) Discomfort (hot summer): Bldg.A Pav1: 16h Bldg.B Pav4: 13h to 18h	Better than actual (cooling of glasses due to their partial shading by the screen) Desconforto (hot summer): Bldg.A Pav1: None Bldg.B Pav4: 14h	Far better than actual (better cooling of glasses due to their shading by the brises-soleil) Discomfort (hot summer): Bldg.A Pav1: None Bldg.B Pav4: None

Finally, the brise-soleil solution proved to be the most adequate one in the relation between energy and environment. It provides satisfactory illuminance levels and adequate homogeneity, although reduction in exterior visibility. Energy savings vary as well from very low to considerable, but are the most significant among the three studied solutions and, considering thermal comfort, it provides the better results. As a conclusion, based on the results found for the specific case studies, despite the difference in the amount of energy savings in each buildings, in both of them the results point out to the film coated as the weakest solution, the screen as a quite good one, and the brise-soleil as the more adequate of them.

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Solutions for thermal renovation of precast concrete wall panels – Case study

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ABSTRACT: Concrete residential buildings present the largest retrofitting challenge in Eastern European countries and represent one of the most used structural systems for multi-family residential buildings in Romania. In order to reduce the heat loss through the façade and to meet the modern internal ambient regulations, it is necessary to improve the energy efficiency of residential buildings by sustainable renovation solutions. In this way, besides the economic and social benefits, there are also predicted large reductions in environmental emissions. The study presented in this paper considers two initial situations for the precast concrete wall panels, whether taking into account the embedded insulation or not; the latter situation is considered due to the high degree of thermal insulation degradation, arrived during the years. The final aim of this research is a comparative study on different thermal retrofit solutions for sustainable renovation of prefabricated concrete residential buildings. Aspects related to costs, raw material consumption, environmental impact and energy efficiency are considered.

1 INTRODUCTION

The residential buildings with concrete structure represent one of the most used structural systems for multi-family residential buildings in Eastern Europe, including Romania and, due to the lack of ambient original design, they represent now the largest retrofitting challenge in Eastern European countries.

Sustainable development in construction sector assumes implications in design options (the choice of building materials etc.), in architectural aspects and should contain considerations on energy efficiency and environmental impact. Most of the results derived from environmental impact analyses carried on buildings clearly show the fact that the dominant impact factors are related – directly or indirectly – to the energy use (Ciutina et al. 2009). It should be underlined that even in the case of materials, much of environmental impact is due to the material processing, transportation, machine use etc. that could be translated in terms of energy.

Almost all research institutes show that the building sector represents the largest energy consumer, therefore being also the primary source of carbon dioxide, accounting for half of all global warming gas emissions. In conclusion, energy consumption could be considered as the principal culpable for the environmental impact. At a global level, there exists an interaction among energy, economic growth and sustainable development. This is known as the "energy trilemma" and involves three parameters: energy consumption, economic development and environmental impact (Khan 1992). The interaction of parameters is of a prime importance in finding solutions.

2 ROMANIAN BUILDING STOCK

Population and Housing Census of 18 March 2002 (National Institute of Statistics 2002) has shown that the existing housing fund in Romania is consisting of 4,846,572 buildings (8,110,407 homes), of which 23.5% urban buildings (52.5% of households). Most of these homes are located in buildings with ages between 15 and 55 years, characterized by a low level of thermal insulation and advanced wearing. In terms of energy consumption, the residential sector ranks second in the economy. In the year 2001, final energy consumption in the domestic sector was 7197 thousand toe (tons of oil equivalent).

The structure of existing residential buildings in Romania is usually made of masonry, pre-cast concrete panels, or reinforced concrete frames and / or diaphragms and the envelope of these buildings usually is characterised by a reduced level of thermal insulation, between 0.54 and 2.43 (see Figure 1).

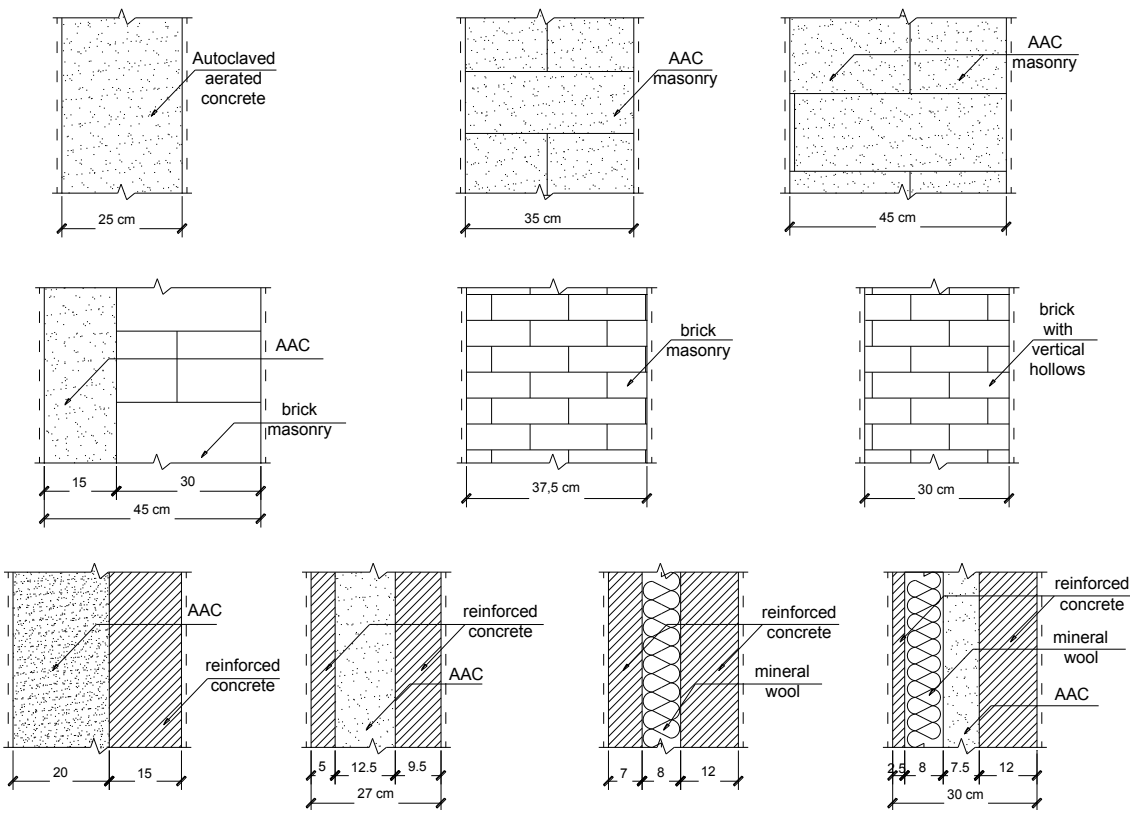


Figure 1. Typical external wall sections used in Romania between 1960 and 1990. (Dan et al. 2007)

It should be noted that, up to now, the rehabilitation of these structures was never done or started, only a very shy process. Usually for the residential buildings, having flat roofs, that underwent improvements, the only measures taken were the conversion of the roof to an attic or a loft. In a few cases, external wall insulation (usually a polystyrene layer of 5 cm), disposed over the existing finishing was applied. Considering these aspects, the general policy (sustained also at governmental level by the "thermo-energetic programme" is to enhance the thermo-energetic performance in buildings, conducting also to reduced environmental impact, durability and structural safety of the buildings.

A large number of low and medium-rise residential buildings were made of precast concrete panels structures. These panels were mass produced items, in specialized plants, transported and assembled on site. Since 1960, this type of structure has been widely used in housing construction and, in particular, for the construction of residential buildings with four and eight sto-

ries, respectively, for single and boarding homes, based on standardized building designs, carried out by IPCT (Institute for Standardized Building Design), adapted to local conditions and technology by County Design Institutes. The most used building designs are the projects IPCT no. 770, 994 and 1013-1168 (for four-story buildings), IPCT 772 (for eight-story buildings), each with several types of sections (GP 110-04 2005).

3 WALLS RENOVATION SOLUTIONS

3.1 *Overcladding*

The aim of this research is a comparative study on different thermal retrofitting solutions for sustainable renovation of prefabricated concrete residential buildings. Due to the low disturbance of the inhabitants and to both thermal and cost efficiency, overcladding has become the most popular solution for renovating the exterior of buildings. The main types of overcladding solutions are presented by many researchers and companies, emphasizing their features and advantages. Rodriguez (2010) presents the main benefits of this system: an increase of the service life, revenue and value of the building, better appearance, addressing internal problems by higher thermal and acoustical performance, reducing both energy and maintenance cost.

Lawson et al. (1998), besides describing overcladding solutions and highlighting their key features, proposed some design considerations based on the following performance requirements: structural performance, robustness, rapid installation, insulation, weather-tightness and breathing of the walls, durability, fire and impact resistance, aesthetics and easy repair and maintenance. A variety of materials can be used for over cladding, such as panels of polystyrene, composite (or sandwich) panels or metallic cassette panels supported by light steel subframe members, attached to the existing structure. The insulation is laid behind the new siding and may be attached directly to the existing wall. In order to apply a global renovation strategy, overcladding is often combined with over roofing and changing of the windows; in this way, the overall savings in energy use are efficaciously increased. A large number of buildings in Europe have been already overclad using a variety of cladding systems.

Most modern overcladding solutions are designed as 'rain screens', a cavity being formed between the new and existing wall (see Figure 2), as external wall insulation used in this manner has superior performance, since it eliminate the condensation risk. Rain screen cladding consists of an outer weather resistant decorative skin, having available a wide range of materials, finishes, colours and patterns, fixed to an underlying structure by means of a metallic substructure. This type of facades is not normally sealed and a ventilation cavity is provided behind the cladding panel, in which water resistant insulation can be provided. To enable ventilation and drainage of moisture, ventilation openings are disposed both at the bottom of the wall system and above windows.

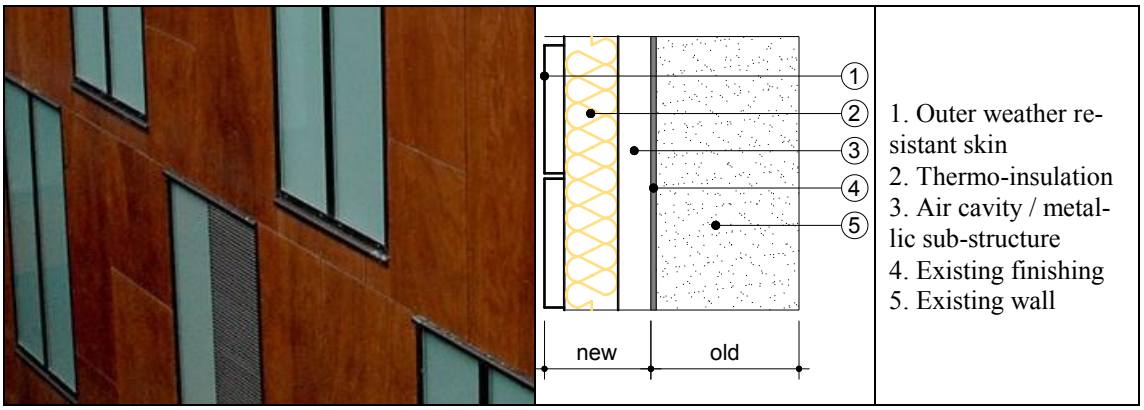


Figure 2. Modern thermal retrofitting solutions - Rain screen panels (Drayton Windows Limited, 2010).

The research has two phases, comprising a large number of thermal retrofitting solutions. The first part focuses on the 'traditional' solutions, Solutions 1 to 4 (see Figure 3) presented in this paper, while the second one, under research at the CEMSIG Laboratory, will focus on

modern solutions, such as composite (or sandwich) panels, metallic cassette panels, thermal cavity system walls.

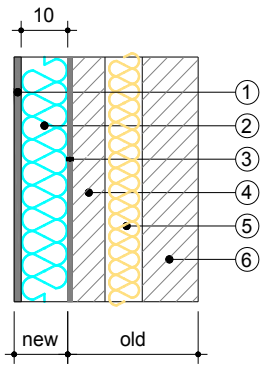
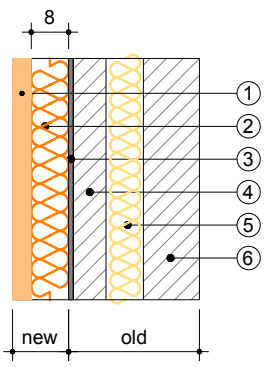
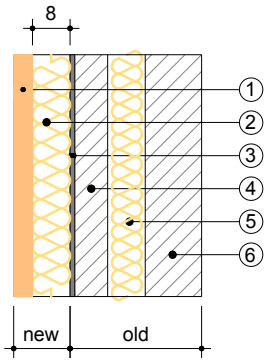
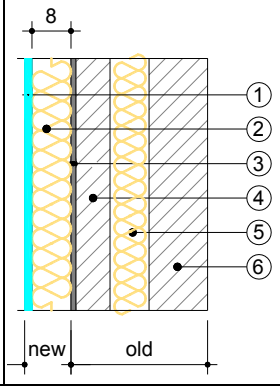
Solution 1		Solution 2	
	1. Exterior plastering / Polyester wire lattice (glass fibre) 2. Thermo-insulation (expanded polystyrene) 100mm 3. Existing finishing 4. Protection layer (concrete) 5. Embedded thermo-insulation 6. Reinforced concrete		1. Rigid mineral wool 80 mm 2. Fibreboard siding 3. Existing finishing 4. Protection layer (concrete) 5. Embedded thermo-insulation 6. Reinforced concrete
Solution 3		Solution 4	
	1. Cold-formed profile / Mineral wool 80 mm 2. Fibreboard siding 3. Existing finishing 4. Protection layer (concrete) 5. Embedded thermo-insulation 6. Reinforced concrete		1. Cold-formed profile / Mineral wool 80 mm 2. PVC siding 3. Existing finishing 4. Protection layer (concrete) 5. Embedded thermo-insulation 6. Reinforced concrete

Figure 3. Components of the thermo-systems proposed.

3.2 *Solution 1: Polystyrene attached directly on the façade*

Solution 1, the most commonly used Exterior Insulation and Finish System (EIFS), consists of polystyrene foam insulation installed with mechanical fasteners to the substrate, glass fibre mesh, and exterior plastering. In the past, moisture problems have occurred, therefore, most exterior insulation systems today include a vapour barrier installed at the external face of the existing wall.

While polystyrene is widely available, affordable, well insulating, it has a few drawbacks. It is not resistant to insects; sunlight degrades if it is not properly protected. Nevertheless, its main disadvantage is the high flammability, necessitating the addition of a flame-retardant chemical, a persistent, bio accumulative toxin; moreover, polystyrene emits toxic smoke when burned, therefore it may require construction of an additional firebreak.

3.3 *Solution 2*

The second proposed system consists of rigid mineral wool and fibreboard siding. Its natural fire resistance gives it an advantage over other insulating materials, with melting point at around 700°C and no smoke developed. Another advantage of this solution is that the insulation is within the cladding system, while the installation technique is very fast due to large size panels. However, this system has the disadvantage of the high weight of the insulating material, which leads to additional structural permanent load.

3.4 *Solution 3*

The system consists of mineral wool installed on a stud framing and protected by fibreboard siding. Having the advantage of lower weight, the insulating material has, just like the rigid mineral wool, excellent fire, acoustic, and thermal properties, is hydrophobic, doesn't need flame retardants, and is termite resistant, making it an attractive alternative to polystyrene. The major disadvantage of this solution is the stud framing inside of the cladding system, insulation being placed between these studs. The areas around the studs are not insulated properly.

3.5 *Solution 4*

This system is very similar to Solution 3, only the siding is different, in this case PVC instead of fibreboards. This solution is not very popular in Romania, but it is widely used in other countries (e.g. the United States). Although the siding is lighter and easier to install, it has the downside that it emits toxic smoke when burned.

4 ECONOMIC AND ENERGETIC ASSESSMENT OF RENOVATION SOLUTIONS

The starting point for the economic and energetic assessment is the as-built wall system, with two layers of reinforced concrete and embedded insulation (see 'old' strata in Figure 3).The discussion that arises is if the embedded layer of insulation is still effective. In many cases, during rehabilitation works was discovered that the insulation layer is highly damaged or destroyed In this conditions, two initial situations were considered Further, aspects related to costs, raw material consumption, environmental impact and energy efficiency (R-value insulation properties) are presented.

In the recent years, energy saving measures have become more and more popular due to the rising prices of energy (fuels) and due to Romanian governmental programmes:

- Green House Program – Environment Fund Agency under Order 950/17.06.2010 issued by Ministry Of Environment;
- Sectoral Operational Programme "Increase of Economic Competitiveness" (Pos Cce), Priority Axis 4: Increasing Energy Efficiency and Security of Supply, In the Context of Combating Climate Change, Area of Intervention - Efficient and sustainable energy (improving energy efficiency and environmental sustainability of the energy system).

Different studies showed that it is cost effective to invest in energy saving insulation measures, as the payback time is low, justifying thus the investment. Previous economic assessments have shown that the renovation work will return savings in heating bills and increase the value of the building due to the improved internal and external environment; therefore, the renovation work can be self-financing over a 20-year period (SCI 2008).

The cost efficiency of energy saving increases when no energy insulating components are present prior to the renovation and when the insulation measures are combined with other renovation measures: renewal of finishing elements, replacement of windows or glazing, efficient heating installations (Vrijders et al. 2010). Therefore, renovation could be considered to be more efficient (from environmental and economical point of view) than demolition and reconstruction.

For each of the proposed solutions, an economic assessment has been performed. The costs presented in Table 1 represent estimated values for the proposed technologies, being subjected to present Romanian conditions of the building economic environment.

Table 1. Estimated costs for the proposed solutions (EUR/sqm).

System	*Solution 1*	*Solution 2*	*Solution 3*	*Solution 4*
Materials cost*	11.63	9.27	8.16	7.21
Labour	3.3	3	3.3	3.3
Machinery	0.38	0.38	0.38	0.38
Total	15.31	12.65	11.84	10.89

**includes basic materials and fastening means*

The cost for Solution 1, which is currently the most used in Romania, is by 21% to 40% greater than the cost of alternative solutions 2, 3 and 4. All three solutions using mineral wool as the insulating layer have similar costs, the one using rigid mineral wool being slightly more expensive.

From the thermal insulation point of view, Table 2 shows the procedure of calculation of the thermal resistance for the existing external wall configuration by using Equation 1. From the wall materials, there have considered only those having an important thermal resistance (mortar, polystyrene and reinforced concrete). The stratification of this wall, together with the proposed thermo-systems is given in Figure 2.

Although the designed stratification is the one presented above, due to the high degree of degradation or even absence of the embedded thermal insulation, documented during the renovation of such residential buildings, further on in this study, the existing wall will be assumed to have no insulation.

The proposed solutions were chosen in such a way to achieve similar indoor environment, by having thermal resistances for each of the obtained walls as close as possible. Although the purpose is to obtain similar thermal resistances for each proposed renovation solutions (see Table 3), one cannot arrive to a unique value by considering standard layer thicknesses for the insulating materials.

Table 2. Thermal resistance computed for the initial stage, considering the embedded insulation.

No.	*Layer*	*Thermal conductivity, λ (W/mK)*	*Layer thickness, d (m)*	*Thermal resistance, R_k=d/λ (m^2K/W)*
1	Reinforced concrete	2.03	0.19	0.094
2	Mineral wool G100	0.048	0.08	1.666
3	Internal plastering	0.93	0.01	0.011
4	External plastering	0.93	0.02	0.021
				R_0=1.761

Table 3. Thermal resistances of the proposed renovation solutions.

No.	*Solution*	*Effective thermal resistance of the existing wall (m^2K/W)*	*Thermal resistance of the insulation layer only (m^2k/W)*	*Effective thermal insulation of the retrofitted wall (m^2K/W)*
1	Polystyrene and external plastering	0.262	2.289	2.551
2	Rigid mineral wool sided with fibreboard	0.262	2.42	2.682
3	Mineral wool sided with fibreboard on cold-formed structure	0.262	2.2	2.462
4	Mineral wool sided with PVC on cold-formed structure	0.262	2.579	2.841

$$R_{ef} = R_i + R_e + R_o = 0.167 + 1.761 = 1.928 \quad (1)$$

where R_i = thermal resistance of the limit layers at the inside; R_e = thermal resistance of the limit layers at the exterior

5 ENVIRONMENTAL ASSESSMENT OF RENOVATION SOLUTIONS

The environmental impact was determined by considering the above input data for the renovation solutions under consideration, by life-cycle assessment (LCA), conducted using SimaPro computer software (SimaPro 2008). All the results are given in “eco-points” (Eco-indicator’99) in order to have unitary and comparable outcomes. The method used for impact analysis is Eco-indicator’99 (Ecoinvent Centre 2004).

5.1 *System Boundaries*

Ideally, an LCA should include the entire life cycle of the system and all the processes linked to it, but in practice, depending on the goal of the study, decisions have to be made regarding the inputs and outputs included in the analysis.

Therefore, in the analyses were included the production, installation and end-of life of the materials included in the renovation work. In order to set the input elements (inventory), both for simplifying the model and timesaving, the inventory analysis has been done according to system boundary conditions, in which several aspects were considered:

- the use of the building was not taken into account because the solutions were chosen in such a way to achieve similar indoor environment, therefore a similar energy use could be forecasted;
- transportation was not taken into account, although the values (especially the weights) are different from system to system;
- energy and equipments used for construction purposes (such as cranes and other technological machinery) were not integrated in comparison.

5.2 *Life Cycle Inventory (Input Data)*

For LCA calculation of building, the input materials have been considered according to the stratifications presented above. In order to have an easier input of construction materials in LCA tool used, there have been computed average values for the weight of materials. These have been estimated for each solution, the values representing an aggregate average per square meter of constructive element. This represents in fact the inventory used for SimaPro.

It is certain that the process is not complete without an end-of-life for the materials if considering the life-cycle approach. Normally the final destination of waste building materials represents a problem in every country, but may differ even within a country, from zone to zone.

For the purpose of our study, the end-of-life of integrated materials was thought according to present conditions in Romania for recycling, reuse and disposal. These are summarised in Table 4, for the main building materials considered.

Table 4. End-of life for building materials.

Building material	*Reuse [%]*	*Recycling [%]*	*Burn [%]*	*Landfill [%]*
Steel – steel profiles, steel tiled sheets	---	100	---	---
Wooden materials	35	---	65	
Concrete, mortar	---	---	---	100
Other inert materials	---	---	---	100
Other combustible materials	---	---	100	---

5.3 *Interpretation of life-cycle analysis results*

Considering an environmental impact analysis for the construction stage on different impact categories, the highest impact values result for Solution 2, followed closely by Solution 1, which is in fact the most used system nowadays in Romania, as it can be seen in Figure 4, presenting the results on impact categories. This fact is also confirmed by the single-score result (see Figure 5), in which the best impact (0.82 points) is obtained in case of Solution 3, about 40% smaller than the global score of Solution 2 (1.66 points). By far, Solutions 3 and 4 are the best choices, having a significantly lower environmental impact.

In case of Solutions 2, which has the largest impact due to the weight of the insulating material, the main impact category is respiratory inorganic emissions, due to the production process of rock wool, bringing 51% from the total score. It must be noticed that with this exception, for each of the other solutions, more than 60% of the total score is given by the fossil fuels, used generally in processing of materials.

It should be noted that even though the life-cycle impacts of mineral wool- production—primarily energy consumption—are significant, some of these are nowadays mitigated by producers through the use of pre-consumer recycled slag from iron manufacturing.

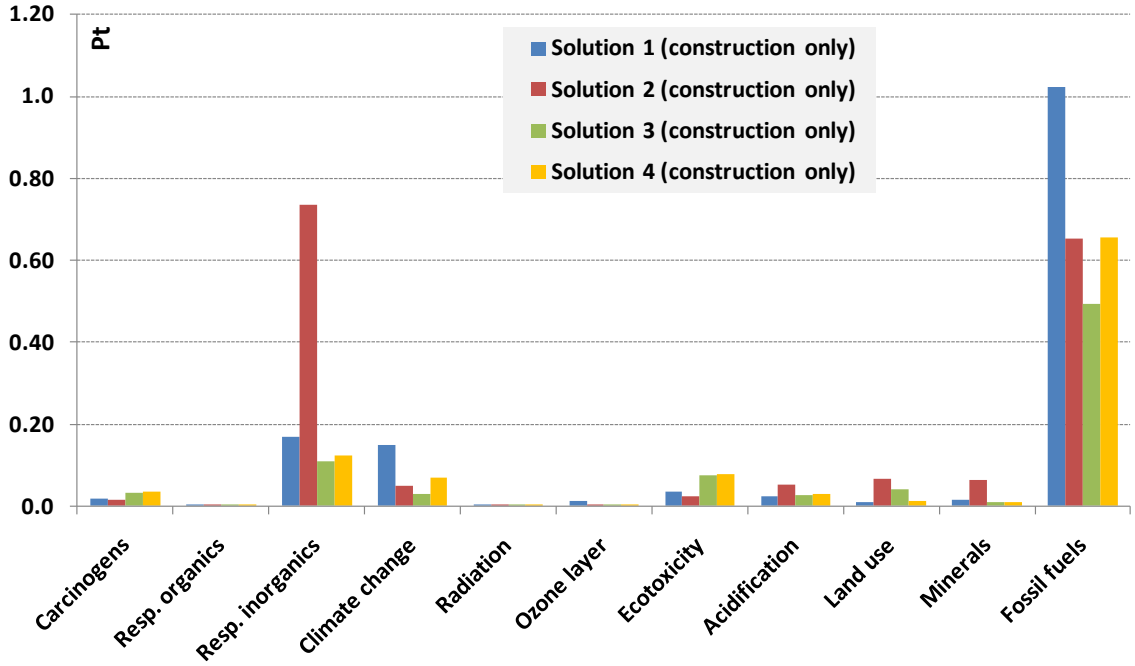


Figure 4. Comparison on environmental impact for the construction stage only (weighting).

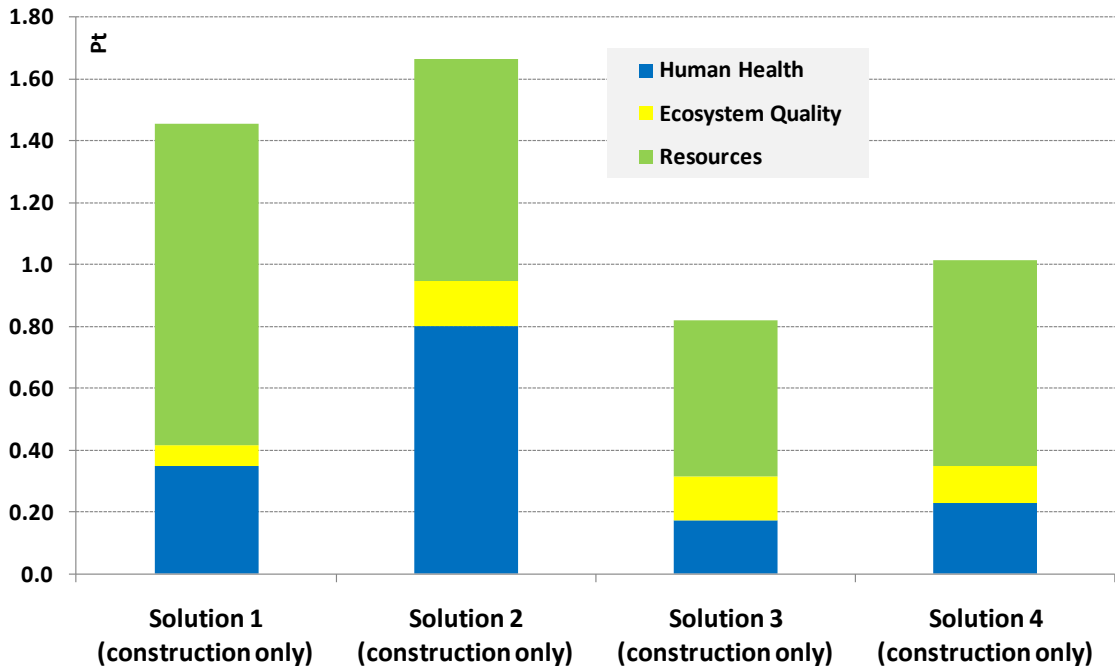


Figure 5. Comparison on environmental impact for the construction stage only (single score).

The life-cycle comparison, for construction and disposal scenario, conduct to similar results to those for the construction stage only (comparison of Figures 6 and 7 with Figures 4 and 5 respectively). Ranked in a single score (Figure 7) it results that Solution 2 affects the environment more than twice compared to Solution 3. The same impact categories (fossil fuels, respiratory inorganic substances, climate change and ecotoxicity) bring the greatest impact.

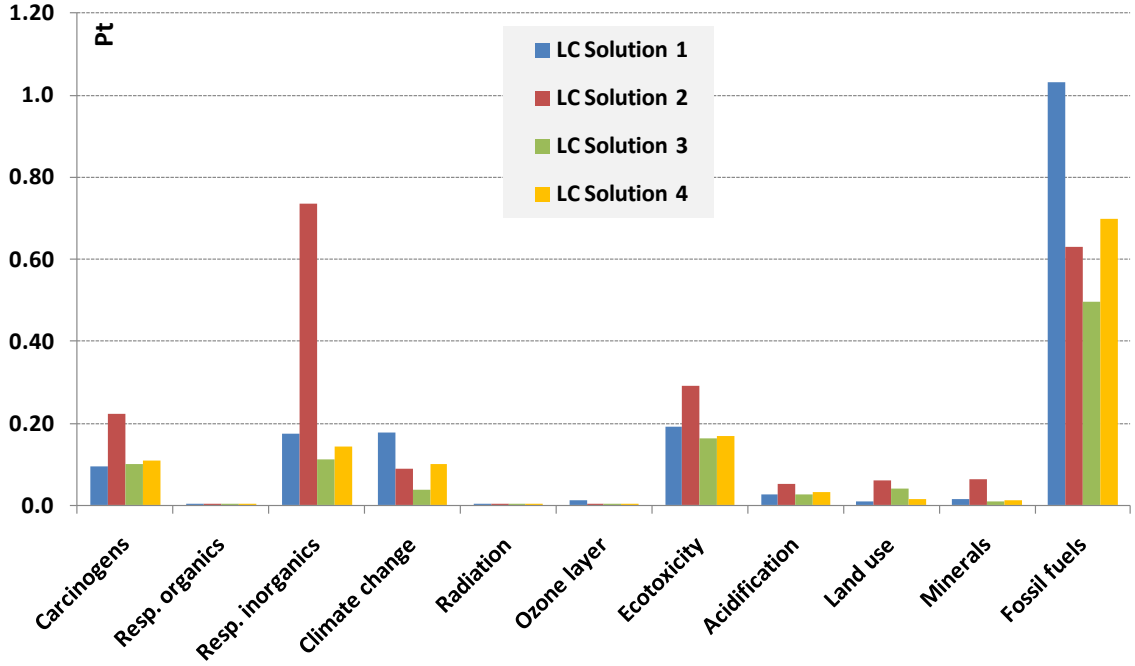


Figure 6. Comparison on environmental impact for the construction and end-of-life stage (weighting).

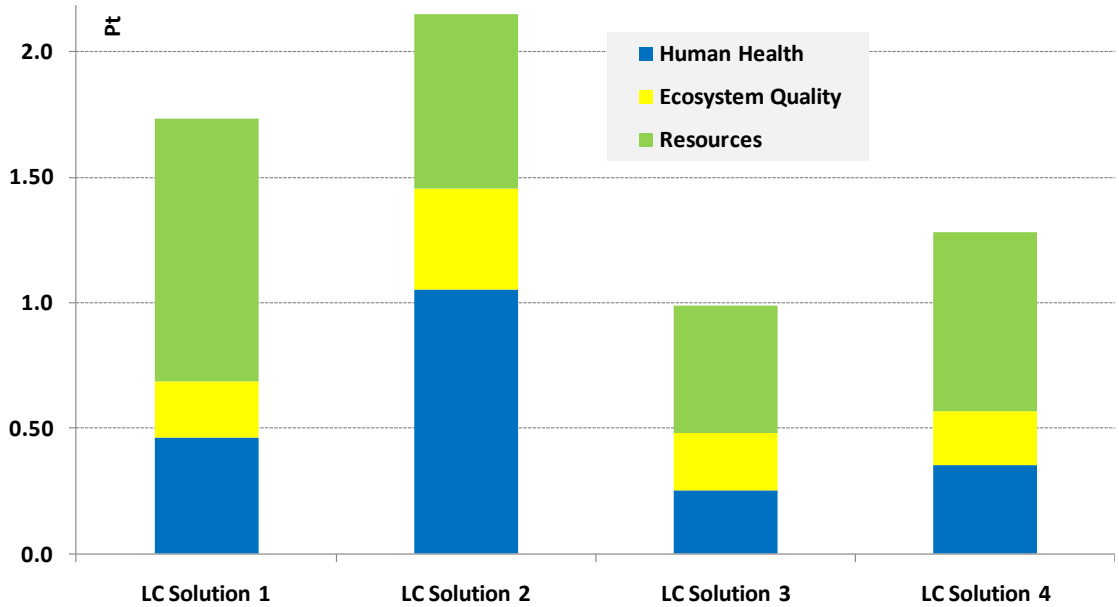


Figure 7. Comparison on environmental impact for the construction and end-of-life stage (single score).

In the case of Solution 4, it can be noticed that the incineration process considered at the end-of-life of the PVC, since usually it is handled in waste-to-energy schemes, brings almost 40% of the environmental impact for the entire LC. Changing the considered disposal scenario to landfill municipal waste or recycling (although nowadays an insignificant quantity of PVC is recycled) would decrease the impact.

Of course, many parameters (such as national or regional peculiarities, climatic zones or distance from the material distributors) may affect these results. From this point of view, one has to observe the trends and not the figures given by analyses.

6 CONCLUSIONS

The study performs an analysis of thermal renovation methods for precast concrete wall panels. The proposed renovation solutions are evaluated from economic, thermo-energetic efficiency and environmental impact point of view, integrating also a documentary study regarding cost efficiency.

Previous experiences in thermal renovation have shown that the embedded thermal insulation of precast concrete panels is highly degraded or is inexistent, indicating the need for thermal renovation. Therefore, the study proposes four renovation solutions, one of them being widely used in Romania (Solution 1), in the attempt that all would lead to similar thermal resistance:

1. Polystyrene and external plastering;
2. Rigid mineral wool sided with fibreboard;
3. Mineral wool sided with fibreboard on cold-formed structure;
4. Mineral wool sided with PVC on cold-formed structure.

The economic assessment and the LCA environmental analysis prove the fact that the most used solution is not the cheapest nor the most 'eco' solution. The most effective solutions from the environmental point of view are the solutions consisting of mineral wool on cold-formed structure (Solutions 3 and 4).

7 ACKNOWLEDGEMENT

This research is related to the PhD work of Ms. Iulia Tuca, partially supported by the strategic grant POSDRU/88/1.5/S/50783, Project ID50783 (2009), co-financed by the European Social Fund – Investing in People, within the Sectoral Operational Programme Human Resources Development 2007-2013.

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Maintenance and retrofitting measures for a monumental building in the Vesuvius area

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ABSTRACT: In this paper, cost effective and sustainable maintenance and retrofitting measures are used in order to upgrade the seismic safety of a masonry monumental building in the Vesuvius area. First, the seismic behaviour of the construction is investigated throughout modal dynamic and push-over analyses developed by using two different computer programs, namely AEDES and SAP 2000. Later on, aiming at eliminating the seismic deficiencies of the investigated building, sustainable, reversible and cost effective retrofitting interventions based on the use of metal elements have been designed and applied into the structure. Finally, the effectiveness of such devices has been proved by numerical analyses on the retrofitted building, whose seismic behaviour is considerably improved.

1 INTRODUCTION

Italy is one of the Mediterranean Countries most exposed to the seismic risk. Considering that a wide cultural and historic heritage is located there, the need to preserve monumental buildings represents an important task for both allowing them to survive destroying quakes without collapse and safeguarding human life. For this reason, ongoing restoration and retrofitting interventions on existing monumental constructions are currently performed on the Italian land. In some cases, since many existing buildings are located into high seismic risk areas, repairing, refurbishment and retrofitting interventions are also required on buildings damaged by possible catastrophic events experienced within the Italian regions.

This work is aimed at the seismic retrofitting of a strategic monumental masonry palace. The examined building is known as *Palazzo di Città* and is located in the historical centre of Torre del Greco, a town in the province of Naples. It has been deeply investigated in the framework of the Research Project COST C26 Action "Urban Habitat Constructions under Catastrophic Events" (http://www.civ.uth.gr/cost-c26/). In particular, within the Working Group 4 (WG4) "Risk Assessment for Catastrophic Scenarios in Urban Areas", some seismic analyses have been performed aiming at assessing the building behaviour under earthquake (Formisano et al., 2008). In addition, volcanic analysis on the study palace have been carried out in order to evaluate its behaviour under a probable eruption of the Vesuvius volcano. Considering that the building showed bad seismic performances, in the current framework appropriate reversible, cost effective and sustainable interventions have been designed and successfully applied to it.

The investigated construction was built as the ancient castle of the first urban nucleus of Torre del Greco, known as *Castrum Turris Octavae* (Castle of the Eighth Tower). During the Angevin Age, the eastern part of the castle was built by including the first ancient norman-swabian tower. In 1420 the castle became property of Alfonso D'Aragona, who decided to improve it with some special interventions, making it his occasionally residence until 1456, when the castle, in very awful conditions, was transferred to the Carafa family. In 1698 the feud was annexed to the Regio Demanio and, after some issues of law, the castle became the common

property of the University under the regency of the first democratic "dummy baron" Giovanni Langella (elected by people).

In 1794, the castle was not destroyed by a disastrous volcanic eruption, thanks to its location far above the ground (28 mt on the sea level) and, therefore, it was equipped as "strategic" building to be used for the emergency management.

In the XIX century, the palace was refurbished by the town Municipality, which decided to upgrade the building in 1927 by means of both the consolidation of masonry structures and the modernization of wiring and plumbing systems. Nevertheless, in 1989, the conservation state of the palace was very poor, as depicted in Figure 1a. As a result, the town Municipality commissioned restoration works, which were completed in 2003 (Fig 1b).

Nowadays, *Palazzo di Città* has not only a historical and architectural importance, but also a strategic one, due to the fact that it hosts the public offices of the town Municipality, which cover a rectangular surface of about 1185 m^2 (Florio et al. 2009).

The building has a tuff masonry structure and develops on two stories surmounted by a pitched roof. The original tuff walls have been consolidated by means of both concrete injection and spritz beton in the last restoration works. The first floor is composed by original vaulted ceilings sustaining the reinforced concrete slabs recently built. The second horizontal structure level was completely restructured by substituting the old floor system with wooden and steel floors. The roof, which is supported on the left side of the building entrance by RC circular columns, has a wooden structure covered by clay tiles.

Considering that both the structure is articulated into a rectangular shape with ratio between sides greater than four and only some floors are infinitely rigid in their plane, the palace can be considered as irregular in plan. This structural behaviour, which has been numerically investigated in the next section, has been improved by designing simple metal based retrofitting techniques.

(a)

(b)

Figure 1. Street view before refurbishment interventions of 1989 *(a)* and present-day main entry of the *Palazzo di Città (b)*.

2 SEISMIC VULNERABILITY ASSESSMENT

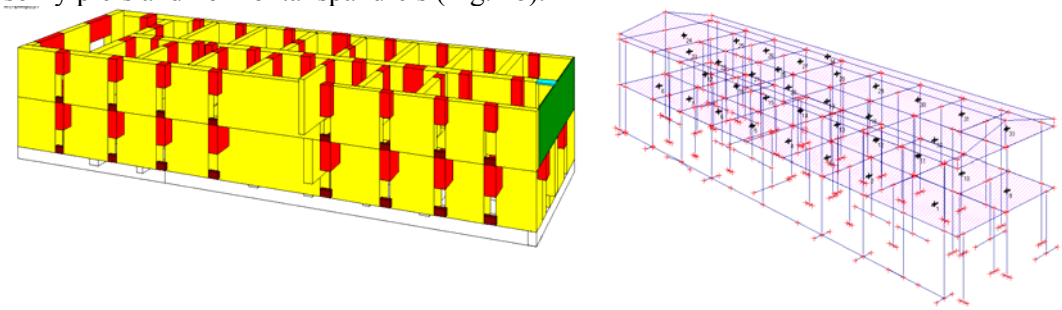
2.1 *General*

Seismic vulnerability is the major step towards a complete evaluation of the seismic risk. Aiming at appraising the major or minor propensity of the examined palace to be damaged under earthquakes, a mechanical analysis procedure has been applied. The employed methodology is based on the application of the Capacity Spectrum Method (CSM) (Freeman 1978), which evaluates the building seismic performance by intersecting its capacity curve with the design response spectrum of a given earthquake level.

Therefore, the first preliminary phase for the application of the CSM is the implementation of a numerical model of the examined structure so that push-over analyses along its main plane directions can be performed and, subsequently, the performance points (PPs) can be detected. To this purpose, two different models have been created by using the AEDES non linear numerical code and the SAP2000 computer program. The results provided by these two analysis programs are presented and compared each other in the following sections.

2.2 *The AEDES model*

Firstly, a FEM model of the *Palazzo di Città* has been created with the AEDES software (2009) by using the PCM macro-model analysis module (Fig. 2a). Later on, the implemented model has been exported into the PCE software in order to obtain an equivalent frame model, composed by a finite number of beam elements with rigid links corresponding to the intersection between masonry piers and horizontal spandrels (Fig. 2b).



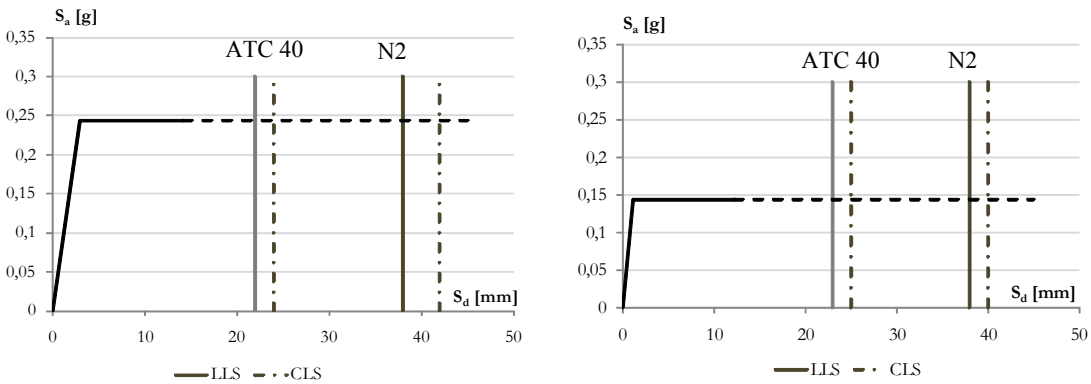
(a) *(b)*

Figure 2. Macro-element model *(a)* and equivalent frame model *(b)* of the *Palazzo di Città*.

By performing a preliminary dynamic modal analysis, it has been found that the first vibration mode is in the transverse direction, it being characterised by a period of 0.223 s, the second is characterised by torsion movements and the third is of longitudinal type.

Then, seismic pushover analyses have been performed in direction X and Y in order to assure a direct comparison between the building capacity and the demand spectrum representative of earthquakes. In each pushover analysis, two different load distributions according to the new technical Italian code (M. D., 2008) have been considered: the first is proportional to masses, while the second is proportional to masses multiplied by the displacements corresponding to the first vibration mode. Therefore, for each plane direction, the mean shear-displacement curve between the two different distributions has been plotted and converted in the Acceleration-Displacement Response Spectra (ADRS) format. The achieved curves have been considered as the effective capacity curves of the building.

According to M. D. 2008, two different earthquake design spectra, namely the life safety limit state (LLS) and the collapse limit one (CLS), characterised by the probability to be exceeded during the structure life equal to 10% and 5% respectively, have been considered. Consequently, these two spectra have been converted in the ADRS domain with the purpose to identify PPs. Afterwards, these elastic response spectra have been adequately reduced according to the N2 Method (Fajfar 1999; Fajfar 2000) and the Overdamped Spectrum one (Freeman 1998; ATC-40 1996). So, by considering the two limit states and the two spectrum reduction procedures applied, four different performance points have been achieved for each analysis direction (Fig. 3).



(a) *(b)*

Figure 3. AEDES analysis results: identification of performance points in the X *(a)* and Y *(b)* directions.

Finally, the vulnerability indexes have been calculated as the ratio between the displacements corresponding to these performance points and the ultimate one of the structure. The results obtained from the analysis are summarised in Table 1.

Table 1. Vulnerability indexes computed by means of the AEDES analysis software.

	Vulnerability Indexes			
	N2		ATC 40	
Limit State	X	Y	X	Y
LLS	2.68	3.10	1.66	1.88
CLS	2.97	3.26	1.70	1.96

The evaluated indexes show that the most vulnerable direction is the transverse one. It may be noted that all the achieved indexes are larger than 1; this means that the performance points, corresponding to the displacements required by the considered seismic event, are always greater than the ultimate structural displacement. Therefore, the building is not able to resist the ultimate limit state earthquakes foreseen by the technical Italian code.

2.3 *The SAP2000 model*

The *Palazzo di Città* FEM model has been also implemented within the SAP2000 computer code environment (CSI 2010) (Fig. 4).

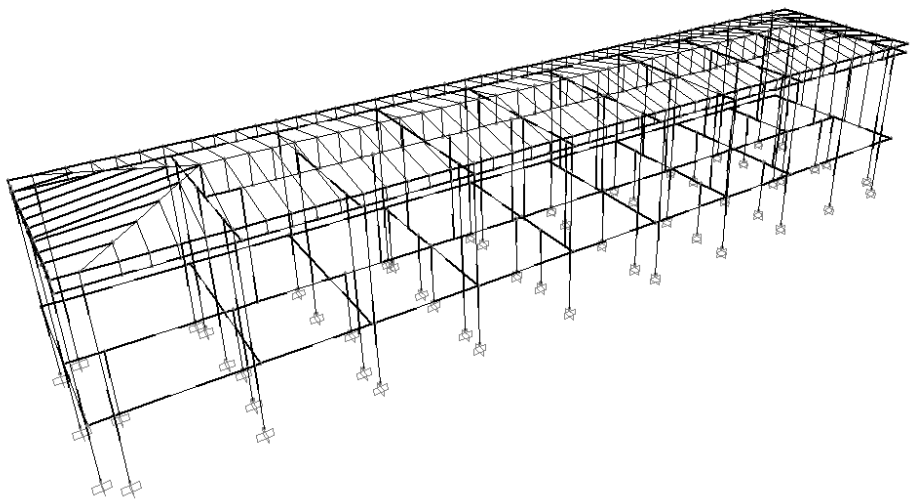
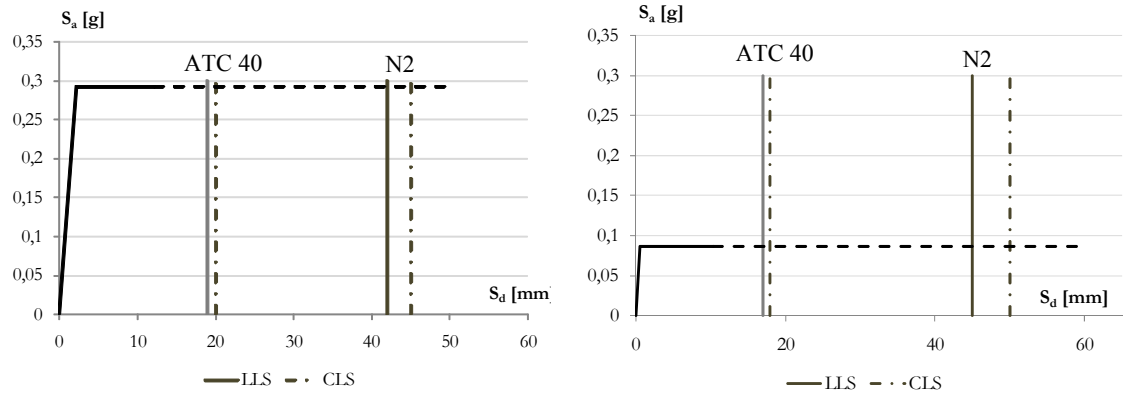


Figure 4. Equivalent frame model implemented with the SAP2000 program.

A preliminary modal dynamic analysis has provided the shape of the vibration modes and the corresponding elastic periods of the structure. In particular, the first vibration mode is of transversal type (T_1=0.228s), the second mode is rotational (T_2=0.251s) and the third one is longitudinal (T_3=0.185s).

Afterwards, static non linear analyses have been carried out both in the longitudinal direction and in the transverse one in order to obtain the push-over curves of the structure. Similarly to the analysis performed by means of the AEDES program, two load distributions have been considered. Thus, both for each direction (longitudinal and transverse) and force distribution (proportional to masses and proportional to vibration modes), the shear-displacement curve has been drawn.

Subsequently, the mean curve between the considered distributions has been plotted, it being representative of the effective behaviour of the investigated structure. Similarly to the previous analysis, the achieved capacity curves have been subsequently converted into capacity spectra in order to apply the CSM. So, also in this case, considering two ultimate limit states (LLS and CLS) and two analysis directions (X and Y), four PPs by applying the N2 method and four PPs by using the ATC 40 one have been achieved, as displayed in Figure 5. Finally, the vulnerability indexes have been calculated, they being listed in Table 2.



(a) *(b)*

Figure 5. SAP2000 analysis results: identification of performance points in the X *(a)* and Y *(b)* directions.

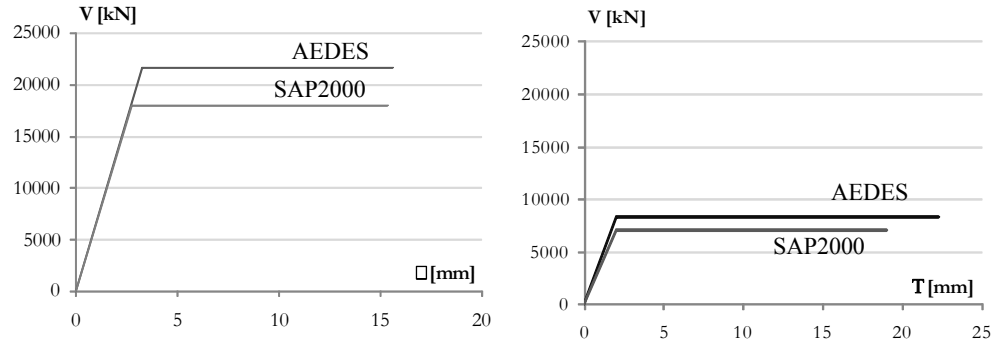
Table 2. Vulnerability indexes computed by means of the SAP2000 analysis software.

	Vulnerability Indexes			
	N2		ATC 40	
Limit State	X	Y	X	Y
LLS	3.43	3.96	1.57	1.70
CLS	3.92	4.34	1.68	1.75

Also in this case, the evaluated indexes reveal that the weakest direction is the transverse one. Finally, the analyses confirm that, since indexes always are larger than 1, the structure collapse should occur under the considered earthquakes. For this reason, retrofitting interventions should be programmed.

2.4 *Comparison among results*

After the mechanical response of the examined building has been assessed by means of the two above calculation programs, a comparison between the two resulting SDOF (Single-Degree-of-Freedom) capacity curves has been done, as depicted in Figure 6.



(a) *(b)*

Figure 6. Numerical comparison between SDOF curves in the longitudinal (X) *(a)* and transverse (Y) *(b)* directions.

It may be noticed that the curves deriving from the two programs are rather coherent in terms of both stiffness and ductility. On the other hand, in terms of resistance, the SAP2000 code underestimates the shear strength, with a similar percentage gap in the two directions (about 25%). Therefore, the AEDES software, which has been created with the specific purpose to analyse masonry structures, provides results more accurate than the SAP2000 one, which is a program used for modelling each type of structural typology, especially steel or concrete framed structures, and furnishes results on the safe side.

With regard to the results provided by the application of the CSM, it is possible to detect that the use of the two spectrum reduction approaches has led to the same vulnerability estimation. In fact, both according to the N2 method and the ATC 40 one (overdamped spectrum), the most seismically vulnerable direction is the transverse one (Y) for the two considered limit states (LLS and CLS). In addition, the N2 method gives results on the safe side as respect to ATC one (Florio 2011). For this reason, it is the method recommended by seismic Italian regulations (M. D. 2008) for the behaviour assessment of existing buildings. Finally, the mean values among all indexes calculated for each direction have been determined (Table 3).

Table 3. Mean vulnerability indexes of the studied palace.

Direction	LSV	CLS
X	2.35	2.50
Y	2.65	2.82

3 THE RETROFITTING INTERVENTION

The performed analyses have evidenced the high structural vulnerability of *Palazzo di Città*, mostly due to the presence of deformable floors at second level and to the absence of metal ties inside the vaults. Thus on the basis of the achieved study, sustainable retrofitting measures are herein proposed for the restoration of this monumental palace.

In general, retrofitting and rehabilitation techniques should be sensitive to the issue of sustainability and to environmental aspects. Above all, a retrofitting technique may minimize building costs and waste and, moreover, be flexible and reversible.

In case of monumental buildings, the strengthening systems based on steelwork are advisable. In fact, steel-based consolidation systems show high mechanical performance and also provide great flexibility in restoration activity. So, the main advantages of steel, which are related to the lightness and the stiffness of the material, apart from the harmonic coexistence with masonry, can be profitably exploited. Moreover, in terms of sustainability, steel elements (as ties or beams) satisfies the demand of reversibility, they being easily replaceable. Steel based systems in restoration also contain low waste due to accurate design specification of steel elements, which provide an overall sustainability improvement, as it has significant influence on both the indoor environmental performance and the use of working energy (Cöcen & Efthymiou 2008).

As a result, the predominant use of metal elements, able to combine structural performances and sustainable issues, has been successfully done for retrofitting *Palazzo di Città* on the basis of the interventions described as follows.

Firstly, the creation of a rigid diaphragm at the second level floor has been made, in order to assure a box-type behaviour of the building based on an adequate distribution of the seismic forces towards all the bearing walls. This has been done by creating a horizontal RC slab able to offer a diaphragm function.

Second, the use of metal ties, which represent an ancient and widespread intervention technique used to eliminate the horizontal thrust of arches, vaults and roofs, has been made. This system is also an effective and reliable technique to obtain a good connection between structural walls, ensuring a box-type behaviour of the entire structure. Moreover, this technique allows to avoid all the out-of-plane overturning mechanisms of masonry walls. The metal tie intervention technique herein proposed consists of the insertion of metal bars, having a diameter of 20 mm and 35 mm in the direction longitudinal (X) and transverse (Y), respectively, at the vault support along two orthogonal directions in order to both eliminate the vault thrust and connect masonry walls each other.

Finally, since two transverse walls are not continuous for the whole short length of the building, transverse connections between longitudinal walls have been created by placing HEB300 steel beams within the existing floors. This intervention enable to have a continuous and almost equally spaced connection between the longitudinal walls of the building, so assuring a better plan regularity.

The scheme of the described retrofitting interventions is shown in Figure 7.

In order to test the efficiency of the seismic retrofitting design, a new FEM model of the palace taking into account all the designed interventions has been set-up by using the SAP2000

program. In particular, aiming at considering the rigid diaphragm at the second floor, the *diaphragm constraint* in the program command library has been employed. Moreover, tendon elements have been inserted in the model in order to consider the presence of metal ties.

First of all, a dynamic modal analysis has been carried out on this retrofitted model. By viewing the results of the Table 4, it is noticed that the modal behaviour of the structure is drastically changed, since modal shapes are clearly defined and the torsional mode is the third one instead of the second one. In addition, a considerable increase of the structural stiffness for each of the fundamental vibration modes occurs. Definitively, the modal behaviour of the building is totally improved.

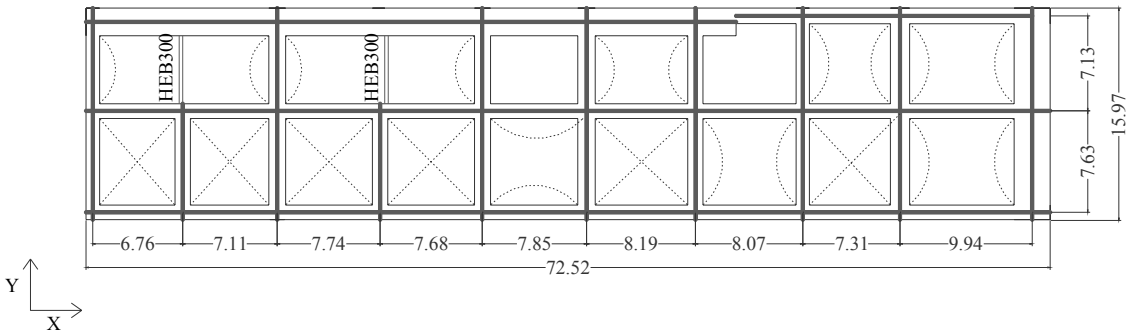
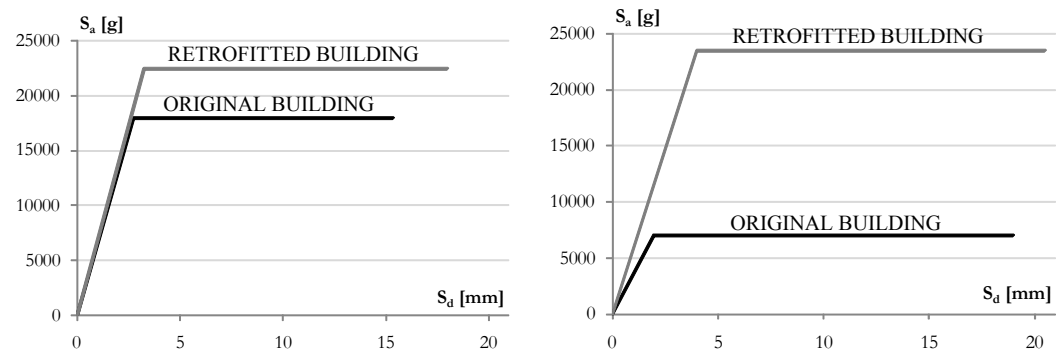


Figure 7. Retrofitting interventions performed at the ground level of the examined palace (units in meters).

Table 4. Comparison between the dominant frequencies of the original building and the retrofitted one.

Original building		Retrofitted building		Stiffness increase [%]
Vibration mode	Period T [s]	Vibration mode	Period T [s]	
1. Transverse	0.228	1. Transverse	0.174	23
2. Torsional	0.251	2. Longitudinal	0.114	54
3. Longitudinal	0.185	3. Torsional	0.100	45

Later on, seismic pushover analyses have been carried out in the longitudinal and transverse directions of the building and the same seismic vulnerability assessment procedure already performed on the unretrofitted SAP model has been repeated. Thus, two different capacity curves have been achieved and then converted into the ADRS format. As shown in Figure 8, from the comparison between the original model curves and the retrofitted building ones an increase of resistance of about 20% in the longitudinal direction and of about 70% in the transverse direction occurs. Also, an increment of ductility of the order of 15% and 8% in longitudinal and transverse directions, respectively, can be noted. Afterwards, the building performance points have been detected by means of the aforementioned N2 reduction procedure, so leading to the vulnerability indexes summarised in Table 5. From this table, it is apparent that, since the indexes are lower than 1, the retrofitted building is able to withstand the earthquakes given by the new technical Italian code at the ultimate limit state.



(a) *(b)*

Figure 8. Comparison between SDOF push-over curves of the original FEM model and the retrofitted one in the longitudinal (X) *(a)* and transverse (Y) *(b)* directions.

Table 5. Vulnerability indexes of the retrofitted buildings computed by means of the N2 method.

Limit State	X	Y
LLS	0.72	0.66
CLS	0.77	0.72

4 CONCLUSIVE REMARKS

In this paper refined seismic vulnerability assessment methods based on a mechanical approach have been applied to a monumental masonry building in the Vesuvius area. To this purpose, the implementation of numerical models of the building by using two distinct computer codes has been done. Pushover analyses performed in the longitudinal and transverse directions of the palace have provided its capacity curves, which allowed to evaluate the performance points and, consequently, its vulnerability indexes. The application of this mechanical procedure has revealed the high vulnerability of the examined construction, which should collapse under the ultimate limit state earthquakes foreseen by the new technical Italian code. For this reasons, some sustainable retrofitting interventions, namely a RC slab at the second floor, metal ties at the vault support and HEB300 beams as connecting elements of longitudinal walls, have been set up, their effectiveness to improve the building seismic behaviour being proved by numerical analyses. Thanks to these interventions, the modal behaviour of the retrofitted structure is drastically improved, with clearly defined modal shapes and a considerable reduction of the modal periods related to each fundamental vibration mode with respect to the ones deriving from the original building. Finally, push-over analyses have been carried out on the retrofitted building and the application of the N2 method has proved its capacity to sustain earthquakes at the ultimate limit state along the two plane directions with damages from heavy to very heavy. In the whole, the achieved results represent a clear demonstration of the usefulness of metal devices as simple and very reliable and sustainable retrofitting system of existing masonry buildings.

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Sustainable Conservation Methods of Improvement and Structural Strengthening of Old Timber Elements of Traditional Turkish Houses

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ABSTRACT: It is said that, traditional Turkish house, which we are trying to describe, with its tiled roof, extended timber projections, all surmounting a heavy stone bearing wall base, has become an icon known worldwide. Most of these constructions are at risk of disappearing, as the evidences of their cultural significance representing their spatial organization, its period's art concept, traditional design and construction technology, emphasizing how important they are. In this context, this study aims to put forward the general construction typology and deterioration reasons of the timber framed Turkish Houses dating back to 18th-19th centuries, and discusses the common approach in the repairing the timber structures for their sustainability.

1 INTRODUCTION

Timber, with rough stone, is the oldest building material the man used, also the most complete before steel was available, because it can be solicited both to compression and tension, therefore bending. Its use was continuous up to the present time. The conservation of timber structures has improved in recent years with a growing appreciation of their historical significance. However there are still difficulties presented because of the limited number engineers with an understanding of timber structures. There are several ways of repairing a timber structure depending on the amount of deterioration the timber elements have.

2 ACQUAINTANCE OF TIMBER STRUCTURES OF TRADITIONAL TURKISH HOUSES

Wood, timber is the main element used in all types of buildings in Anatolia very efficiently combined with stone. Wood can be both used as the structural system element as joists, lintels and plates and as the building components such as fireplace, cupboard and etc. or as the ornamented elements both painted or unpainted.

Timber elements are mostly used as the primary structural elements in residential buildings, and secondary elements in public buildings (Zeren Tanac M, 2010).

It is said that, traditional Turkish house with its tiled roof, extended timber projections, all surmounting a heavy stone bearing wall base, has become an icon known worldwide. Most of these constructions are at risk of disappearing, as the evidences of their cultural significance representing their spatial organization, its period's art concept, traditional design and construction technology, emphasizing how important they are (Tanaç, M., Karaman Ö, 2008).

The construction system of the houses located in Agean Zone of Turkey is a mixed type as common in other regions. First floors are built as masonry made of stone with mud mortar, which are supported by horizontal timbers embedded into wall. The upper floors are built most

commonly by Hımıs technique, but in some cases both Bagdadi and Hımıs techniques are used in the structure system of the upper floors. In this case Hımıs is used in the body of the building while the eaves and the projections are built by Bagdadi. The type of wood used in the timber framework is yellow or black pine (the local flora of the region), kufeki stone (is the local stone type found in the region) is used as the infilling material of the walls. In this study the wooden structural elements are classified as (Tanaç, M., Karaman Ö, 2008):

- Timber Frame
- Hatıls and Lintels
- Projections
- Roof and Floor system
- Timber Building Components

The elements of timber frame can be listed as;

- Lateral load bearing elements: Sole plates, top plates, headers, lateral connection elements and joists.
- Vertical load bearing elements: Posts and secondary posts.
- Diagonals: Diagonal props and bracings.

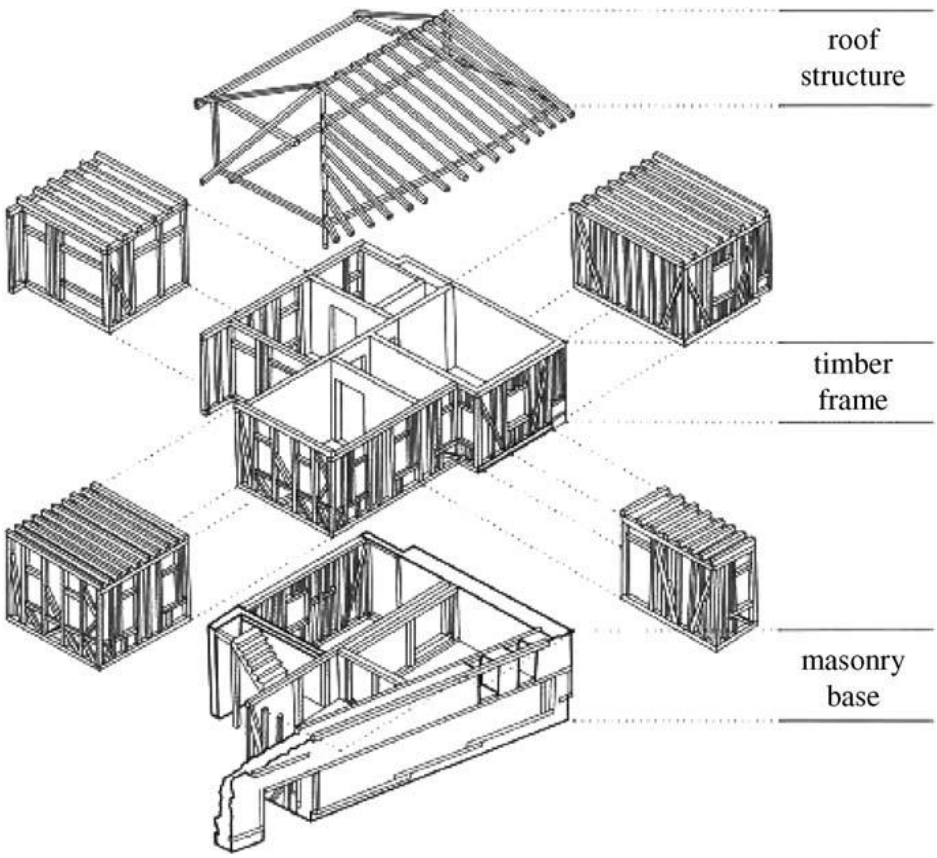

Figure 1. Construction System of Timber Houses (Güçhan Şahin N. (2004), Observations on Earhquake Resistance of Traditional Timber-Framed Houses in Turkey, Building and Environment-42, pp. 849).



Figure 2-3-4. Urban Pattern of the Traditional Settlement (Mine Tanac Photo Archieve-2009).

Figure 5. Sofa Projections to Courtyard.

Figure 6. Room Projections to Street.

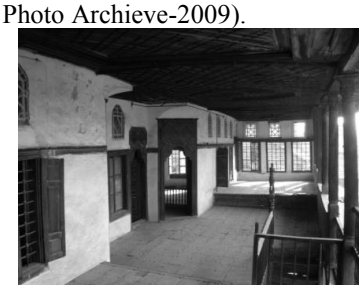

Figure 7. Sofa.

Figure 8-9. Hatıl Construction System.

Figure 10. Hımıs Construction System.

Figure 11. Bagdadi Construction System.

Timber is used as the building component as well as the structural system element in Traditional Turkish houses. Wood is a structural and ornamental element, which is used in Traditional Turkish Architecture frequently as a local material during the centuries. These elements can be classified as;

- *Doors***,** door ornamentations and doorjambs
- *Windows* and window ornamentations
- *Fireplace* and fireplace ornamentations
- *Cupboards* and its ornamentations
- *Ceiling* and its ornamentations
- Wooden facade ornaments such as plasters
- Ornament Elements on wooden projections
- *Stairs*, balustrades, and handrails and their ornamentations

- *Eaves* and their ornamentations

The main structural deteriorations can be seen on:

- Timber roof elements (crashing, demolishing) and eaves
- Masonry wall, timber frame system connections
- the horizontal timber element embedded in the masonry wall (Fungi attacks)
- projections
- carrying system elements; diagonal braces, posts and beams
- Timber floors and coatings
- exterior building components; wooden shutters, windows, bagdadi plasters, doors
- Interior building components; wooden windows, doors, stairs, bagdadi plaster, ceiling and floor decks.

Most of these constructions are at risk of disappearing because of lack of care and restoration. When the damage assessments have been discussed and the reasons for their deterioration have been analyzed, it is seen that Wood being the basic construction material of this type of houses because of its vulnerability cannot be protected against exterior factors. Due to the rapid deterioration of this material, today one can encounter limited number of these constructions.

3 REASONS FOR THE DETERIORATION OF TIMBER FRAMED CONSTRUCTIONS

It must be observed that, if a building has survived, this means that its structure is well designed and that it performed in a satisfactory way throughout its existence. Nevertheless, due to aging, biotic factors, wind, fire, moisture, etc. the ancient structures are affected by decay of the material and mechanical failures. The performance of a structure as a system is ensured by the subsidiary members, by the braces and by the units working through the connections (Tampone & Messeri, 2006).

Ahunbay (Ahunbay, 2004, s. 38-45) (Tampone & Messeri, 2006) classifies the deterioration factors of all the monuments mainly as internal factors and external factors. The location of the building, incorrect methods of constructions, wrong choice of materials, defective workmanship, ground-soil properties are defined as the internal factors, long-term outer effects (Fungus, invasion of insects, frost, wind), natural disasters (earthquake, flood, etc.), man-made reasons like abandonment, incorrect methods of construction, wrong choice of materials, fire, wars, vandalism, air pollution, lack of laws in protecting the structures. The failures are characterized by displacements, rotation, loss of verticality, loss of planarity, deformation (bending, twisting, etc.), loosening the connections.

When Traditional Turkish timber structures are examined in deterioration reasons framework, the most important factor of the deterioration seen in this settlement is the abandonment. Abandonment can be accepted as the starting point of the other deterioration factors. The owners of these big timber structures moved to the new developing part of the town, to reinforced concrete multi-storey apartment buildings, rented their houses to people with lower-income, or left them to their elders whom cannot take care of the repair expenses of the buildings, or left them as they are. The new owners of the houses prefer to live in the courtyards of the buildings where they built new one storied concrete houses, or if they prefer to live in the old structures, they modify them with defective workmanship, incorrect attempts at restoration, incorrect methods of construction, changing the sizes of windows, closing the sofas with aluminum joinery. The emptied timber structures are exposed to long-term outer affects especially rain and wind, which causes fungi attacks, and insect invasion.

From these reasons mentioned above, deterioration of timber structures starts from the components meant to protect the structure from exterior damage, masonry foundations, roofs and surfaces of the building. As Tampone (Tampone G. , 2001, s. 120) says when defining hierarchy and configuration of the general characteristics of the timber structures, a hierarchic organization exists between the systems (timber roof), the units (truss), the members (beam,post, Joists, etc.) and the connections (timber to timber connections, masonry to timber connections). So when deterioration starts in any part of the structure even in the connections, it will spread immediately to the whole picture. As a matter of fact, these effects decrease the carrying ca-

pacity of the timber structure, cause contortion of the sections, causes breaking of the members and finally collapse of the system as the final event.
The main structural deteriorations can be seen on:

- Timber roof elements (crashing, demolishing) and eaves
- Masonry wall, timber frame system connections
- the horizontal timber element embedded in the masonry wall (Fungi attacks)
- projections
- carrying system elements; diagonal braces, posts and beams
- Timber floors and coatings
- exterior building components; wooden shutters, windows, bagdadi plasters, doors
- Interior building components; wooden windows, doors, stairs, bagdadi plaster, ceiling and floor decks.
- The beams of a timber floor resting on masonry walls can produce a hammering effect on the supporting wall, if not properly tied.

4 REPAIR AND IMPROVEMENTS

Assessment of timber structures may be carried out under various circumstances. The easiest case includes the retrofitting of well preserved structure to its original condition, which can be handled with minor replacements or strengthening. In this case it is assumed that the number of years in service is proving of its safety. However, in most cases, either due to conservation problems or change of use, judgement about material strength damage quantification is required (Cruz, Machado, Palma, 2009).

Universally accepted principles are that the load bearing structures must continue to play their planned function, intervention works must be reversible, as far as possible, at least in the intentions, and recognizable, and the interventions should be easily detectable on the spot (Tampone, Meseri, 2006).
For the conservation and the strengthening of an ancient timber load-bearing structure, a few principles are recommended. The general aims of the principles of preservation of old structures are to conserve the "*authenticity*" of the structure and its function in a condition of sufficient safety.

An important point of discussion is what means authenticity for a load bearing structure. Authenticity is the original configuration of the material. The Nara Document states that (1994) *"depending on the nature of the cultural heritage, its cultural context, and its evolution through time, authenticity judgements may be linked to the worth of great variety of sources of information. Aspects of the sources may include form and design, materials and substance, use and function, traditions and techniques, location and setting, and spirit and feeling...the use of these sources permits elaboration of the specific artistic, historic, social, and scientific dimensions of the cultural heritage being examined".*

Making some strategic assessment on ancient timber structures one should take these into account and consideration:

- The historical value of the fabric
- The overall condition of the structure and hence
- The scale of repairs
- The options for the future uses.

One should recognize that different kinds of approaches might be appropriate for different kinds and periods of structure.

- One might try to retain the timbers in a condition as close as possible to the original structure carrying out its original function of supporting the building.
- Or a new structure to support the original timbers that simply remain as an historic artefact.

Between these two there may be a choice of options that the engineer should be able to assist in deciding between. In considering the overall strategy the choices are between;

- Repairing and restoring the as-found structure
- Providing supplementary structure

To obtain the aim of repairing and restoring the as-found structure, at least four levels of interventions, hierarchically should be settled according to the building process that of members (ties, beams, struts), connections, structural units and structural system with supplementary elements. Essential aims when studying a timber structural complex is the identification of the kind of hierarchic organization existing between the systems, the units, the members and the connections present. (Tampone, G. 2001)

When we turn to the tactics of repair, timber with providing supplementary structure, the methods can be loosely divided into three kinds.

1. Those using modified traditional methods
2. Those using steel
3. Those using epoxy resins with or without some reinforcement

If the first option, using modified traditional methods which one is commonly used in repairing the timber elements of Traditional Turkish houses is chosen, one needs to consider the choice between

- Repairing in-situ and,
- Dismantling for repair, either completely or in part.

To preserve the authenticity of the old timber element, the strengthening methods those using modified traditional methods is the most preferable, and most common used one in the cases seen in Traditional Turkish houses. When strengthening the timber structures with modern timber elements, traditional carpentry details and fasteners are commonly used. This method enables the protection of the authenticity of the old timber elements but on the other hand doesn't make the intervention works reversible and detectable during the process. The trend "timber-timber" to strengthen timber structures can also be intended for the use of modern products such as glue laminated wood. This method is used rarely in interventions that take place in Traditional Turkish houses. The repairs that use the modified traditional techniques are made in-situ (Tampone, G., Meseri, 2006). Using traditional materials as the supplementary elements is the easiest way to obtain the authenticity of the old structures.

The repair method of using steel elements as supplementary elements is once commonly carried out by engineers as cutting and putting in supplementary steelwork, and was later deprecated by those who favoured a more "traditional" approach, with traditional carpentry methods or with modern carpentry methods by modern steel fasteners. (Tampone, G.,2001). This method has problems in obtaining the authenticity of the old structures.

In both replacement of supplementary steelwork or supplementary modern carpentry by modern steel fasteners cases, the supplementary elements are visible, and have to form a junction with secondary materials; it does involve a greater loss of historic fabric. In that respect the use of supplementary steelwork is perhaps to be preferred where the repair is not seen.

One problem can be added to the steelwork supplementary elements, and this is the behaviour when used as an adhesive to join steel reinforcing plates to timber. The problem is what is happening at the interface between these two materials, the timber and steel.

Another fact is unfortunately the jointing methods used in new structures are not always appropriate for historic structures. Moreover, historic structures use details that are not used in modern carpentry and therefore for which there is no guidance within design codes, using modern materials and modern methods.

The method of using epoxy-resins as either consolidant, or to replace lost timber appeared to offer a solution for those who wanted the minimum loss of historic fabric, but this ran into technical difficulties. The use of this technique in unsuitable locations where exposure to the weather seems to have resulted in accelerated decay of timber adjacent to the epoxy-resin repair.

There is another method which is commonly used in the repairs of Traditional Turkish Houses and which is not a very correct approach to preserve the authenticity of the building. This method is used when there is no chance to consolidate the ancient timber element. If the amount of the crack of the element is too big, then the method of replacement of suitable timber structures, by steel or again timber structures can be used. In the last situation, the lack of expertise on wood as a structural material often leads to replacement of suitable timber structures,

by steel or new timber structures more adjusted to current engineer knowledge.

5 CONCLUSION

As stated in the declaration of "principles for the preservation of historic timber structures" by Icomos (Principles for the preservation of Historic Timber Structures, 1999), diversity of historic timber structures, the various species and qualities of wood used to built them, vulnerability of the structures to external effects (humidity, insect attacks, fire,etc.), the increasing scarcity due to its vulnerability, misuse, and the loss of skills and knowledge of traditional design and construction technology must be taken into account when dealing with a timber structure, and makes the structures, items that should be analyzed, and documented.

Most of the Traditional Turkish Houses dating back to 18th and 19th century's constructions are at risk of disappearing because of lack of care and restoration, as the evidences of the timber structures and their cultural significance representing their spatial organization, its period's art concept, traditional design and construction technology, emphasizing how important they are.

When the damage assessments have been discussed and the reasons for their deterioration have been analyzed, it is seen that Wood being the basic construction material of this type of houses because of its vulnerability cannot be protected against exterior factors. Due to the rapid deterioration of this material, today one can encounter limited number of these constructions. This makes the case even more important status.

When maintenance and repair of these constructions come into question, one should apply the principles of Venice Charter, the Burra Charter, and other related UNESCO and ICOMOS doctrines when protecting and preserving a historical timber structure. Decisions of repair and maintenance should be taken in accordance with each structure and the features of its structural details. In cases with no possibility of maintenance, details pertaining to the original structure should be kept as records in the structures. Making some strategic assessment on ancient timber structures one should take these into account and consideration:

- the historical value of the fabric
- the overall condition of the structure
- the scale of repairs
- the options for the future uses.

As Tampone (Tampone & Messeri, 2006) declares; to obtain this aim, at least four levels of interventions, hierarchically should be settled according to the building process that of members (ties, beams, struts), connections, structural units and structural system with supplementary elements. The general aims of the principles of preservation of old structures are to conserve the authenticity of the structure and its original function in a condition of sufficient safety. A restoration approach which is concerning all these items can be sustainable.

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Sustainable Restoration of the Roof of a Large Indoor Pool

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ABSTRACT: During an inspection of the roof of an indoor pool from 1971 in Potsdam (Germany) it was observed, that the roof and the column structures of the building are partially damaged by corrosion. The roof construction is a suspended simple-bent pre-stressed shell between two stiff edge beams. The span of the roof is 39.5 m. The edge beams are supported by A-frames. After further investigation on the damaged areas (including tension tests, tension tests on notched tendons with different load cycles, tests of the bearing capacity of sleeve splices and screw nuts) the conclusion was that the joint of the tension rod and the concrete column had to be restored. This was accomplished through the attaching of a new supporting construction to the existing parts, which took over the load from the old connection. At both sides of the columns pre-stressed DYWIDAG-single-tendons (St1080/1230, diameter of 36 mm) were used. They have to bear a maximal tension force of 835 kN. With this unusual restoration technique, a fast and relative inexpensive retrofitting of the construction could be carried out. The existing construction had to be modified only marginal, and the typical appearance of the building was preserved. This solution stands for sustainability.

1 HISTORY

In 1969 began the construction of an indoor swimming pool in Potsdam, Germany (Fig. 1). It was built simultaneously with the buildings in Rostock, Leipzig and Dresden. Similar objects were built shortly after in Erfurt and Halle. All of these indoor pools have a, for their time modern, suspended roof construction, which turned out to be a new territory for the constructing companies. The results of this are the till this day emerging constructional defects. During the building the constructors tried to build an exceedingly compact roof, which was necessary for the suspended roof construction.

Figure 1. The indoor swimming pool.

The indoor pool was completed in 1971. Already at the end of the 80´s the roof construction turned out to be leaky. That is why first restorations and modernisations were done at the begin-

ning of the 90´s. In 2006 the indoor pool was temporarily closed because of heavy damages on the construction.

The paper will describe an unusual restoration technique. A fast and inexpensive retroffiting of the roof will be presented, which does allow to extend the life cycle of the indoor pool for at least 6 years.

2 THE STRUCTURE

The building consists of two parts. The hall part with a 50 m long swimming pool and the outbuilding with the non-swimmers pool, the technical facilities, the sanitary rooms and a sauna. Over the hall area spans the suspended roof construction. The outbuilding is a traditional reinforced concrete construction.

The roof construction over the hall area is a suspended simple-bent prestressed shell between two stiff edge beams (Fig.2). The span width of the roof is 39.5 m. The edge beams are supported by A-frames. The walls are entirely separated from the roof. Between the edge beams cables are hang up. The roof cladding is made from prefabricated concrete panels which are connected with suspension hooks to the cables and have small steel pins at the cables to provide a shear-proof connection between each other. The longitudinal groove is made of C25/30 concrete. In the groove are 4 longitudinal reinforcing rods ($2\phi 10 + 2\phi 12$) with a yield stress of 400 N/mm^2 and every 20 cm flat ϕ 6 binder with a yield stress of 220 N/mm^2. The concrete panels are 4.5 cm thick. The corrosion protection of the steel parts in the roof construction should be ensured by the prescription of a minimal concrete coverage and a coating with epoxide resin containing paint.

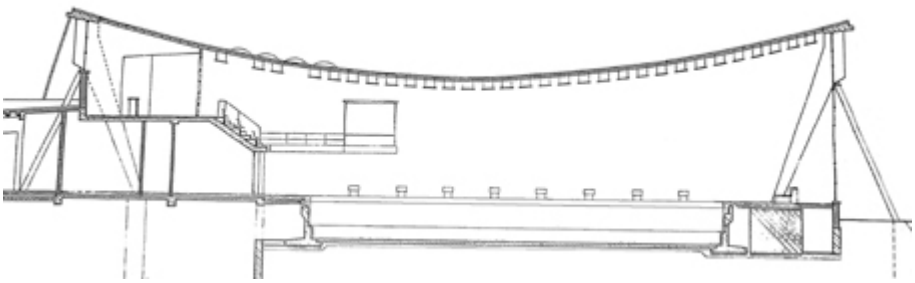

Figure 2. The section of the roof structure of the building.

The cables are steel rods with the quality class St 60/90 and a diameter of 26 mm. The length of the cables is varies between 36.88 m and 40.56 m, depending on the place of installation. The maximal length of the rods just 22.0 m is, so the cables had to be extended by sleeve splices. The preset sag of the cables in the middle point is 3.166 m in the completed construction. The cables are pretensioned with an initial load. The value of this initial load was set so, that in the completed roof are even in case of a total snow load are just compressive stresses. This way the danger of a rip of the grooves is banned. The horizontal component of the cable-force in the completed roof is 128 kN.

The edge beams are 6.0 m long prefabricated single-span reinforced concrete beams. 8 cables are connected to each girder. The beams are made of C25/30 concrete and reinforcement with a yield stress of 400 N/mm^2.

The columns (Fig. 3) on which the edge beams bear on are prefabricated A-frames. They are 9.22 m high and below the height of 2.69 m divided into a tension rod from steel and a compressed rod form concrete, with a span of 5.98 m at their foot. The head part and the concrete bar are rectangular concrete sections which are restricted to their foot. The tension rod is a steel eye bar with a 200x150 mm cross section in the middle of the bar and 200x355 mm cross sec-

tions with 122 mm diameter pinholes on its ends. The head part has a length of 2.177 m, the compressed bar a length of 7.65 m and the tension rod a length of 7.76 m.

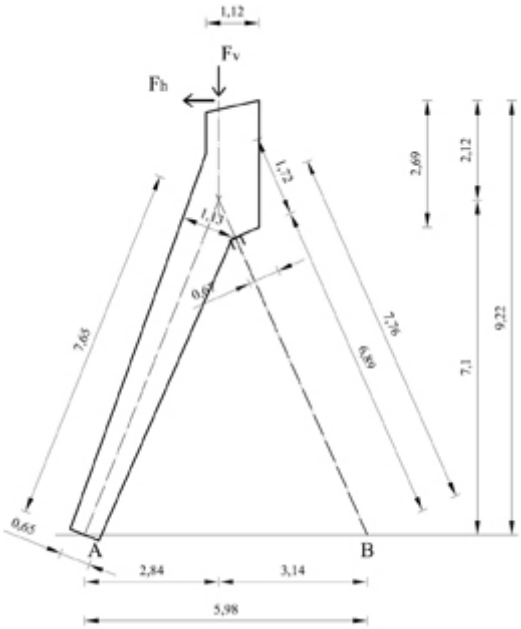

Figure 3. The geometry of the columns.

The horizontal loads of the roof construction are transmissioned to the columns at the column head. Together with the forces that are acting directly on the columns, the following loads result for them:

-Maximal tensile force of 1630 kN,

-Maximal compressive force in the compressed bar of 3432 kN with a simultaneous moment of 819 kNm,

-Maximal moment in the compressed bar of 3177 kNm with a simultaneous compressive force of 3334 kN,

-Maximal moment in the top part of 4021 kNm with a simultaneous compressive force of 3275 kN.

The head-section and the compressed bar are fabricated as one member. The connection of the tension rod to the concrete member is solved trough a hinge (d = 120 mm) between the eye bar and an anchor plate. The anchor plate is fixed with 8ϕ26 stay rods to the concrete member.

The foundations are equipped with a tilting plate at their top to allow a potential rotation of the column. The acting transversal forces are transmissioned by tholepins. For more details see Franke & Heinze (1969), Quade (1969) and Acker & Heinze (1969).

3 THE DAMAGES

During an inspection of the indoor pool in February 2006 is was observed, that at the connection between the tension rod and the concrete column heavy corrosion damage occurred on the screwings (Fig. 4). The damages were especially heavy on the northern facade of the building. Here were the joints, which lie outside the façade are covered by a sheet-metal lagging. Behind this lagging moisture could congregate, which was leading to increased corrosion. The bad accessibility of this part was a reason why the damage could only be discovered at a close inspection. Besides this it was assessed that the roof is leaky which meant that water could get to the tendons of the roof construction. The indoor pool had to be closed temporary in the spring, until the faults of the structure would be resolved, since the structural safety of the construction was not ensured anymore.

Figure 4. The corroded joint of the tension rod.

The primary objective by the assessment of the bearing capacity of the damaged structure had to be the investigation of the condition of the tendons and the sleeves, especially the screwings, because these were the critical members of the connections.

4 MATERIAL TESTS

The steel of the tendons which was used for the tests was retained from the structure of the indoor pool.

The investigation of the bearing capacity could be divided into following four tests, made by the Lab (FMPA) of the BTU:

1. Tension test on specimen according to DIN 50125
2. Tension tests on notched bars with 1.000 und 10.000 load cycles
3. Tests of the bearing capacity of the sleeve splices
4. Tests of the bearing capacity of the screw nuts

All tests of the bearing capacity were carried out with a testing machine of the type MTS (peak load 500 kN, accuracy class 1). The tests 1, 3 and 4 were run force controlled with a test speed of v = 3150 N/s (calculated according to the parameters of the DIN 10002).

After the tension tests the stress-strain curves were calculated on the basis of the load-displacement diagrams. The values of the tensile strength as well as the ultimate strain and the contraction at failure were determined through calculations. The determination of the yield point R_{p02} was made graphically based on the stress-strain curve with an appropriate big scale. The values of the yield strength R_e can not be specified, because the material shows a discontinuous transition from the elastic to the plastic region.

In Table 1 it can be seen, that the measured yield strength of the material St 60/90 lies between 556 and 566 N/mm^2, what is under the nominal yield strength of this steel of 600 N/mm^2.

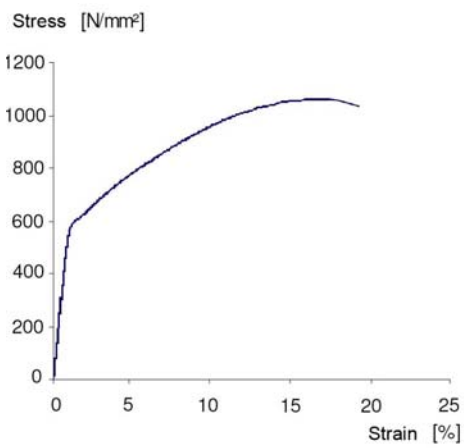

Figure 5. The stress-strain curve of the specimen Z-1.

Table 1. The results of the tension tests.

	Specimen Z-1	Specimen Z-2	Specimen Z-3
d_0 [mm]	19,9	19,9	19,9
d_u [mm]	16,1	16,3	16,6
S_0 [mm²]	311,0	311,0	311,0
S_u [mm²]	203,6	208,7	216,4
L_0 [mm]	99,5	99,5	99,5
L_u [mm]	111	112	110
R_m [N/mm²]	1063	1064	1082
R_{p02} [N/mm²]	566	558	556
A [%]	11,6	12,6	10,6
Z [%]	34,5	32,9	30,4

Within the tests on the notched bars round specimen were tested with a rising tensile load with 1000 and 10,000 load cycles. This was made to investigate the behaviour of the tendons in case of a sectional weakening, caused by corrosion or potential notches. These round specimen are made from the material of the roof construction. At the fabrication the original diameter of the tendons was kept and a 2 mm deep revolving notch with an angel of 60° between the sides was milled. In the notch base is according to the geometry of the machine a radius of ca. 0.1 mm (Fig. 6). The tests were carried out with 1000 and with 10,000 load cycles. The load was applied with a sinusoidal cycle with a frequency of 1 Hz. The test duration was according to that 17 minutes at 1000 cycles and 170 minutes at 10,000 cycles. The summary of the results of the tests are shown in Table 2.

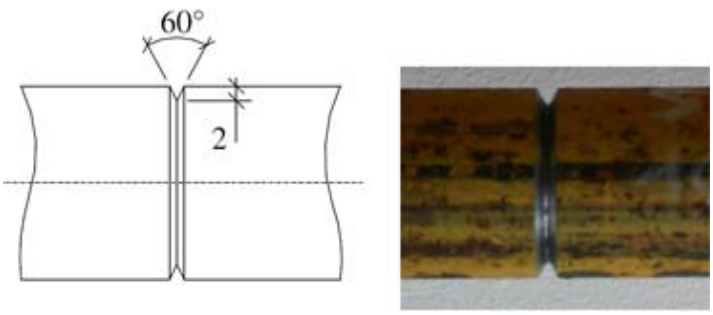

Figure 6. The rod with the circumferential groove.

Table 2. Parameters and results of the tests.

Notched bar	Load cycle N	Lowest load F_{min} [kN]	Highest load F_{max} [kN]	Observation
KSt1000-1	1.000	86	150	Test succesful
KSt10000-2	10.000	86	150	Test succesful
KSt1000-3	1.000	86	150	Test succesful
KSt10000-4	10.000	86	150	Test succesful
KSt*	1.000	86	200	Test succesful

For the bearing capacity tests of the sleeve splices, four sleeves from S235J2G3 were fabricated according to the plans at hand. The length of load transmission is 20 mm on both sides of the sleeves (Fig. 7). Table 3 shows the relevant loads and the causes of failure for the particular sleeve splices.

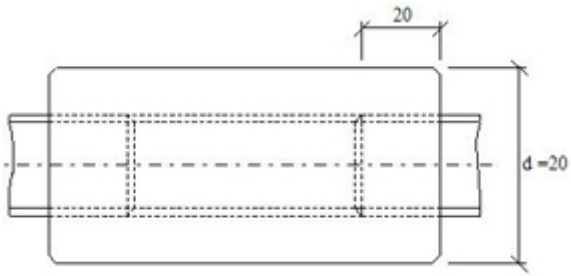

Figure 7. The sleeve splice.

For the bearing capacity tests of the screw nuts, a device was build according to Figure 8 for a tightening test. The diameter of the hole is d = 30 mm, the nut was shortened to 28 mm. The peak load for the failure here was F_{max} = 461 kN. The limit of elasticity lied at F_e = 171 kN. The displacement contains the unavoidable deformation of the load transmission device. The cause of the failure was in the majority of cases the fracture of the tendon at the end of the thread.

Table 3. Summary of the tests of the bearing capacity of the sleeve splices.

Sleeve splice	Load at elasticity limit F_e [kN]	Maximum failure load F_{max} [kN]	Failure reason
MS-1	190,4	390,2	Failure of prestressed steel on thread run-out
MS-2	159,3	414,9	Failure of socket screw thread
MS-3	161,7	390,4	Failure of prestressed steel on thread run-out
MS-4	163,0	374,3	Failure of prestressed steel on thread run-out

Figure 8. Experimental set-up for the load capacity test of the screw nut.

After the analysis of the test results and the comparison of the load bearing capacity it was obvious that the roof construction had a sufficient bearing capacity, but the connection of the tendons in the columns did not.

5 RESTORATION

The requirement for the restoration concept was, that the structural safety of the building is not affected by the actions. After the assay of the building it was decided to restore the columns whose tension members are outside the facade. The penetration point of the tension members through the concrete column, the points of force transmission (inside) and the joints of the tension members had to be retrofitted.

The strengthening was carried out through the installation of additional parts. A new construction would bypass and unload the original connection. This way there was no critical intermediate state like in case of a replacement. (Fig. 9-11).

Figure 9. The lower joint of the by-pass construction.

Figure 10. The upper joint of the by-pass construction

Figure 11. The restored column line

The area of the anchor plates on the concrete columns were laid open, in doing so the grouting was removed carefully. The cheeks on the concrete columns were cut off. The overhang of the existing threaded rods was cut off to ca. 1 cm over the counternut. The anchor plates were derusted and cleaned. 350 mm high U-profiles were laid pairwise on the created supporting areas and their bedding were sealed. The forces from the tendons were transferred by a 80 mm thick steel plate to the 350 mm high U-profiles. On each U-profile 3x2 stiffeners were applied because of the high local loads. The profiles bear directly on the concrete construction. (Fig. 10 and 12).

At both sides of the columns in each case a single tendon was placed between the U-profiles. They were guided directly beside the columns through the facade. The tendons are DYWIDAG-single-tendons without bracing, with quality class St1080/1230 and a diameter of 36 mm (DIBt 2006). They have to bear a maximal tension force of 835 kN. The tendons were to prestress with 50 % of the calculated service loading. The pretension was alternating (Fig.13).

Using four bolted wedges a plane bearing surface was created on the chamfered part of the tension rods. The wedges were connected with 50 mm thick steel plates with eight M27 10.9 screws to the tension rod. Like at the inner construction a pair of 350 mm high U-profiles were placed under the bearing surfaces. Between these profiles the single tendons were placed. At the lower connection the U-profiles and the force transmitting plates were made identical. (Fig. 9 and 12).

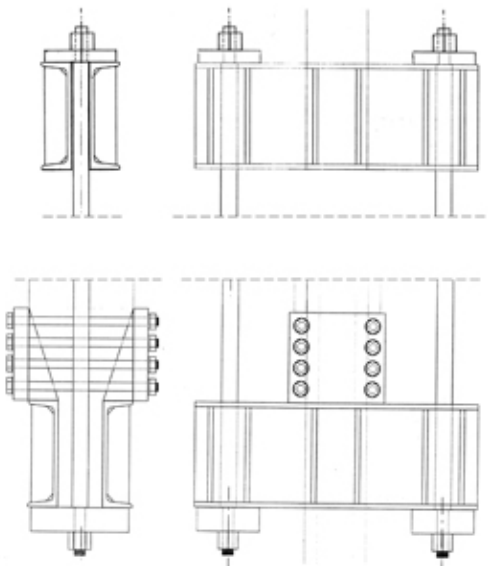

Figure 12. The new connection.

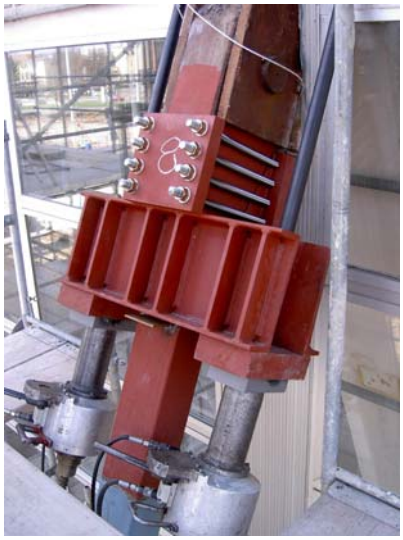

Figure 13. The pretension of the tendons.

6 CONCLUSION

With this for structural engineering unusual restoration technique, a fast and relative inexpensive retroffiting of the roof construction was carried out. By that measures the life cycle the indoor pool could be extended for at least 6 years. The next inspection will be performed in 2012. Moreover, the existing construction had to be modified only marginal, and the typical appearance of the building was preserved. This solution stands for sustainability. For more details see Boehme (2009).

In the restoration were involved:

Client: Energie und Wasser Potsdam GmbH
Report, calculation: Dr. Zauft Ingenieurgesellschaft für Bauwesen mbH, Potsdam
Structural design, construction: Ed. Züblin AG, Direktion Ost, Berlin
Proofing engineer: Prof. Hartmut Pasternak, Braunschweig

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Building envelope rehabilitation costs variability

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ABSTRACT: In recent decades, there has been a great deal of investment in Portugal in the construction of new buildings to the detriment of the rehabilitation of existing ones. As a result, the historic centres of towns and cities are deteriorating, while their suburbs are spreading. One of the main problems affecting the rehabilitation of residential buildings is that it is extremely difficult to accurately estimate the costs involved. Although there are established methods (and technical documents available) to aid the costing of new buildings, there is a lack of official information about the costs of rehabilitation works, particularly as regards the external envelope of buildings.
This paper demonstrates how to determine rehabilitation costs (with particular emphasis on the envelope of residential buildings) by gathering information from specialized companies, assessing price variability and consulting databases of rehabilitation costs from other countries. It also presents some examples of costing for particular rehabilitation jobs.

1 INTRODUCTION

In the construction and rehabilitation of buildings, sustainability is a concept and that incorporates values not usually considered in economic analysis such as property appreciation, environmental protection or reduction of energy consumptions and emissions.

The rehabilitation of buildings can contribute to sustainability because it is based on core activities for human development: preservation of cultural values, environmental protection and economic and social benefits. Rehabilitating an existing building has economic advantages when comparing the sum of the costs of demolition and reconstruction with the usual construction costs for new buildings. Examples of these benefits are the easier urban integration and utilization of existing public facilities, the application of natural building materials and also the reduction of quantities of new materials.

In recent decades, there has been a great deal of investment in the construction of new buildings to the detriment of the rehabilitation of existing ones. However, various studies undertaken have shown that even the most recent buildings frequently show significant signs of external envelope deterioration, particularly damage to renders and dispersed cracking. There is also often marked deterioration of glazed parts, which may need to be replaced (in which case, the opportunity is often taken to improve thermal insulation conditions).

This paper argues that political decision-makers should be encouraged to redirect funds away from new construction projects towards the rehabilitation of existing residential buildings. One of the main arguments for this has to do with the appearance of our towns and cities. Buildings in the historical centres are often in an advanced stage of physical decay, which contributes to the depopulation of those areas. Meanwhile the suburbs continue to grow, generating the need for new investment in infrastructures.

The rehabilitation of residential buildings should be approached as an integrated process, involving diagnosis, the intervention decision, estimation of costs, the preparation of a plan of intervention, the monitoring of the work, and subsequent maintenance. The decision to intervene in a building will depend, essentially, upon the financial resources available. When the developer understands what is necessary, he can decide whether to opt for total or only partial rehabilitation. For this reason, it is very important to know the costs involved in rehabilitating the outer envelope of buildings and their variability, particularly given the fact that the outer vertical envelope represents around half of total costs. Indeed, when roof parts are added, then the percentage is never less than 65%.

Cost determination is an attempt to translate the expenses involved in carrying out a particular project to a certain standard so as to provide as accurate a notion as possible of the real cost of the work. Underlying all civil construction costs are value yields (labour, materials, equipments, etc), which influence the quantities of the means of production contributing to the production of any unit amount. The cost represents the sum of all work (labour, materials, equipment, taxes, administration, etc) necessary to carry out a particular job or service and corresponds to the amount paid for it.

As for the estimate, this will reflect all the expenses that the company envisages that it will have in a particular job, plus the anticipated profit margin. Expenses or costs may vary in accordance with different components and are divided into direct costs, construction site costs, indirect costs and profit. Gathering information about costs in the domain of rehabilitation is difficult and laborious. Not only are there constraints that need to be taken into account that are not present in new buildings, but also the process requires human and material resources to enable the information to be collected and processed in a credible way.

2 DETERMINING BUILDING COSTS AND PROVIDING ESTIMATES

Cost determination is an attempt to translate the expenses involved in carrying out a particular project to a certain standard so as to provide as accurate a notion as possible of the real cost of the work. Underlying all civil construction costs are value yields (labour, materials, equipments, etc), which influence the quantities of the means of production contributing to the production of any unit amount. The cost represents the sum of all work (labour, materials, equipment, taxes, administration, etc) necessary to carry out a particular job or service and corresponds to the amount paid for it.

As for the estimate, this will reflect all the expenses that the company envisages that it will have in a particular job, plus the anticipated profit margin. Expenses or costs may vary in accordance with different components and are divided into direct costs, construction site costs, indirect costs and profit.

Gathering information about costs in the domain of rehabilitation is difficult and laborious. Not only are there constraints that need to be taken into account that are not present in new buildings, but also the process requires human and material resources to enable the information to be collected and processed in a credible way.

3 DETERMINING REHABILITATION COSTS: SPECIFIC ISSUES

Knowledge and effective cost management are basic requirements for the economy of rehabilitation operations. Efficient methods do exist of determining costs and carrying out economic-financial assessments. However, these are only effective when there is complete and accurate understanding of the costs involved, since these provide the base information underlying such methods and analyses (Aguiar et al., 2002).

With new buildings, there are documents to support the costing process, and information is available about expenses and value yields. In rehabilitation work, however, which often involves less familiar tasks, it is exceptionally difficult to establish reliable yield values and consequently unit costs. Given all the parameters involved, determining such costs is usually ex-

tremely difficult, especially as there is no official information available about prices practised. Thus it is useful to analyse the factors contributing to price variations.
Factors affecting rehabilitation costs are diverse and difficult to quantify. They include:

- Conditions affecting circulation, access and the setting up of the construction site;
- The size of the building, number of floors and housing units to be renovated, and the average area involved;
- The presence of the occupants during the works;
- Manpower availability;
- The cost of topographical surveys, assessments of the prior state of the building and other preliminary studies; the undertaking itself; the re-housing of occupants during the course of the work; technical administration, inspection and management of the work, and miscellaneous external costs (compensation for damage to neighbouring buildings or streets, insurance, etc).

Rehabilitation works are qualitatively different from new constructions. For example, they involve the repair of defects and improvements. They may also include small jobs that belong to the domain of periodic maintenance. The work may be done using traditional techniques and materials, or sometimes with sophisticated technology and materials, both of which will obviously affect the cost. There is also the need for preliminary work, such as demolition or prior consolidation (which is of course unnecessary for new buildings). These all bring additional expenses which often lead to surcharges.

Repair, reconstruction, the replacement of parts, and improvements may also make use of techniques and materials that are in current use for new works. However, this does not mean that rehabilitation costs are similar to the costs of a new building. On the contrary, rehabilitation jobs often involve more difficult working conditions, which negatively affect the returns (Aguiar et al., 2002).

In rehabilitation interventions, each case is specific, and it is not always possible to obtain all the information necessary for costing through initial diagnoses and assessments. Consequently, it is not easy to standardize costs or rates of return. That is to say, there are multiple contextual factors that need to be taken into account in order to obtain specific information about the costs of particular jobs or tasks involved in rehabilitation work. Yet such information is of interest not only for the building contractors (for the preparation of estimates and control of the project) but also for the developers (who need to anticipate costs of undertakings and keep control of their company's budget).

Information about rehabilitation costs should be presented as systematically as possible, indicating all the main elements. These are:

- Working conditions (particularly access and the need for auxiliary equipment);
- Detailed description of tasks to be carried out (degree of complexity, quantity, locale, difficulty of execution, etc);
- Degree of complexity of the operation in which the task is included.

There exists some information grouped in the form of various global indexes that can help determine costs:

- Cost structures per type of rehabilitation (taking into account initial and final quality indexes);
- Rehabilitation costs/m^2 of gross construction area, relative to building parts or to the whole building (rehabilitation types);
- Costs of rehabilitation/household (by type), etc., particularly useful for the entities involved to decide whether or not to go ahead with rehabilitation operations, and to what extent (Nunes, 1995).

In the light of the above, rigorous costing requires a complete diagnosis of the building by qualified experts, and the preparation of detailed specifications of the various jobs to be carried out.

4 DIVULGING REHABILITATION COSTS

Few methods of structuring rehabilitation costs are known, and those that have been divulged in the foreign literature have many limitations or are difficult to adapt to other countries (Braga, 1990). In general, estimation methods are based upon a description of the building and classification of the state of degradation. They may be divided into a preliminary phase, where the decision is taken to demolish or rehabilitate, following in-depth studies, a physical examination and overall cost assessment; and a second phase, which corresponds to the rehabilitation proper. A series of comparable buildings (Standard Buildings) may also be studied, on the understanding that the costs will be approximately the same.

As yet in Portugal there have been no publications providing typical rehabilitation costs. In this country, the usual procedure is to produce an estimate based on a prediction of the various tasks necessary and their total cost, empirically defined on the basis of knowledge acquired from previous works.

Comparisons with other countries are useful, particularly when rehabilitation is more common than new construction work. In those situations, the publication of rehabilitation costs is considered to be of major importance for market transparency and for the maintenance of competition in the sector. In France, there is a public organization, the Rehabilitation Cost Observatory (OCTR), whose mission is to inform the public of the basic costs of rehabilitation work, using figures obtained from the records of processes to support property owners and tenants (ANAH, 2010). In Spain, companies can obtain precise information on line about standard costs of rehabilitation work (Precios, 2010), while in the United Kingdom, there is a document available entitled "Rebuilding Costs Guide" (ABI, 2010). Interested parties may also do an on-line estimate of costs in order to have an idea of the resources that will be required for rehabilitation work.

5 STUDY OF THE VARIABILITY IN REHABILITATION COSTS

In a recent Doctorate study (Lanzinha, 2006), an analysis was conducted of a series of interventions in recent buildings in order to create a primary database of the real costs of interventions in residential buildings located in Oporto, in northern Portugal, with special attention given to the outer envelope. The respective records (of works by the same designer) were analysed, consisting of execution plans (including both written documents and drawings), bids entered by different companies in response to the calls-for-tender launched by the condominium administrators, and assessment reports of the bids tendered. The study also described the constitution of each building in the sample, the construction systems used for the envelope and the main problems detected. Finally, the total value of the rehabilitation work was indicated. The analysis of the interventions and the 33 bids tendered by the various contractors yielded a diverse group of average prices for rehabilitation work. This provided a cluster of average unit costs and enabled the creation of a computer programme called "ESTIMA – Estimate of the costs of rehabilitation work on residential buildings" (Lanzinha, 2006), consisting of three inter-related modules (the first involved records of works already inserted, resulting from previous studies), complemented by a study of the variability in rehabilitation costs of relatively recent buildings (Pinheiro et al.,2009; Sousa, 2009; Sousa & Lanzinha, 2009; Sousa et al., 2009).

6 DATA COLLECTION AND PROCESSING

In 2008, the list of works in the computer programme ESTIMA was extended and a selection was made of the most common kinds of work carried out on the external envelope of residential buildings (Pinheiro et al., 2009). Particular emphasis was given to the façades (vertical envelope), as this is the part that usually costs the most in works of this type.

Around 300 Portuguese companies were consulted and 20 different participated in total. Approximately 6% of the works took place in the south of the country; 11% in the north and 28% in the central zone. Information was not available about the location of the remaining 56%.

It should also be pointed out that, though some responses were received, it was in fact very difficult to obtain information on this matter, which demonstrates the atmosphere of distrust or lack of interest that exists in the sector.

After the data from the estimates had been processed, it was found that the greatest discrepancy and highest prices were in the category of General Costs. For example, in the case of costs of "assembling, maintaining and dismantling the construction site", the amounts varied between €515.98/un. and €71,896.46/un within the same company.

Other examples where marked discrepancies were found were:

- In the opaque parts, the "treatment of façades covered with ceramic tiles" were costed at between €42.27/m^2 and €12.83/m^2 by different companies;
- As regards glazed parts, the "replacement of lacquered aluminium window frames" varied between €141.37 and €750.00 per m^2, among different companies;
- In the category 'roof', the "preparation of screed mortars" varied between €6.51/m^2 and €48.63/m^2 in jobs performed by the same company.

Although there may be differences as regards the materials and details of the job, and even in the difficulty of executing this type of work, nothing justifies such enormous price differences. While we might expect discrepancies between different companies, it is startling to find price discrepancies for the same job in estimates provided by the same company. This matter clearly warrants further attention. When companies present such divergent prices for items measured as a global value, they are taking probably advantage of extensive clauses to increase their profit margins.

As regards the opaque parts of the façade, one case involved only the application of ceramic tile, while another contemplated not only the provision and application of the tiles, but also the application of thermal insulation and mouldings to parts of the roof. It was found that this second job, despite being much more extensive, had a lower average price (€31.79 /m^2) than the first one (€32.80/m^2), which is neither predictable nor logical. The comparison is presented in Table 1.

Table 1 – Comparison of jobs and prices

Sub-Categories	Jobs	Average cost
Opaque zone	Application of external thermal insulation system with mechanical fixation to the wall rendered and painted.	€16.81 / m^2
	Application of external thermal insulation system with mechanical fixation to walls covered with ceramic tile.	€27.80 / m^2
Roof	Application of ceramic tiles to roof	€32.80 / m^2
	Supply and application of ceramic tiles to roof including thermal insulation panels and mouldings with eaves, roof ridges, cornices and chimneys with zinc-plated flashings.	€31.79 / m^2
Balconies and terraces	Repair/replacement/painting of metal railings	€80.34 / m^2
	Replacement of railings on the balconies of façades in pickled and metalized iron painted and enamelled.	€70.15 / m^2
Rainwater drainage	Installation of zinc drainpipes	€23.17 / m^2
	Repair, replacement and painting of zinc drainpipes	€13.45 / m^2

In the subchapter 'Balconies and terraces', another case is described that involves the repair/replacement and painting of metal railings, and yet another where the railings are only replaced and painted. This time, the difference between them was a mere €10.19, when we might have expected the repair job to have been more costly.

To complement this study, we also compared the prices quoted by these companies with reference costs for rehabilitation jobs given on a Spanish internet page.

As we can see, works in Spain are generally more expensive than the average in Portugal, a fact that can be explained by that country's higher economic level and average wage. However, there is a great difference in the quantification of costs related to "Repairs of tiled roofs, including cleaning and repair of structural elements, replacement of worn-out parts, painting and protective treatment [m^2]. In Portugal, this costs €120.00 and in Spain €28.06. The same occurs

with the job "Painting the wooden surfaces of window frames [m^2]" where the prices in Portugal is €160.04 and in Spain €30.01(Sousa, 2009).

To gauge the opinion of the companies as regards aspects that could influence rehabilitation work and their respective costs, a questionnaire was prepared. The following problems were identified by the companies as influencing significantly the execution of rehabilitation works:

- Difficult access to the locale and limited amount of space for the construction site;
- Lack of collaboration as regards additional safety measures and increased risk in demolition jobs;
- The fact that few rehabilitation works were undertaken;
- Lack of detail in the preliminary analysis, which meant that unexpected anomalies were often encountered.

As regards aspects that affected the price with relation to new construction work, the following were mentioned by the companies:

- More manpower and transport required per unit of work, and the time-consuming nature of rehabilitation jobs compared to new constructions;
- Lack of technical knowledge (to enable the selection of the best solutions), specialized manpower and divulgation of rehabilitation techniques.

As to the execution of rehabilitation works, the following were mentioned as the main problems:

- Deficiencies in the plans (written documents and drawings) and in the job descriptions;
- Poor conditions for the setting-up and operation of the construction site, and presence of occupants at the site;
- Excessive bureaucracy and delays in licensing different projects.

The suggestions presented by the companies for overcoming problems in the domain of rehabilitation were:

- "Simplification (of legislation) in licensing procedures for rehabilitation projects";
- "The contracting of firms that specialise in rehabilitation projects, in order to ensure that the pre-existing situation is accurately described and full details are supplied";
- "The need for legislation to limit as much as possible the licensing of new constructions in order to encourage the rehabilitation of old buildings, as a way of restraining the unbridled growth around the edges of towns and cities that is turning the centres into residential deserts";
- "In half the time and with half the cost, contractors working on new buildings can produce double the amount of work compared to rehabilitation jobs, which makes rehabilitation an unappealing option".

7 PROPOSALS OF SPREADSHEETS FOR COST RECORDS

The most significant interventions can be identified through observation and direct intervention in rehabilitation works, and by means of a survey focusing on techniques used, the returns on the resources used and the main problems in execution. This has been the method used by the National Laboratory of Civil Engineering (LNEC) in Portugal to divulge information about the costs of works on new buildings, and it should also be applied to rehabilitation works.

Normally, observation records are stored in the form of spreadsheets that are standardised for each construction job. The recorded items may undergo various treatments, and by recording them in this way, we can obtain a list of the most significant jobs; the specific nature of each job and the respective unit of measurement; the quantification of the returns from resources (materials, equipment and manpower) involved in each job.

The records were obtained using the same process, despite the great difficulty in acquiring the collaboration of the people who have this knowledge.

The preparation of proposals for returns records or cost records of jobs was based upon a dialogue with the head of a construction team specialising in rehabilitation, who helped to identify the practical procedures and construction tasks typical of such work. This was then completed with the collection of information about materials and associated costs. Table 2 gives an example of the records created.

Table 2 – Example of cost record for sub-task of applying insulation to a continuous façade with medium texture paint

Task	Application of fiberglass netting with two layers of glue for vertical coating with minimal overlaps of 10 cm, in which the second layer of glue has a sand or trowelled finish. Application of regulation primer and medium-texture paint between the two layers of glue. Finally, removal of rough surfaces on the façade using sandpaper (for mortar), after the second layer of glue has dried for 24h.						
	Description	Quantity	Unit	Unit Cost	Unit	Partial Cost	Unit
Materials	Netting	1	m^2	0.68	€/m^2	0.68	€/m^2
	Glue	3.2	kg/m^2	0.75	€/kg	2.40	€/m^2
	Primer	0.6	kg/m^2	0.52	€/kg	0.31	€/m^2
	Paint	5	kg/m^2	3.60	€/kg	18.00	€/m^2
Manpower	Foreman	0.125	h/m^2	10.56	€/h	1.32	€/m^2
	Assistant	0.125	h/m^2	8.13	€/h	1.02	€/m^2
					Total	23.73	€/m^2

In order to carry out the works described in these records, it is necessary to consider some individual tools. These are not individually identified in the records, as their inherent cost is included in the percentage of charges.

The figures given for manpower were estimated using the formula $S_h = (V_m x12) / (40x52)$, in which S_h is wage per hour and V_m the monthly income for 2009. The amounts involved were suggested by the business associations operating in the sector (150% for 2009). The percentage of indirect costs and construction site costs, plus the anticipated profit margin, were then added to the figures obtained.

8 CONCLUSIONS

As predicted, this study has confirmed that there is a great variability in the way prices are calculated for rehabilitation jobs. This is seen not only in the prices supplied by different companies for the same job, but also in the great divergence of prices proposed by the same company for similar jobs.

It should be pointed out that the cost of jobs (which are generally in line with what might be expected, as confirmed by the companies consulted) depends upon the conditions in which they are executed, such as the height, atmospheric conditions, materials required, the specific nature of the work, site accessibility, time required for the job (given that a job is never undertaken in isolation and that the manpower used may not be specialised), the existence of residents at the site, commercial strategy used, etc. Costs also depend upon the need for specialised manpower, the measurement unit used and the dimension of the job. However, nothing justifies the enormous difference in prices that was found during the course of this study.

These results therefore prove the urgent need that exists to standardise as much as possible the costs attributed to particular jobs by different companies. In this light of this, the best action would seem to be to prepare returns records which will facilitate the preparation of estimates for rehabilitation jobs.

The list of spreadsheets of different kinds of work should be constantly added to and updated, so that it becomes increasingly reliable as a basis for bids in calls for tender, as well as for the preliminary work involved in preparing estimates, budgets and reference values for rehabilitation works, whether these operate according to a price series system or, in special situations, with an overall price. Later, this should lead to the establishment of more secure average values, with the possibility of introducing “nuances” in accordance with the specific characteristics and conditions of each particular rehabilitation job.

The responses obtained from companies (as regards the main difficulties in determining rehabilitation costs, the aspects that differentiate these prices from those related to new constructions, and the main problems in carrying out rehabilitation work) have enabled us acquire a deeper understanding of issues that of major interest. The importance of contracting and creat-

ing offices specialised in rehabilitation projects was highlighted by the companies consulted. This area of intervention also needs to be regulated by defining the skills required by the technicians that produce assessment/inspection reports, in order to better qualify the companies that operate in the domain of planning, inspection and execution of rehabilitation works.

As this matter has now started to attract interest, with some collaboration from specialists in the field, there are intentions to study it further, in order to facilitate the rehabilitation of buildings and coordinate the various parties involved, thereby enabling them to gain the necessary efficiency.

Hence, let us finish with some suggestions for future developments:

- There is a need for an official document that establishes recommended prices for rehabilitation works;
- We should continue to prepare records of the costs of rehabilitation work, based upon the yields from manpower, materials and equipment obtained through direct observation or from databases collected from companies specialising in this type of work, with a view to publishing them;
- A Rehabilitation Cost Observatory should be set up to gather and divulge information relating to reference costs (such as the one that already exists in France);
- A more elaborate survey of work costs should be undertaken so that contractors do not feel the need only to undertake new construction jobs;
- The means of measuring rehabilitation works need to be improved, to avoid situations whereby the same cost calculation includes works charged at an overall rate when they are of completely different types and involve different working conditions.

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Rehabilitation Strategy: Sustainable Development Centre, Malta

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ABSTRACT: The Xrobb il-Għaġin Sustainable Development Centre is located within the Nature Park at Xrobb il-Għaġin, Malta. The main aim of the project was to rehabilitate an existing complex of deteriorated buildings, and to transform them into a Sustainable Development Centre. The new centre was planned to accomodate a new scientific and educational facility. The sustainable rehabilitation strategy of the buildings was based on a comprehensive and approach, addressing various aspects, including the following; architectural value of the buildings and the functional requirements, structural interventions and repair of the structures, the conservation of resources, water conservation, waste water recycling and waste management, services, the inclusion of energy efficiency measures and alternative and renewable energy sources.

1 GENERAL

The Xrobb il-Għaġin Sustainable Development Centre, is located on the Xrobb l-Għaġin peninsula to the southeast of the island of Malta. The Centre is located within a Park covering an area of 15ha, surrounded by agricultural land and the Mediterranean Sea, and close to the village of Marsaxlokk, circa 2.5km to the west. Between 1974 and 1996, the Site was the location of a Relay Station of Deutsche Welle–Radio (DW-R), which covered the Near Middle East and North African Region for transmissions in different languages; the station was initially used also by radio Canada International and later by Voice of the Mediterranean. The station consisted of a complex of buildings which housed the main activities of the operation and three small outbuildings. Following the DW-R's departure from Malta, the station buildings and the surrounding grounds were made available for the Fish Farming Industry, and a company used to operate blue-fin tuna farming until 2006. The area was also used for limited agricultural activities, hunting and trapping. The existing buildings were left in a state of disrepair (Gauci, 2008). The Ministry for Resources and Rural Affairs, Malta, with the collaboration of Nature Trust Malta (NTM), embarked on the transformation of the Site into a Nature Park, through a rehabilitation project involving the afforestation of the part of the peninsula and the protection of an area of high ecological value. The project was supported by a grant from the Norwegian and EEA Funding Mechanisms. The buildings making up the ex-relay station complex were considered to be important examples of 1960 -70s architecture in Malta, and were restored, to be used as a Sustainable Development Centre. The Centre includes offices to be used by NTM who is responsible for the implementation of the afforestation project and the overall management of the Site, and the Department of Electrical Power and Control Engineering, Faculty of Engineering, University of Malta, who will be conducting research on renewable energy technologies. The complex also includes a hostel and will host an education facility in environmental management, including ecological rehabilitation, afforestation, and energy conservation.

2 OVERVIEW OF THE EXISTING BUILDINGS

The station complex, designed by Deutsche Welle Architect, Willi Schalenbach, includes features typical of 1960-70s architecture and is considered to be of Architectural value. The station buildings represent the regional development in international communications during the second half of the 20th century. The objective of the rehabilitation strategy was to restore the buildings in the complex, provide for flexibility of the spaces and adapt them to a new function through a structured intervention, whilst retaining the architectural integrity.

The original buildings consisted of load-bearing masonry construction. In general, the buildings were constructed on reinforced concrete foundations with reinforced concrete ground slabs. Walls consisted of globigerina limestone blocks. Various structural roofing systems were identified, and included mainly two main typologies; reinforced concrete cast in situ slabs; and composite slabs consisting of precast pre-stressed concrete inverted T beams, with concrete blocks supported between them, and with overlying cast in place structural concrete. Different varieties of roof slabs were identified in the original structures, namely slabs with a single or with a double beam system. Other reinforced concrete elements included the cantilever slabs and shading devices, the cornice & architectural features including the roof water drain details.

Figure 1. A representation of the Sustainable Development Centre after rehabilitation.

3 THE REHABILITATION STRATEGY FOR THE COMPLEX

3.1 *General*

The strategy for the Sustainable Rehabilitation of the Xrobb il-Ghagin Complex, was based on a comprehensive approach, addressing the architectural integrity of the buildings, new functional requirements, structural interventions & repair, resource conservation, waste management, services, energy efficiency and renewable energy sources. The strategy also required the consideration of planning issues, accessibility and landscaping schemes. The project is considered to be one of the first conservation interventions on the 20th century architectural heritage in Malta. The rehabilitation of an existing building rather than reconstruction resulted in a larger challenge, in the adaptation of existing spaces for the new uses. In addition the project required longer timeframes for completion, planning and site management and particular skills in specific operations including dismantling and repair. The rehabilitation strategy also allowed for conservation of resources and reduction in waste generated. The implementation of the Strategy was considered as a exercise to assess the various processes and methodologies adopted. The investigation & design were carried out during 2006 & 2007, and rehabilitation works were carried out between 2008 and 2010.

3.2 *Structural Assessment Methodology*

The scope of the assessment was to investigate the buildings, and structural elements, and to assess the state of the structure and defects. The investigation was based on a detailed inspection of the buildings and elements, following a structured survey, including detailed visual investigation records; photographic survey records, records and assessment of the structural systems, structural element typologies and defects. The data was mapped out on detailed drawings and re-verified. The defects were classified with respect to type, location, extent and materials. A testing plan for materials and structure was prepared on the basis of the investigation carried out. The data of the investigation was used in order to identify and understand the actions on the structures, the failure mechanisms, and causes of deterioration (Borg, 2008).

A number of defects were also noted in the structural elements, with the partial collapse of roof structural elements recorded. The main defects in reinforced concrete elements were cracked concrete, reinforcement corrosion and concrete spalling. In various instances, this resulted in detached concrete and exposed excessively corroded reinforcement and loss of elements and architectural features including the cornice and cantilevers on the façade (Figure 2). Specific roof structures were excessively deflected, in view of past actions on the roofs. Other defects in the roof system included longitudinal cracks along the beam elements of the slabs, and defects and cracks in the concrete block-work supported between beams in the roof slabs.

Defects were also noted in masonry wall structures namely hairline cracks and local defects in stone, due to impact and misuse, and defects as a result of inadequate interventions during past alterations to the buildings. Loss of finish and mortar on exposed surfaces was also recorded. Services were non-functional, the finishes were in a bad state of repair, and most apertures were missing or damaged.

An assessment of materials was carried out. Concrete cores were extracted from various parts of the structure & different structural elements including beams and slab elements, following a plan. The concrete core strength, concrete density, and depth of carbonation were determined in the experimental investigation. Furthermore the investigation provided information on the roof structure and finishes. The compressive strength of cores extracted from the slab at ground floor varied between 23.5N/mm^2 and 28.5N/mm^2, and for beam elements at roof level, varied from 20.5N/mm^2 to 24.5N/mm^2. However values of 15.5N/mm^2 (reinforced concrete element), and 10N/mm^2 (structural cast in place concrete over precast beams slab roof system) were recorded. The depth of carbonation of the concrete in the cores varied between 25mm and 50mm. The cover to reinforcement varied and in some case was less than 25mm.

3.3 *Rehabilitation & Repair*

Various aspects were taken into account in the appraisal exercise of the existing original structure, including; the age of the structure, exposure of the building to an aggressive environment and proximity to the sea, deficiencies in materials used, defects in detailing, defects associated with workmanship, lack of maintenance of the structure and previous inadequate uses of the building, and actions which were not in line with the intended use.

The scope of rehabilitation was to address the structural performance, structural integrity and also the durability of materials. In specific cases, the intervention required the re-introduction of elements which were missing due to deterioration or past interventions. The structural elements were classified: elements to be retained; elements which required repair; deteriorated elements requiring replacement and dismantling; elements which as a result of their position in the structure or due to the sequence of works had to be dismantled. In various instances, it was required to replace elements which were excessively damaged and beyond repair particularly where repair was not possible due to the inferior quality of materials, inadequate details, or where repair was not feasible. The latter case included the cantilever elements, various architectural reinforced concrete features on the facades and on the external envelope, and roof structures. Precast Prestressed hollow concrete slabs, together with cast in place reinforced concrete slabs in specific areas, were adopted to replace the deteriorated roof structure.

Specific reinforced concrete elements required repair using appropriate materials & techniques, in particular patch repair. The extent of such repair depended on the state of the elements.

In the case of masonry elements, various parts of walls have been reconstructed and/or repaired. Stone masonry block-work was used in all external areas to ensure the architectural integrity of the buildings. Concrete masonry block-work was used in specific internal partitions and walls. Adequate pointing and rendering of walls were implemented through the application and use of the adequate materials, taking into consideration also the site exposure. Various measures were proposed to ensure quality in the rehabilitation of the buildings, during the Design Phase, the Construction Phase, and also the Service Phase. A grade C35/45 concrete was adopted for the reconstructed reinforced concrete elements. An exposure class of XS-1 (EN 206-1, 2000) was considered in structural engineering design, referring to corrosion induced by chlorides from sea water; concrete exposure to airborne salts but not in direct contact with sea water. Particular attention was given to details including adequate concrete cover and waterproofing. A quality assessment plan was implemented and a site management team was responsible for operations, execution of works, and for ensuring good workmanship including adequate compaction of concrete and concrete curing. The buildings are required to be used within the limitations set in the design brief, including design loads and other set criteria. A maintenance plan and an inspection strategy have been proposed and implemented (Borg et al, 2010).

Figure 2. Existing deteriorated structure & reinforced concrete elements on façade prior to repair.

4 RESOURCE CONSERVATION & WASTE MANAGEMENT

4.1 *General*

The repair of the existing buildings through a sustainable rehabilitation strategy was considered, rather than demolition and reconstruction. Rehabilitation as against reconstruction, addresses both the conservation of resources, and the reduction of Construction & Demolition waste. The rehabilitation of the existing buildings resulted in less waste generated from demolition, and less consumption of new resources. The objective was to adapt an existing building, to accommodate a new function, whilst retaining the architectural integrity.

4.2 *Construction & Demolition Waste*

The rehabilitation of the buildings required the replacement of various deteriorated structural elements, following the assessment of the state of the elements. The minimum possible elements from the existing structure where replaced, whilst it was ensured that the repaired and rehabilitated buildings could reach the required functional and performance levels. This approach led to a reduction in the waste generated during rehabilitation. The waste generated during the repair and rehabilitation, was also considered for reuse and recycling.

During rehabilitation it was necessary to dismantle the elements and part of the structure to be replaced, rather than demolition, particularly in order to safeguard the existing structure and

elements which were retained. This methodology based on a different approach from demolition, supported further the reuse and recycling of waste generated from the rehabilitation of the buildings.
The reuse and recycling required the separation and classification of the waste materials. The Waste Management Plan methodology was adopted, and the waste materials generated were identified and quantified. Stone masonry block-work was dismantled and stacked in a storage area on site. These elements were classified into two main groups; those suitable for reuse in secondary construction, and waste block-work to be recycled for production of crushed stone for screed and other uses. The reinforced concrete elements were classified on site into two groups; dismantled concrete elements, and reinforced concrete beams and slabs. These were transported for recycling. The steel reinforcement was separated from the reinforced concrete elements for recycling, and concrete crushed for the production of recycled concrete aggregate. Properties of the recycled concrete aggregate were determined for the purpose of classification.

Figure 3. Dismantling and classification of waste: wall masonry elements and RC roof elements.

4.3 *Water Management and Waste Water Recycling*

The rain water and surface water runoff in the site is collected in the existing water culverts and stored in the reservoirs. The original large reservoir was repaired and modified resulting in a large reservoir and two smaller reservoirs which allow for better management of water. The water is collected from all the roofs and open spaces and is used as secondary water in the buildings and for irrigation purposes in the afforestation scheme. The new buildings incorporate water saving features and accessories in the bathrooms.

The waste water generated in the complex, is treated in a biological sewage treatment plant, built within the site. The expected daily maximum flow amounts to $10m^3$/day. The sewage treatment plant was installed below ground, and consists of different zones made up of glass reinforced polyester tanks. The treated effluent is of the recommended quality for irrigation in the landscaping scheme and afforestation project.

5 ENERGY EFFICIENCY MEASURES

5.1 *General*

The scope of the energy efficiency measures in the project is to reduce the energy consumption within the buildings, to minimize internal cooling and heating loads and to maintain thermal comfort. The aim of the rehabilitation strategy was to exploit the features already existing on site and in the buildings, and introduce additional measures for improved energy efficiency. The various measures led to satisfactory indoor comfort levels which were achieved without the use of power consuming equipment.

5.2 *Thermal Efficiency*

The Thermal efficiency of the buildings depends largely on the building envelope i.e. the walls and roof elements. The external walls of the buildings are approximately 510mm thick and consist of two skin masonry construction each with a thickness of 230mm & a 50mm air space. The U-value of the walls is lower than that recommended for Malta. Insulation was introduced in roofs to reduce thermal losses; the expanded polystyrene insulation used has low heat transfer characteristics and is lightweight. The use of reflective coating on the roof and a weather resistive barrier were also considered to maintain the R value, and to prevent air and moisture movement into and out of the conditioned space.

5.3 *Shading Devices, Apertures & Natural Lighting.*

The reinforced concrete cantilever structures, particularly along the south east and south west facades of the main building, are an important characteristic of the building. These elements provide effective external shading to windows, eliminating direct solar radiation particularly during the summer season. The building roofs benefit from the shading provided by the photovoltaic and solar water heater roof installations thus reducing the roof's thermal gain.

Windows provide less resistance to heat flow than walls, roofs and floors. Double glazing was used for all apertures in the buildings, to reduce the transmission of heat. The frame aluminium profile was specified to be sealed and air-tight. In addition, the use of louvers on the external face of the apertures allows for air movement and ventilation, and the shutters are designed to provide visual privacy and security. Large openings provide for adequate natural day lighting in the main spaces & reduce the need of artificial lighting in buildings. Light-pipes were installed in specific spaces, to improve on the natural light from windows, and in the corridors & spaces were no windows are present. Light coloured finishes were used on roofs and external walls to reflect radiation, and the internal spaces were finished in light colours to reflect maximum natural light in interior spaces.

5.4 *Ventilation, Site Conditions, and Buildings Configuration*

Cooling in summer is promoted through adequate cross ventilation within the buildings, achieved through the large openings, and the high level apertures in specific spaces. Sea breezes were exploited in view of the disposition of the buildings on the promontory and their location. Furthermore the main building is elevated above ground level by c. 850mm; this improves further natural ventilation. Ventilated ground slabs were considered in specific areas.

The trees and shrubs surrounding the buildings also act as windbreakers. The landform and vegetative cover influence the amount of reflected solar radiation. The discomfort caused by glare is reduced. Soil, trees and shrubs have lowest reflection values and trees provide shade and shaded ground area around the buildings (Borg et al. 2010).

6 ENERGY USE & RENEWABLE ENERGY SOURCES (RES)

6.1 *General*

The Sustainable Development Centre includes three types of commercially available Renewable Energy technologies; photovoltaic (p.v.) electricity generation, wind electricity generation through micro-wind turbines and solar water heating. The building's electrical system was designed to keep the use of electrical energy at a minimum.

6.2 *Photovoltaic Systems and Wind Turbines*

The electrical set-up shown in figure 4 was designed to cater for the grid connection of both p.v. and wind energy sources. For the p.v. systems, the dc current produced by the photovoltaic panels is transformed via inverters into a single phase a.c. voltage allowing power to flow into the electricity supply.

In the case of the micro-wind turbines, wind generator's varying frequency voltage output initially undergoes rectification and then conversion to 50Hz a.c. voltage by means of an inverter similar to that used by p.v. systems. A data-logging system is used to monitor and log the performance of the p.v. and wind systems and various related environmental parameters.

The p.v. system was designed to have three types of p.v. technologies, mono-crystalline, poly-crystalline and thin-film. The aim of having three different p.v. technologies installed under identical conditions was to be able to log the 'actual' generation performance of each technology over a number of years. In this way a 'practical' study of which technology is most suited to the Maltese Islands can be carried out. With regards the micro-wind turbines, two technologies were considered: a vertical axis turbine and a horizontal axis turbine. The latter technology is considered as the more efficient, however it was decided to have a mix of turbine designs so as to expose the general public to both types of technologies and their suitability to the natural and the built environment. In this case the wind turbines were considered to be installed in the same area and exposed to the same conditions and wind resource. Direct comparison between the performance of each turbine can therefore be made. The p.v. and wind system of inverters was designed to allow electrical energy generation in grid connection mode and in 'controlled' stand-alone mode. In the case of electrical grid failure, this system makes it possible to power the building to a limited extent as long as the p.v. and wind are still generating electricity. The stand-alone inverter is programmed with a load shedding program so as to provide electricity only to the building's high priority loads (e.g. fridges and selected lighting). The system of solar water heaters (SWH) was designed to provide the hot water supply of the showers/toilets with little demand on the electricity supply (Borg et al, 2010).

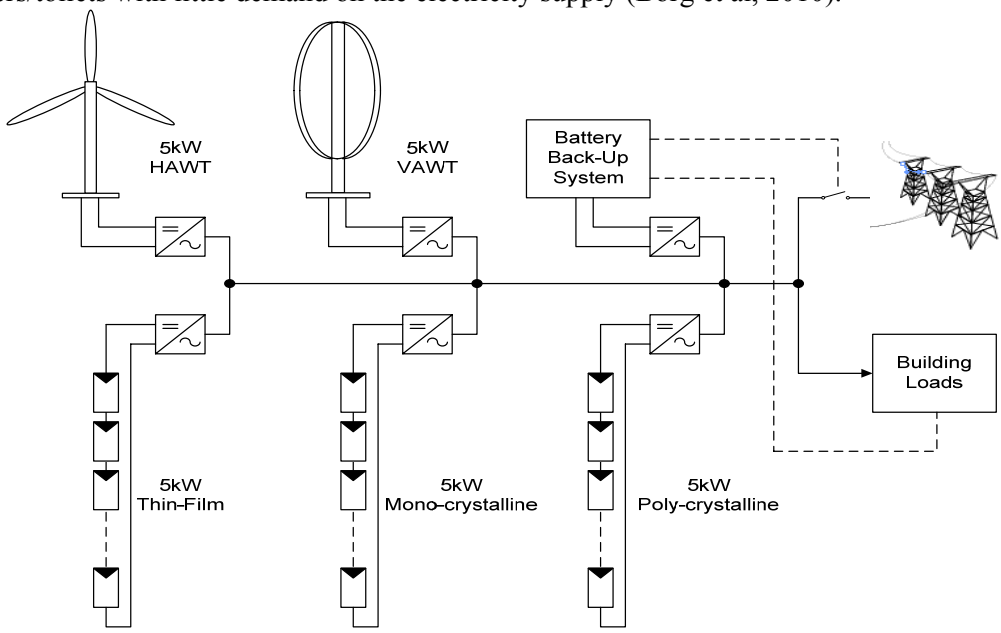

Figure 4. The Grid-connected and Standby RES System.

6.3 *Efficient use of Electrical Energy*

The project of Xrobb l-Għaġin allowed for the redesign of some of the electrical and mechanical systems, and this gave the opportunity to design for the most efficient use of energy. The most responsible attitude towards the usage of energy is to reduce inefficiencies as much as possible and take corrective action in situations where there is energy wastage. Electrical energy is mainly used for heating/cooling, lighting and power. The buildings do not make use of electrical air-conditioning but rely solely on natural ventilation and proper insulation. Energy saving lighting technologies are used wherever possible, and motion sensors were considered for installation in common areas to turn on the lighting only when necessary.

6.4 *Reductions in CO_2 from the RES Systems*

The annual energy generation by the photovoltaic (p.v.) sources (SMA, software) and the wind sources (Gipe, 2004) was estimated. The energy saved by using solar water heating rather than electrical heating is shown in Table 1. Not only do the Renewable Energy Sources reduce the building's electrical energy consumption; they also contribute to the reduction of CO_2 emissions (Table 1). (During 2006, it was reported that 0.8782kg of CO_2 were emitted for every kWh generated (Enemalta, website)).

Table 1. Annual kWh savings and reductions of CO_2 emissions.

RES Technology	Annual Savings	Annual Reduction of CO_2
	kWh	Tonnes
PV System	23500	20.5
Wind System	16000	14.0
SWH System	20075	17.5

7 CONCLUSIONS

The Sustainable Development Centre, within the Xrobb il-Għaġin Nature Park in Malta, is considered to be the first centre of its kind in the Maltese Islands, with the scope of addressing environmental management, ecological rehabilitation, afforestation, and energy conservation.

The Rehabilitation Strategy adopted was based on a comprehensive approach, addressed various fundamental principles, including the architectural heritage, functional requirements, structural interventions and repair of the structures, conservation of resources, water conservation and waste water recycling, waste management, services, energy efficiency in buildings, and alternative and renewable energy sources. The strategy implemented, was required to transform the existing deteriorated buildings, into a functional and energy efficient Sustainable Development Centre. The Sustainable Development Centre has an important role in the promotion of environment and science education.

8 ACKNOWLEDGEMENTS

The authors form part of the Design Team of the Nature Park & Sustainable Development Centre. The authors would like to thank Nature Trust Malta (NTM) & the Ministry for Resources & Rural Affairs (MRRA), Malta. The project was supported by a grant from the Norwegian and EEA Funding Mechanisms.

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The engineering of the prehistoric megalithic temples in Malta

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ABSTRACT: The prehistoric megalithic structures of Malta and Gozo date back to a civilization of 4500 to 5500 years ago. Although now in ruins, their longevity is remarkable, and must be due to the inherent durability of limestone, properly selected, as well as to the underlying engineering principles and construction. Prehistoric civilizations are often, erroneously, perceived as technologically primitive, however these prehistoric structures are technologically remarkable. This paper proposes engineering principles underlying its longevity. Hitherto, many of the features of the extant structure have been explained as having "decorative" functions. The author suggests that these features should be assessed in the light of the possible engineering and constructional processes adopted; this approach is based on the belief that, particularly for civilizations in which energy resources were stretched, it would not make "resource" sense, if these features were not there for a specific purpose – it would not be, using modern terminology, sustainable.

1. INTRODUCTION

The megalithic temples of Malta have been dated back to the 4th millenium BC. The oldest of the major temple sites, Ggantija in Gozo, has been dated, on the basis of recalibrated radiocarbon dating, to 3600 to 3000 BC, the "youngest", Tarxien, to 3000 to 2500 BC. This is therefore looking a civilization that lasted at least 1000 years. It is still not clear where it came from and where it disappeared to, and why.

The temple sites understandably underwent a number of changes over the 3500 – 2500 BC millenium. The Lower Temple in Mnajdra, for example, belongs to the older Ggantija phase, whilst the Middle Temple belongs to the Tarxien phase. It is therefore not surprising to find a significant difference in the characteristics of the stonework, in the quality of the workmanship, and in the decorative details. On the contrary, it is indeed surprising to observe that the structural principles, on which the temples are based, apparently remain so consistent over this period. These principles also appear to be surprisingly sophisticated.

To our knowledge the Maltese prehistoric megalithic temples are the oldest expressions of free-standing stone architecture. This extraordinary statement is made even more amazing not only by the fact that more than thirty prehistoric sites have been uncovered in the barely 320 sq.km. that make up the Maltese Archipelago, but also that the structures with similar characteristics, found in other neighbouring Mediterranean countries, such as the Balearics, the Iberian Peninsula, or Sardegna, generally have a much younger pedigree, and, in any case, do not have the whole range of characteristics of the Maltese megalithic structures.

Malta's prehistoric temples are a series of megalithic structures that were "discovered" in the 19th century, although some of the major sites were recorded by travellers at least as far back as the 17th century. The 19th century and early 20th century saw the first systematic archaeological campaigns to uncover more of these structures. The early campaigns were probably not as scientific as they should have been, and included some degree of reconstruction, and also the removal of some earth mounds that, in hind sight, might have been central to understanding the way these temples were built. In order to understand the structural behaviour, and especially the construction methods, adopted by the prehistoric builders, it is obviously necessary to, first of all, translate, in our minds, the extant ruins into hypothetical complete structures. It is also necessary to avoid being misled by what may have been mistaken reconstruction carried out since the 19th century, but also, perhaps, before this "modern" period of interest in the monuments.

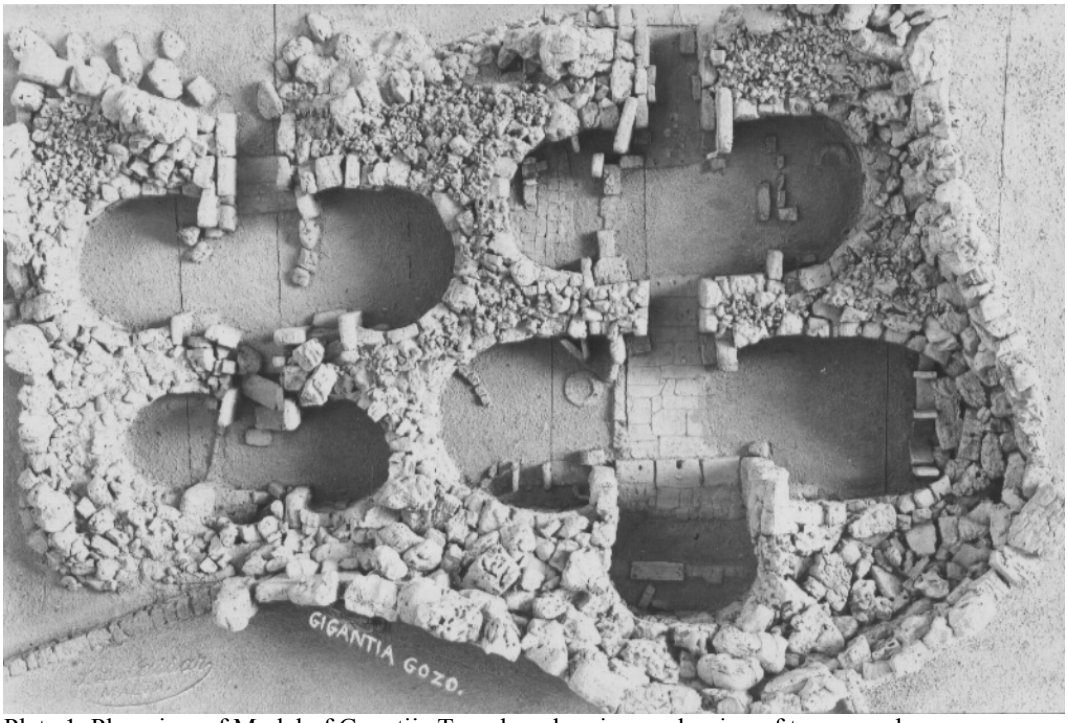

Plate 1. Plan view of Model of Ggantija Temples, showing coalescing of two complexes.

In his letter of the 19th November 1840, J.G.Vance[13] describes the excavations carried out, at Hagar Qim, at the request of the Governor General Sir Henry Bouverie, and records how "the remains of ancient architecture" were uncovered, and how "a number of well-proportioned blocks…., scattered in different directions…., some lying in heaps, others singly" were found at the site. Although these descriptions are quite detailed, it is not easy to relate the megaliths illustrated in this letter to the way the configuration of the massive stones in this temple complex would be read today.

In subsequent years, the scattered blocks were lifted back in place, or what was presumed to be their original place. A degree of reconstruction and re-interpretation, often without detailed records, took place in many of the important temple sites, and these may lead to mistaken hypotheses about the original structures. In Mnajdra, for example, it is known that the front section of the Middle Temple was extensively re-modelled in the 1930's, as was the rear perimeter wall. Some photographs of the excavation, of both the Hagar Qim and Mnajdra sites, record that the land surrounding the temple structures was much higher than is now the case. The photographs also record the removal of an earth mound at the back of Mnajdra – how much of this mound was modern, and how much prehistoric is nowhere recorded.

2. SHAPE AND MODELS

The temple structures have a number of consistent characteristics. The megalithic structures are assembled from large stone blocks, so-called megaliths, apparently without the use of any bedding mortar. The stability of these stone structures therefore depends on the structural form, as well as on the mutual interlocking of the rough surfaces of adjacent blocks. The constructional features include the use of (i) upright free-standing block assemblies, that form "trilithon" portals along the main axis of the temples, (ii) other upright blocks that are used to define the semi-circular apses, which are arranged sequentially along the axis, and (iii) horizontal megaliths, laid in "courses", forming horizontal arches that corbel out, one course above the other, to form vault-, or dome-, like structures. These inner walls are surrounded by external walls with specific constructional features, such as the alternation of tangential and transverse orientation of the megaliths to form an interlocking outer ring. The space between the inner walls and the outer wall is, generally, filled in.

The basic typology for a temple unit consists of a longitudinal axis, normally also an axis of symmetry, terminating in an apse, and along which is a varying sequence of pairs of lateral apses, or lobes. The external shape of one temple unit is thus broadly ogival, merging into a concave façade. The temple complexes, particularly the four major ones, however, consist of more than one temple unit, and the basic configuration is modified as one temple unit follows another in time, and coalesces with the previous one to form one single complex.

The temple plan typologies range from the three lobes of Mgarr, or Mnajdra (Upper Temple), through the five lobes of Ggantija or Mnajdra (Lower and Middle Temple), to the seven lobes of Tarxien. The temples have obviously been modified over the centuries, sometimes extensively. The odd apse, in these configurations, is the one at the end of the axes of the temples – which is more or less developed depending on the site. It is reasonable to presume that the sequence of pairs of apses, along a linear axis, owes at least as much to constructional and structural requirements, as to the requirements of ritual.

One of the most fascinating aspects of the study of the prehistoric megalithic temples is that amongst the archaeological material excavated are found what must be considered as amongst the oldest architectural models, now preserved in the National Museum of Archaeology. The larger of these models refers to what appears to be a typical pair of apses, which pair forms the basic unit in the construction of the temples. It also illustrates what must have been the external appearance of the structures, and perhaps gives a hint of the original roofing system. In the Mnajdra Middle Temple, there is what must then be considered as one of the earliest architectural drawings, or more properly, engravings – the elevation of a typical temple, having similar characteristics as exhibited on the small models. It is likely that both the models and the wall engraving are post-construction representations of the temple structures, possibly with some votive meaning; however, it would be attractive, albeit implausible, to consider these as instructions to the prehistoric builders!

Plate 2. From left: (i) Engraving of façade, (ii) Votive model, (iii) Façade reconstructed from fragments.

3. STRUCTURE

It is known that the structural stability, and, no less important, the constructional feasibility, of the stone roof of a single, circular, cell, such as the *girna* or the *nuraghe,* is based on the stability of the complete horizontal compression ring of stone. A simple description of the corbelled stone chamber could be a series of stone rings, one on top of the other, each ring having a diameter smaller than the previous one. Every complete ring is stable by virtue of its resistance to the compression, (that is, the reduction in the length of the circumference), which would be necessary for the ring to fall through a space that has a smaller diameter. The individual components of the incomplete ring, however, must either be independently stable, or else they have to be supported by some "falsework" until the ring is completed. The individual components of the ring could be independently stable, if, for example, each stone is corbelled off a lower stone, with the projecting part not being too large compared to the part resting on the stone.

Each complete ring of stone, resting on a previous, and larger, ring of stone is inherently stable, because in order for it to collapse under uniform loading, which can only happen by falling inwards, it requires a reduction of its circumference. In other words, if the individual components of the ring are in contact with each other, the stone ring will develop a horizontal compression force to resist such collapse. The stability of the ring therefore depends on the contact between the vertical faces of these "voussoirs", and hence on the shaping of these voussoirs to a wedge shape, so as to achieve full contact. If such a contact were absent, the stability would then depend only on the individual stability of each corbel. A vertical slice through a corbelled structure would be stable only if the structure were closed at the top – that is, only if the slice formed a complete vertical arch.

However, the dome has two mechanisms by which loads can be carried. The first mechanism is that of the horizontal ring, as discussed earlier, and the other mechanism is that of the vertical arch that exists in any vertical section through the dome. The two mechanisms co-exist, and the load is distributed between these two mechanisms in accordance with the relative stiffness of the two – and depending, obviously on the geometrical configuration of the dome. In the so-called "false" dome, the stone rings have horizontal interfaces, and therefore the frictional resistance, vital for vertical arching action, may be diminished (although it is not absent). In the "true" dome, with the voussoir joints cut normal to the curved surface, the vertical arching action may be more significant, although, in many structures this is also impaired by, say, uneven settlement under the dome perimeter. Arching action, in fact, also requires rigid abutments. Furthermore, when the dome has an occulus, that is, an opening at its crown, the vertical arch is incomplete, and therefore the important load-carrying mechanism is the horizontal, or circumferential, ring, at least in the regions around the occulus, whether the dome is termed "true" or "false".

The structural mechanics of the single cell funerary chamber have been extensively studied. Cavanagh and Laxton[3] have published an analysis of the Mycenean Tholos Tomb, which it must be remembered, is at least a thousand years younger than the Maltese prehistoric temples. Cavanagh and Laxton discuss what they identify as the three mechanisms that are available for the stability of the tholos tomb. In addition to the vertical arch action, and to the horizontal ring action, they propose that the system of corbelling is, by itself, also possible, provided the corbelling is taken high enough to bridge the span of the structure. This is only feasible in the context of an overburden that balances the over-turning moment that results as the corbelled wall goes higher and higher. Although, in their paper, Cavanagh and Laxton quote the observations of the original students of the tholos tombs, Cockerell and Donaldson, as saying that "in its horizontal position at least, the arch was clearly understood by the architect who designed these chambers", they discount the importance of horizontal ring action in the Mycenean tholos tomb, primarily because of the major interruption represented by the entrance shaft that pierces the circular shape.

Although this approach ignores the mutual interaction of the different mechanisms, the interruption to the horizontal stone ring, presented by the "entrance shaft", is a very relevant issue to the discussion of the structural system of the prehistoric temples in Malta. The basic structural unit seems to be that formed by a pair of apses. The horizontal circular compression ring is clearly interrupted by the temple axis, an axis that presumably was made necessary by ritual requirements of entry into the spaces created by the stone structures. The particular system of joining pairs of apses, adopted in the local megalithic structures, consists of the "trilithon" portals that not only mark the axis of the temples, but connect one half of a horizontal circular ring, in one apse, to the other half of the horizontal circular ring, in the opposite apse. In other words, the "trilithon" portals form the structural continuity necessary for a modified form of "dome action", which includes both corbelling mechanisms, as well as horizontal compression actions. It is also very likely that any roof structure, now missing, would have contributed a further mechanism of load transfer through a modified vertical arch action.

Plate 3. Clockwise from top: (i) and (ii) Lower Temple Mnajdra, showing corbelling rings over apse;
(iii) External Wall, Ggantija, showing alternating flat and tapered vertical megaliths;
(iv) Split/truncated dome equilibrium, explaining structural need for strong portals along axis.

The term "trilithon portal", that is a portal formed by three megaliths, two uprights and one lintol, is probably also technically incorrect, for the portal is formed by four megaliths. The vertical sides of the portal are not only restrained at the top by the horizontal lintol, but are also embedded, at the bottom, in appropriate holes, or slots, dug into the solid stone thresholds, so as to form a box structure. The top restraint, formed by the lintol, is often not merely dependent on friction, as in a megalith simply laid on top of the uprights, but in many instances the lintols are notched so as to provide a lateral lock for the upper end of the uprights. This box receives the horizontal thrusts from the incomplete circular rings. If the semi-circular rings are wedged against solid abutments, each layer, although incomplete, is stable enough to carry more rings, until the space over the apses is closed by a sort of hemi-spherical dome, or until the reduced span could be covered by flat structural elements (made of stone or timber).

The success of the horizontal arching action depends on the proper contact between the vertical joints of the "corbelled" rings, and between the vertical joint formed with the portal structure itself. The recent reconstruction work on the Middle Temple at Mnajdra[10, 11] has enabled us to observe that the megaliths that form part of the horizontal "corbelled" rings are wedged-shaped,

and are also tightened against each other by stones wedges inserted at the back of the joints, that is, at what would be the extrados joints. It is obvious that, in many other locations in the temples, this tightness of the horizontal stone rings has been lost. The stone lintols over the portals have, in many instances, been damaged, or have disappeared, so that the box portal no longer exists, and weathering mechanisms and anthropogenic actions have otherwise impaired the contact between the vertical sides of the stone rings. At this stage, therefore, the stability of the individual stone members of the ring would be simply that of corbelling over the lower members, and the stability of the whole would depend solely on the stability of this one mechanism.

However, if one were to judge the structural system of the temples simply on what survives, one would be ignoring the greater engineering sophistication that the two-apse unit seems to indicate. And ignoring this would then lead to the question of why would the prehistoric builders go to so much length to form wedged shaped stones, to notch lintols into the portal uprights, to wedge the rings from behind, and to make the other constructional features described above, if they did not have in mind to actuate this mechanism.

Underneath the horizontal corbelled stone rings, the lower part of the inner walls is composed of upright stone panels, of a different geometry to that of the stone corbels. These stone panels, also arranged in a semi-circle, and also locked against the portals, seem to have a slight inclination inwards, and are then locked into place, as a closed semi-circle, by the weight of the surrounding fill. It was originally thought that this fill consists of a mixture of soil and smaller stones. The recent work on the Middle Temple at Mnajdra[10, 11] has shown that, at least for this period of temple construction, the fill consists of carefully inserted slivers of smaller stones, packed tightly against each other.

This infill is then, in turn, contained by the massive external masonry ring, that would, originally, have formed the outer layer of each temple complex. This is the outer appearance that would correspond to the stone models and stone engraving referred to before. The construction of this external skin is also fairly complex. Tampone[7] has shown that, in general, the external skin consists of a sequence of radial and tangential megaliths, leaning against, and locked over, the infill. Tampone has led a study of the temple complexes of Hagar Qim and Ggantija, and, on the evidence collected, has identified an “entasis” in the main uprights, such that the tangential blocks wedge tightly into the external ring by virtue of their own weight. This wedging probably occurs in a vertical as well as in a horizontal plane.

The external appearance of a temple complex has been modified over the millennia since they were built, first of all as a result of the coalescing of adjacent temple complexes built at different periods, and, secondly, because of the loss of stones from these external skins, either through weathering or through human intervention. In Mnajdra, for example, segments of the original external wall of the Lower, older, temple, are now part of an internal wall which marks the boundary between the Lower and Middle temple. The back elevation consists of a rubble wall construction, of recent origin, probably erected to replace missing megaliths – or, perhaps, the missing megaliths were never there? In fact, the same “containing” action on the inner parts of the structure could be achieved by a large external earth mound. In many other prehistoric megalithic tomb structures in Europe, (say Brittany, or the British Isles), the external appearance is, in fact, that of an earth mound enclosing an inner stone structure. It is therefore not unreasonable to hypothesise that the earth mound excavated at the beginning of the century, from the rear of the Mnajdra complex, was meant to be the external containment structure, replaced, in other locations, by the external megalithic ring. Alternatively, it could also be suggested that the external ring was actually the first constructional intervention, intended to stabilize an excavation into an existing soil slope, in order to create the space for the construction of the temple. The removal of all earth mounds around the temple sites makes it difficult to draw any conclusions in this regard.

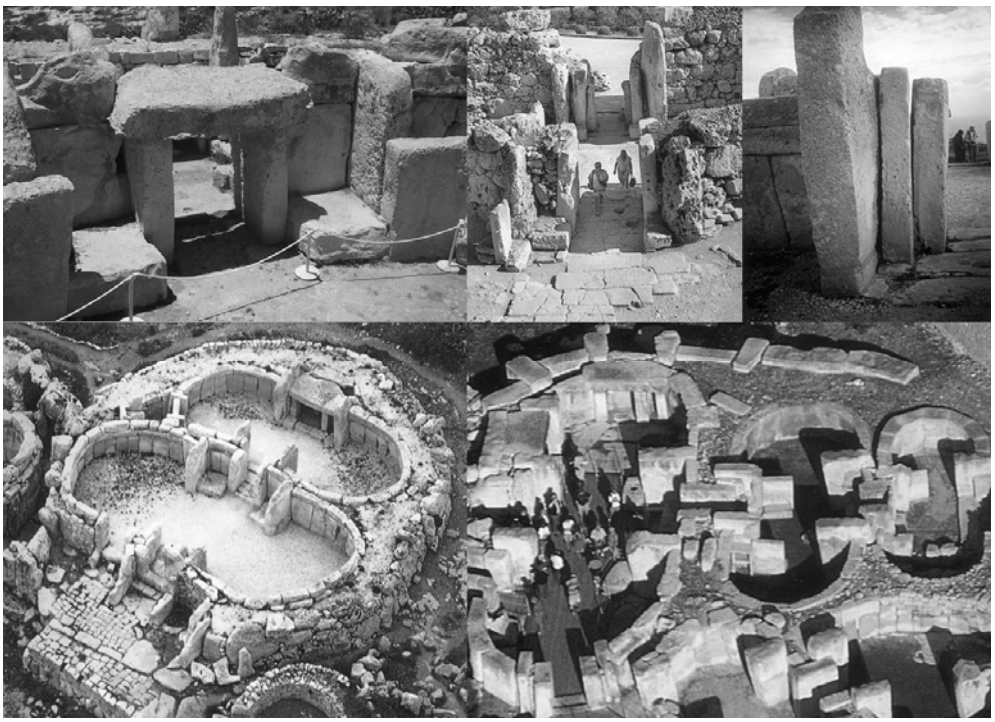

Plate 4. Clockwise from top: (i) Typical portal structure, Mnajdra, with "trilithon" portal, adjacent transverse upright, and low cubic blocks; (ii) Ruins of portal structures, with triple uprights, Ggantija; (iii) Triple verticals along main axis, now displacing slowly, because of missing lintols, Mnajdra; (iv) Axial sequence of aspes with strong portal structures, at Tarxien, and (v) at Mnajdra.

4. ROOFING SYSTEMS

One of the more commonly asked questions about the temples is whether the temples were ever completely roofed over, and if so, with which material. Ashby[1] and others, excavating Hagar Qim at the beginning of the 20th century, opined that the structures were originally certainly roofed over. The small stone models referred to earlier, and the stone engraving at Mnajdra, also suggest that the pair of apses was roofed over, at some level, by horizontal structural elements.

An intense debate has raged since Ceschi[4], in 1939, argued forcibly in favour of a roofing system based on a corbelled structure up to a certain height, and then roofed over by stone slabs, used to create a flat roof over the reduced span over each apse (or pair of apses). Other authors, notably Evans[5], 1959, Tampone[7,8,9], Bonanno[2], 1988, and Piovanelli[6] in 1988, have contributed to this debate. A detailed engineering approach to the problem was undertaken by Xuereb[14], in 1999, as part of his undergraduate research work.

In general, the solutions for roofing systems can be characterized by the following. It is possible that the corbelled stone structures continued upwards, as in the Mycenean tholos, until the upper occulus was very small, and was then either easily roofed over by small stone slabs, or left open. The main argument against this solution is the complete absence of any evidence that the external form of the temples could have been so high as would be required by this structure – as well as by the absence of the volume of stone material that one would have expected to find at the sites of the ruined structures.

It could also be that the apses were left completely open. This could make sense from the functional point of view – given Malta's mild climate; however, this would leave unanswered one very important question. Why would the prehistoric builders make such an effort to erect

corbelled stone apses, if not to reduce the span across the apses? And why would this be necessary, if there were not the intention to exploit this reduction in span?

For the supporters of the thesis that the temple structures did have some sort of flat roof, the primary evidence for this consists of the afore-mentioned models and stone engraving, but also the Tarxien Hypogeum, which appears to replicate some of the architectural features of the temple structures above ground. Amongst those who support this proposal, the debate has also been on whether the flat roofing consisted of timber, or whether it consisted of stone slabs, as proposed by Ceschi.

The main arguments against stone roofing structures include the absence of sufficient remains of what would have been the stones for the roofs, but especially the perception that the locally-available limestone was not strong enough to span the approximately 5m void that would result from a corbelling system, taken up to no higher than 6m above the ground.

Although, the author does not believe that it is yet possible to present conclusive evidence in favour of one material or of another, it is possible to make the following observations. It is not true that globigerina limestone, which is the weaker of the limestones available locally, is not strong enough to span over 5m. The strength of a stone beam depends on its tensile strength, but also on its depth. The issue, therefore, is not whether the material is strong enough, but whether it would be possible to produce, and to handle, stone beams, of reasonably-practical sizes, to span over the 5 or 6m necessary. Laboratory studies by Xuereb[14], using stone beams 5.0m long, 0.5m deep and 0.35m wide, have shown that such a stone beam could successfully satisfy this function. The weight of this single stone beam is not trivial, but it is very comparable to the weights of the megaliths, which can still be observed at the temple sites, and which therefore could demonstrably be handled by the prehistoric builders. It is, of course, necessary to show how such a weight would not only be lifted in place, from the ground, but how it would be lifted up 6m in the air and positioned where necessary. This is a topic that will be discussed in the next section. However, in engineering terms, it could be stated that limestone, obtained in sizes which are feasible, both from the point of view of the quarry extraction operations, and also from the logistical handling and lifting operations, could fulfill the roofing function assumed in this hypothesis.

As to the other main objection, that there is no material evidence of the remnants of such roofing elements, it could easily be argued that the temple sites, once ruined and abandoned, would, very likely, be a source of stone material for other construction activities elsewhere. The use of stone or marble ruins as a “quarry” is a phenomenon that is common throughout many civilizations, and many geographical locations. Indeed, the more difficult question to answer would be why would the prehistoric builders, after so much engineering effort to erect the lower part of the temple structures in stone – presumably considered as a material with great durability when compared to other, easier to handle, building materials such as timber – then opt to erect the more critical roof structures in wood, or other, less durable materials. It is not impossible that they did roof the temple structures in less durable materials, but it would demonstrate a lack of consistency in the architectural concept of the monument, as a structure to last thousands of years. And, frankly, there is no evidence of inconsistency in their architectural or engineering thinking – quite the opposite.

5. CONSTRUCTION PROCESS

The architecture and engineering of the temple structures owes a lot to the raw material that is available on the island. The temple structures are built of globigerina or coralline limestone blocks, of sizes that can vary from half a tonne to over 2 tonnes, and, exceptionally, much more. Local limestone affords reasonably good mechanical properties, and, particularly for the globig-

erina limestone, a reasonable degree of workability. This is, especially in the light of the limited tools available at that time, a very important consideration. The stone blocks could be extracted relatively easily from shallow open quarries, very often in close proximity to the site of the temple structures themselves. The relative compactness of the limestone, particularly globigerina limestone, the absence of marked bedding planes, and the limited amount of fissuring, would have assisted the extraction of large flat blocks of sufficient thickness.

Zammit[15] has written about the tools that would have been available to the prehistoric builders. They would have used hand-axes of flint and quartzite, (obtained from volcanic islands in the vicinity), knives and scrapers of obsidian, wedges of wood or stone, pickaxes made of branched horns of antlers or of flint, stone hammers, wooden rammers, wooden levers, and wooden or stone rollers. The evidence for these tools is found in the archaeological objects uncovered during the various excavations of these prehistoric sites. The discovery of large stone balls, for example, examined in the light of the details in the lower surfaces of some of the enormous stones used for the external wall of Hagar Qim, say, could very easily explain how these balls could have been a feature of the process of lifting upright the enormous megaliths, obviously transported flat. The cart-ruts have also been interpreted as stone "rails" prepared to guide sledges loaded with stone from the quarries to the building sites, although this interpretation is not really satisfactory.

In the structural system explained before, the primary elements in the construction process would be the portal structures. These are the elements that give stability to the apses – the apses would not be stable without these portal structures. It is reasonable to presume, therefore, that the construction of the structure would commence by the construction of these portal structures. The first decision to be taken by the prehistoric builders would thus be the orientation of the axis along which the portal structures would be erected. It would be unreasonable to presume that the choice of orientation axis of a structure, that would be erected with so much effort and skill, and that was intended to last for generations, would be taken lightly. This would confirm the proposals made by other authors that the temples are deliberately oriented either to the stars, or to other stellar bodies such as the moon and the sun.

The first steps would thus be those of preparing the ground, - this would depend on whether the selected site were flat and level, (in which case it would be normal to expect the structures to be founded on an outcrop of rock), or sloping, (in which case, as in the example of the Middle Temple at Mnajdra, the ground would be leveled by careful packing of smaller stones). Once the axis of the temple was selected, the threshold stones, suitably worked and notched as discussed previously, would be put in place, and the uprights on either side of the portal structure dragged to the site and erected in place.

At this stage, before the operations of erecting the portal lintols were embarked upon, it would be reasonable to ensure that the uprights were rigidly held in place. Whichever technique was used to lift the portal lintels, to the not insignificant height of the top of the portal uprights - whether this were an earth ramp from the ground to the level required, or a see-saw level technique described by Zammit - it would always be necessary, at the final stage, to drag the lintol megalith over the top of the upright stones, and this would only work if the uprights were very rigidly held in space.

It is therefore possible to interpret the various features of the portal architecture as a means of providing lateral stability to the whole portal structure. These features include low stone cubes, placed at the foot of the uprights, other uprights oriented at right angles to the main uprights, presumably so as to provide lateral restraint in an orthogonal direction, as well as the system of doubling or tripling the main uprights, in a concentric fashion, along the direction of the axis of symmetry.

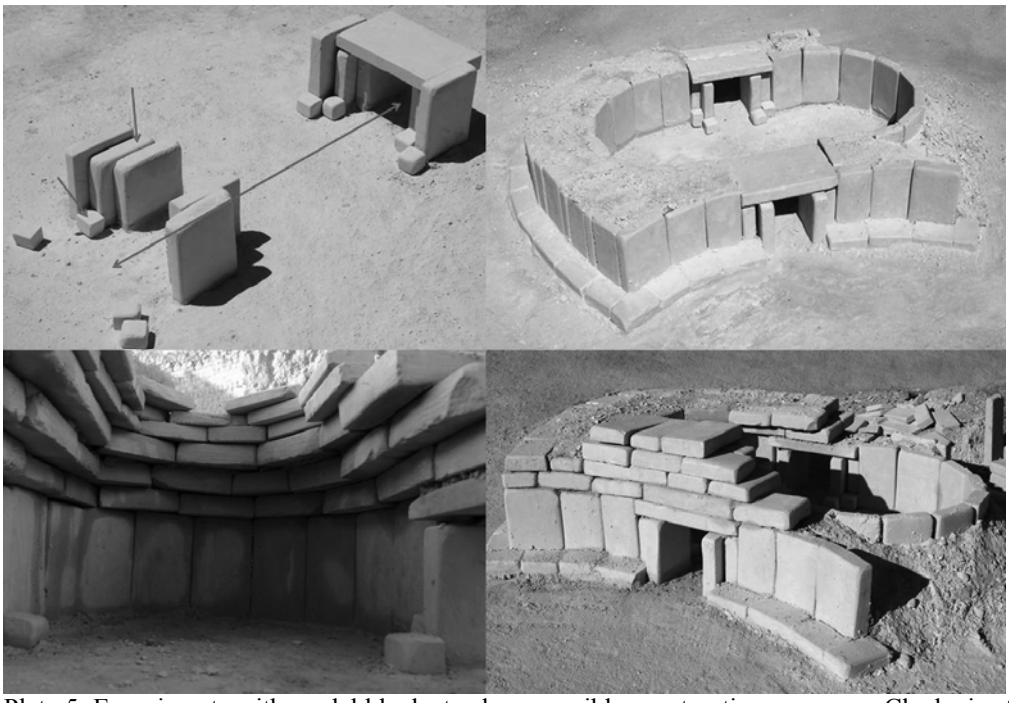

Plate 5. Experiments with model blocks to show possible construction sequence. Clockwise from top: (i) Setting out of axis, preparing strong thresholds, then uprights held in place by low blocks, then lintols pulled over, also, tripling of vertical blocks to consolidate portal; (ii) Semi-circular inner wall of apses erected, consolidated with rubble packing, held by outer wall structure erected over low peripheral plinth; (iii) Concave façade, and erection of flat courses, and beginning of corbelling over apses; (iv) Internal view of corbelling closing gap until flat stones (or timber?) can be laid across void.

Once the portal structure were complete, it would then be possible for the prehistoric builders to define the internal spaces by erecting the first rings of other uprights, of much smaller scale, that form the base of the apses. These uprights would be stabilized by virtue of their slight inclination inwards, but mainly by abutting against the portal structure. The process would then continue by the erection of the horizontal courses of stone, the corbelled layers, by lifting suitably-shaped "voussoir" stones – again either by means of earth mounds, or by see-saw or other lever techniques. Once again, the stability of each corbelled semi-circular ring would be ensured by the abutment, and the wedging, against the portal structure. The corbelled structure would in this way rise up to the height of the portal structure.

The structure would still be liable to distress, for example by displacement of one of the lower apse uprights outwards. The longer-term structural integrity was thus achieved by packing around the periphery of the stone structure already erected, using small angular shaped stones, then enclosing this packing with a low ring of rectangular blocks which would form the plinth, and the means of righting the massive megaliths that form the external walls. The use of stone balls as bearings during this operation, or as locks to hold the base of the megaliths in place has already been referred to.

The sequence of alternate radial and transverse blocks forming the external walls has also already been referred to. The system presumes that the transverse blocks, invariably the largest to be used, would be erected first, in a nearly vertical position, but resting lightly inwards, against the stone infill surrounding the inner walls. The radial blocks, more longitudinal in shape, and worked to form a wedged shaped section, horizontally as well as vertically, would then be lifted in place in order to lock the external wall together.

It is not clear at what stage the concave façade would be erected. It could be that the façade is a merely architectural device, but this is, frankly, not likely. The concave plan shape is very

likely related to the need to absorb horizontal forces at the façade, by a horizontal arching action into the ground. If this were the case, the façade would need to be in place as part of the process of erecting the external wall, if not before this phase.

At this stage, it is likely that an earth mound would have reached the top level of the construction to allow the transport of stone blocks to the upper levels of the temple. The same earth mound would probably exist before the erection of the external wall of the temple. It would therefore need to be removed, during the late stages of the operations, and its retaining function replaced by a continuation of the system used for the external wall. Unless it were vital for the monument to read as a free-standing structure, another hypothesis, however, could be that the earth mound, particularly if located at the back, was retained. The earth mound would also be the means by which any roofing structure, including stone beams, could be dragged up, and put in place. The lateral stability of the walls of the temple structure would be vital for this process.

Over the years during which the temples were in use, the compactness of the structural system would have enabled them to resist earth tremors, unless of gigantic intensity. The shapes described above are in fact amongst the most stable in the case of earth tremors. The temples would, however, be subject to many interventions by subsequent generations of users, including, as mentioned before, the construction of adjacent temples, and the coalescing of different constructional features.

Plate 6. From left (i) 6.5T megalith, Hagar Qim, with concave recesses for horizontal transport over stone balls? (ii) Concave recesses at base of uprights, Hagar Qim, for pivoting of blocks over plinth, or locking in place? (iii) Lateral support structures for making alterations?

It is also possible to trace direct engineering interventions, such as the excavation of the stone infill between inner and external walls, in order to create additional chambers. A case in point exists in the Lower Temple at Mnajdra, to the right of the main entrance. This is the area that was affected by a collapse in 1994[12]. The collapse involved the failure of a curious table-like structure, that provided lateral support to an enormous megalith, located between the Lower and Middle temple, but which clearly belonged to the originally external wall of the Lower Temple. The megalith in question was in fact inclined inwards, compacting what would have been an infill of stones locked against the inner chamber walls. When the need arose to create an additional chamber – (perhaps, because of the ritual need for an oracle chamber?) – it would have been necessary to excavate the stone infill, from the top. It is clear that the prehistoric builders were aware of the pressures induced inwards by the megalith in question, because, it is also clear that, as the excavation proceeded downwards, stone "props", in the form of large flat stone slabs, are inserted into the void, locking against the two stone sides, before the excavation proceeded downwards. Additional vertical props were inserted as the excavation proceeded, in order to make sure that these horizontal props did not fall down. This process was repeated at least twice, in this location, before the whole chamber was excavated. The large vertical column, located immediately to the left of the doorway carved in the apse uprights in order to give access to this new chamber, can also be interpreted as a form of "pile", inserted into the ground as the

excavation proceeded, in order to ensure the stability of the internal wall construction, which, incidentally, contains the highest corbelling system still in existence.

It is possible to identify other locations where stone elements were inserted, from the top, as would be expected once the area were infilled, in order to prop the sides of the chambers during excavation of the spaces between inner and outer walls. These operations were cleverly done, although it is likely that they tended to weaken the overall structure. Nonetheless, they survive, as do a number of other features. This is quite remarkable for 4500 to 5500 year-old structures, and very hard to beat with today's engineering!

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Scenarios for our common built environment

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ABSTRACT: The built environment provides people, economy and social life the framework for almost all activities. The area it has taken from nature is minor compared to agriculture and forestry but its environmental impacts are overwhelming. Changing of the energy and material basis of the built environment is one of the main opportunities of the mankind to alter the global frightening trends. The big challenge of professionals in the sector is now to work for an optimistic world scenario of the sustainable development. Technologies and processes of the sustainable construction are of vital importance for realization of a true transition. The sustainability scenario is one of four scenarios for the built environment that may result from a set of trends that are introduced in the most commonly known world scenarios concerning population, economy, climate, urbanization, energy and technologies.

1 INTRODUCTION

The report “Limits to Growth” was published in the year 1972 prepared by a project team led by Dr. Dennis Meadows (1972). It presented the first prototype of a world model that was based on the new approach of system dynamics. Five major global trends were studied: accelerating industrialisation, rapid growth of population, widespread malnutrition, depletion of non-renewable resources and deterioration of environment. The researchers concluded that the time of growth is limited without changes but the trends can be altered.

The trends have not yet altered; they have grown to global grand challenges. Since seventies, an international will has also grown to pursuits of the sustainable development. The future should be based on understanding of complex relationships between activities of the mankind and functions of nature as well as on understanding of interaction of various sectors.

The mankind needs to respond to the grand challenges within a couple of decades. Environmental threats have become overwhelming, and turning trends of overconsumption of resources and carrying capacity of the nature is of vital importance. The ways the built environment is planned, designed, produced, operated and used are crucial for the change. The material and energy basis of the societies and economies cannot longer rely on non-renewable resources.

The built environment is the man-made world where people live protected from dangers and inconveniences of nature. Its history reflects the history of technologies, economies, cultures and societies. The apparent need to change the built environment poses the question how to make it, and in order to answer to this, there is a need to understand the way the changes have taken place in the past, and try to understand how to influence on changes.

This paper introduces why the real estate and construction sector has a crucial role for the future of the mankind residing in our common built environment. The viewpoint to the history concentrates to tools, machines and technology. By back-casting, both current problems and possibilities become more understandable. The challenges of sustainable construction are stud-

ied by the aid of trend analysis and development of four scenarios for the built environment. As conclusions, the sustainable built environment is introduced as an optimistic transition scenario.

2 TECHNOLOGY DEVELOPMENT AND THE BUILT ENVIRONMENT

2.1 *Introduction to the concept of the built environment*

The mankind creates and shapes the built environment to respond to its social, cultural and economic needs. From the early ages of civilization, inhabitation has tended to cluster at nodes of commerce and political power. Simultaneously with the growing number of people and explosion of urbanization, the built environment has become the only surroundings for billions of people. Yet, according to Koskela (2008) an interdisciplinary discussion on theory of the built environment was opened for the first time only recently.

Needs to better explain the built environment also theoretically grow first and foremost from demands to change the technologies how it is created, operated and used, and this shift requires human and social interventions. The life-cycles of artifacts of the built environment are long compared to machines or consumer goods: most of the buildings completed in these days will last over fifty years. New cities and suburbs can be built relatively rapidly but yet the projects would last years. Before any construction, a series of decisions at various levels of administration and business has to be made. Complexity of technologies, structures of decision-making, networks of supply networks and time-scale mean that efforts to re-shape the built environment need knowledge from various fields but also interdisciplinary methods for a holistic overview.

The built environment is an essential part of foresights on future societies. Its position is on the opposite side to the natural environment as presented in figure 1.

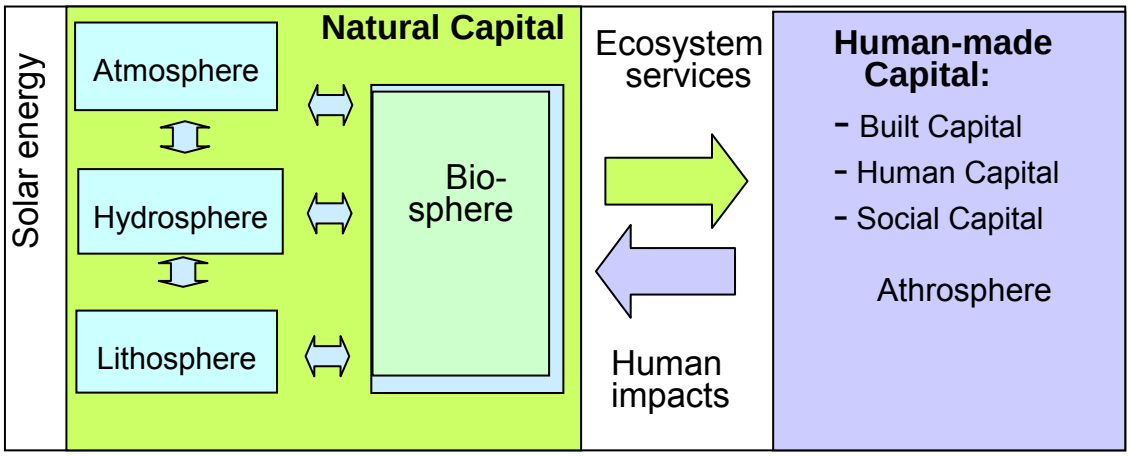


Figure 1. Model for interaction between the built environment and the natural environment (Boumans et al 2002).

The built environment has traditionally been a subject of studies concerning urban development and urban sociology. The interaction between the human behaviour and the built environment has also been studied from the points of views of well-being and issues of technology-human interaction. The fragmented vision is however described by Hillier (2002) who argues that "beyond common sense and accumulated experience, little is known about how patterns of living and working can be affected, for good or ill, by the physical and spatial forms imposed on them". Often the concept of the built environment is also expanded to include various social and economic functions and transport, especially in relation to global forecasts.

Theories of architecture and social sciences deal with the development and interaction of the built environment and societies, economies and individual, and they might give even more plausible descriptions about mechanisms of changes, transitions and innovations. And after all, the complexity of the built environment needs integrated and holistic approaches.

2.2 Back-casting on technologies of the built environment

The ways new technologies have entered and contributed to the built environment may be studied from the points of views of history of technologies, of architecture and more often recently that of the innovation science. In engineering, the history of tools and technology is a natural way to study and explain drivers, factors and phenomena. This is also in accordance with a major line when the current megatrends and their consequences are analyzed. Three main phases are in common used as a starting point to study influences of a technology shift (table1). Their effects to the built environment is briefly described in Table 2.

Table 1. Three Technological Revolutions (Cornish 2004).

View	Agricultural	Industrial	Cybernetic
Origin	Near East 11 000 years ago	Britain, 1750	United states, 1944
Catalytic Technology	Grain cultivation (wheat)	Steam engine	Computer
Benefits	More food per unit of land; grain storable and tradable	Inexpensive, dependable source of power	Fast, cheap decision-making for problems soluble by algorithms
Uses	Feeding people, safeguarding food supply; trading goods (functions like money)	Mechanized pumps, machine powered vehicles, power machinery in factories	Mathematical calculations, processed records, word processing, database management, telephone exchanges, etc.
Effects	Population increase, early cities, roads, shipping, accounting, metal-working, wheeled vehicles, writing, scholarships, science	Factory towns, urbanizations, railroads, automobiles, rising living standards, airplanes, surging demand for natural resources –metal ores, coal, petroleum	Faster, cheaper information handling, better managements of communications, tighter inventory controls, better distribution of goods, higher standard of living
Workers displaced	Hunters, gatherers	Farmers, weavers, craftsmen, home workers	Clerks, typists, telephone operators, typesetters, small grocers, middle managers
New jobs	Early: farmers, construction workers, carters, brewers, specialized crafts; Later: scribes, scholars	Miners, factory workers, ironworkers, steamship builders, railroaders, steel workers	Computer operators, programmers, repairers, systems analysts, web-masters, electronic game designers

Table 2. Effects of technological revolutions to the built environment.

View	Agricultural	Industrial	Cybernetic
Materials	Stone, clay, lumber, later glass	Steel, concrete, gypsum, aluminium, plastics, fiber insulations, chemicals, treatments, coatings	Intelligent, functional materials Nano- and biomaterials
Products	Sun-dried bricks, Timber, stone blocks	Prefabricated concrete components, lifts, sandwiches, composites, technical systems	Composites Components Industrialisation, customisation
Design	Experience, experiments	Experiments, national standards	Standards, modeling, simulation
Building technology	Manual Tools, horsepower	Machines, cranes Workmanship Automated lines Integrated control	Structural and technical systems, robotics CAD-CAM, BIM Monitoring and management
Impacts	Local; quarries	Regional; quarries and mines, dams, cities, railways, highways	Global; urbanization, urban sprawl, megacities, networks, highways

2.3 *Findings and trends from back-casting*

The close interaction between the developments of technology, economy, society and the built environment can be recognized easily from the back-casting studies (e.g. Koukkari 2009[a], Koukkari 2009[b] and Koukkari & Braganca 2009). Aspirations and demands concerning conveniences, services, movement and connections have increased simultaneously with rising living standard. The floor area per household and per person has increased, consumption of water and electricity has increased, consumption of fossil fuels has increased.

The spending to the built environment is based upon an increasing consumption of non-renewable resources and it has resulted to increasing amount of waste and emissions. "The built environment" is one of the main guilty ones for the global threats. In addition to cities, urban areas, megacities and infrastructure networks, huge areas of land have been reshaped due to excavations, dams and artificial lakes. The role of the construction sector is often seen as the manager of this development although there is no simple evidence.

The technologies and processes have evolved mainly by adopting innovatively achievements from other sectors. Causes for major changes in construction are rare. Very often there has been a combination of new inventions, new spirit and new opportunities that has created a new mainstream technology (see figure 2).

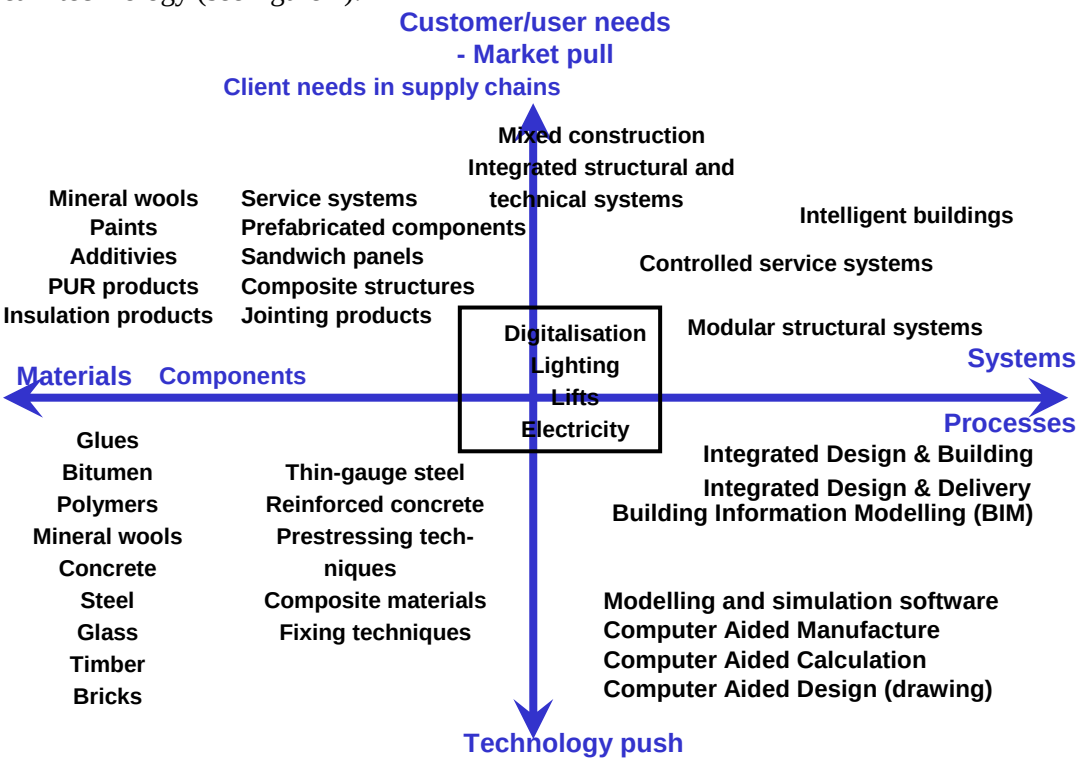


Figure 2. Construction – a broad platform of innovations (Kokkala & Koukkari 2010).

In several past and recent forecasts, accelerating pace of changes of indicators is a basic assumption. Considering changes in history of building and construction technologies, a similar conclusion is appealing: when the major changes of construction technologies are presented in a timescale, their number increases the quicker the closer is our time. In the beginning, construction was based on natural materials and man-power. Gradually, artificial materials and machines have become best practices. Town houses, skyscrapers, malls and offices of the developed world are complicated systems of technical, space and structural systems whose operations are more and more controlled by monitoring and software. The number of materials and single products counts in hundreds and thousands. Putting all the developments in a timescale would lead to a surprise about the merging and uptake capacity of the construction sector

Another perspective to the role of the construction sector is from its positive influences on well-being of people and functioning of economy. In circumstances of the growth of the global economy and the middle class, there is no return to primitive conditions if we speak about a normal life. People in the United States maybe can reduce their average daily consumption of

pure water of 400 litres to some extent, but for sure people in developing countries need more than 40 litres. The similar problem concerns electricity – the consumption in households is almost as big source of CO_2 emissions due to "buildings" as heating and warm water world-wide but consumers in emerging countries will ask for more gadgets and appliances.

The conclusions can only be to search solutions from advanced technologies that produce safer energy and use less energy, and recycling of materials and components. Smart controls and management will be more important in all branches of industries. Utilisation of existing technologies and implementation of state-of-the-art of science is the most likely way to proceed also based on the experiences of the past: development takes place mostly as a continuous series of small steps and modifications.

3 DRIVERS OF SCENARIOS FOR THE BUILT ENVIRONMENT

The built environment is a complex patchwork of buildings, facilities, networks and spaces. In total the built-up area of about 400 000 km^2 takes about 2% of the global land area, but its impacts on the society, economy and nature grow far beyond this share. In Europe about 6% of the land is urbanized, about one fourth is directly affected by urban land use and about 75% of the population lives in cities.

Forecasting development of the built environment is a combination of various methods like back-casting, trend analysis, system dynamic modeling, and scenarios. Forecasting at a longer perspective contains more uncertainties and becomes more illustrative than at short-term.

In the world scenarios, the position of the built environment is crucial as several global grand challenges are met there. The role of the real estate and construction sector is essential in pursuits to balance between circles of nature and resource consumption of societies.

3.1 *Building up scenarios*

Scenarios and scenario analysis have become popular approaches in organizational planning and participatory exercises in pursuit of sustainable development. The methods are used to generate, present, manipulate, and evaluate information about the future (Duinker & Greig 2007). Collectively the methods operate within the domain of three questions associated with

- possible futures — what may happen?
- probable futures — what is most likely to happen?
- preferable futures — what would we prefer to happen?

The World Future Society defines six supertrends that give a way to understand drivers of scenarios, and can also introduce concepts of changing the future as follows (Cornish 2004)

- *Technological Progress* includes all the improvements being made in computers, medicine, transportation, and other technologies as well as all the other useful knowledge that enables humans to achieve their purposes more effectively.
- *Economic growth* is linked to the technological progress because people are eager to use their know-how to produce goods and services, both for their own use and to sell to others. Growth has been tremendous since the Industrial Revolution.
- *Improving Health* is a result of both technological progress and the economic growth. It leads to increasing longevity – which has two important consequences: population growth and a rise in the average age of the population.
- *Increasing mobility* seems to be the principal cause for globalization. People, goods, and information move from place to place faster and in greater quantity than ever before.
- *Environmental decline* continues for the world as a whole because of continuing high population growth and economic development.
- *Increasing deculturation* occurs when people lose their culture or cannot use it because of changed circumstances. In relation to that, the number of languages is estimated to halve from 6000 in next one hundred years. Urbanisation also contributes to deculturation.

By projecting the supertrends forward in time, a new scenario or picture can been created of what the world might be like at some point in the future. The scenarios fall in general in three outcome categories that are disaster, medium case and transformation. Between them might also

be a pessimistic and optimistic scenario. The content may differ depending on the purpose, time-scale, topics and background models. In all, modeling and system dynamics are applied. Hardware is available, and an increasing number of assessing and valuing tools and databanks are on the market thanks to computer capacities.

3.2 *World scenarios*

In the report "Energy 2050", World Scenarios are presented in three classes (see figure 3), in which the transformation scenarios are titled as "Great Transitions" (IEA 2003, based on Gallopin et al 1997). These scenarios examine visionary solutions to the problem of sustainability, through fundamental changes in values and in socioeconomic arrangements. In these scenarios population levels are stabilised at moderate levels and materials flows through the economy are dramatically lowered as a result of lower consumerism and use of environmentally friendly technologies. The *Eco-communalism* scenario represents a regionalist and localistic vision characterised by small-is beautiful and autarkic concepts. The *New Sustainability Paradigm* scenario shares some of these goals but tries to build a more humane and equitable global civilisation rather than retreat into localism.

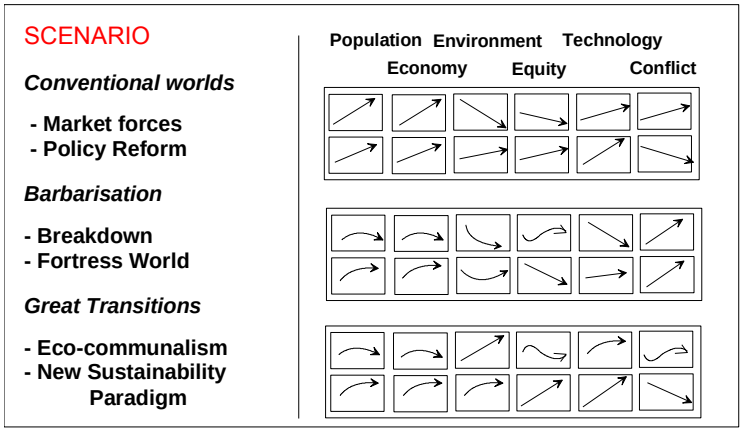


Figure 3. A set of World Scenarios (IEA 2003).

Plenty of forecasts, trend analyses and scenarios are available nowadays at both official governmental websites and websites of international organisation, banks, companies and consultants. The well-known world scenarios are prepared e.g. by the United Nations, Organisation of Economy and Development OECD, International Energy Agency IEA and the World Bank. Many countries open also their scenarios and forecasts for public. All serious world scenarios are summaries of several models and intensive calculations. The scenarios are often introduced to focus to some issues like energy, economy or population but the interaction of several indicators is more or less embedded in models.

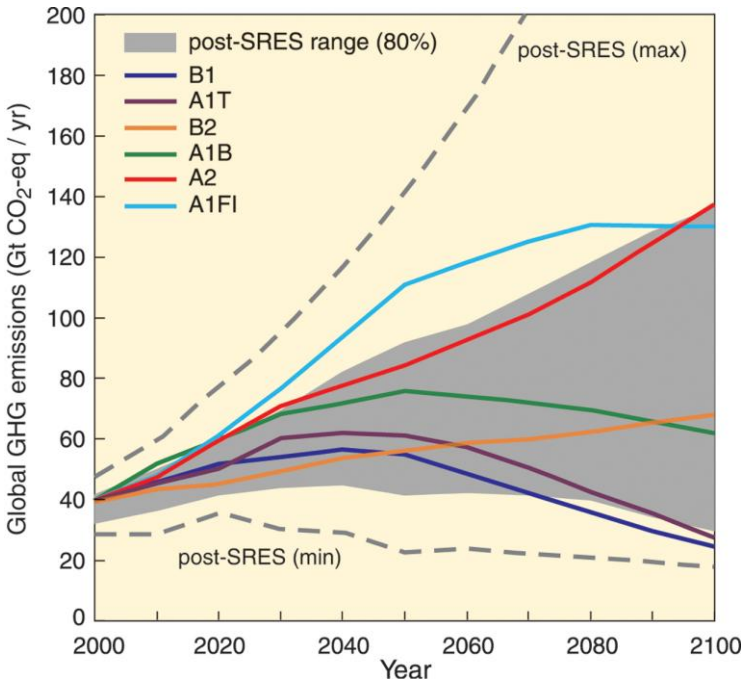
The drivers of the built environment are in common considered from the points of views of needs and aspirations of users, society and economy and of the opportunities of technology development. The demographic changes can be regarded as fundamental for demands of residence, mobility and services. They include increase of the total population on Earth from 6.8 billion up to about 8.0, 9.1 or 10.5 billion by 2050 (UN 2008[a]); increase of the share of urban people of the current 50.1% (UN 2009[b]) and ageing of the societies. The world economy is projected to grow from its current of about 65 billion US dollars as Gross World Product, and projections up to 260 billion are given (EU 2007) ; the number of people in middle class income category grows along the rise of the average income per capita from its current of about 10 000 US dollars.

In building technologies, a diversity of local and traditional technologies will continue to take place but most likely urbanization and needs to improve energy-efficiency will bring the mainstream technologies closer. The centers of globalised post-industrial economy look alike already. The technologies and processes will benefit more and more from the information and communication technologies in manufacture of products, at construction sites and in operation

of buildings and infrastructure. Modelling and simulation will be used at all levels and by all stake-holders in planning and design which facilitate a better implementation of life-cycle thinking in decision-making.

3.3 *Climate Change scenarios*

The Intergovernmental Panel on Climate Change (IPPC 2009) has produced a well-known set of world scenarios that gives a reasonable basis for scenarios on the built environment. The top-down scenarios consider economic growth, global population, introduction speed of energy-related new technologies, material-intensity, regional differences in per capita income and governance. The scenarios were developed to project greenhouse gas emissions in the coming decades but later on they have been used to assess regional and local weather phenomena, actions needed to turn the trends, and impacts to the built environment, land use and water resources. In following figure 4 the scenarios are summarized.



A-scenarios: consumer societies

B-scenarios: toward sustainable development

A1 (three alternatives**):** Very *rapid economic growth*, global population that peaks in mid-century and declines thereafter, and the rapid introduction of more efficient technologies;

A2. Very *heterogeneous world*; the underlying theme is self-reliance and preservation of local identities. Continuously increasing population. Economic development is primarily regionally oriented.

B1. Convergent world with the declining global population after midcentury; rapid change in economic structures toward ***a service and information economy***, with introduction of clean and resource efficient technologies.

B2. an emphasis is on ***local solutions*** to economic, social and environmental sustainability. Global population increases continuously, economic development is at intermediate levels, and technological change is less rapid and more diverse**.**

Figure 4. World scenarios of the Intergovernmental Panel on Climate Change IPCC.

4 SCENARIOS FOR OUR COMMON BUILT ENVIRONMENT

4.1 *Four basic scenarios*

Based on studies on the trends and drivers of changes in the built environment, the following compilation of scenarios is proposed for the built environment (figure 6). In the literature survey concerning the world scenarios and concepts of the built environment, only two scenarios were found with similar objectives. They have been presented by Luebkemann (2008) and a project in the UK (2008). The summary in this paper has different axes and it also tries to integrate more dimensions from the points of views of the built environment.

The axes are chosen to reflect two principal contexts of the built environment: on the other hand relationships with humankind and on the other hand those with the natural environment. They resemble the ways the IPCC scenarios are structured and their background assumptions in which A-scenarios represent consumer societies and B-scenarios development toward the sustainable development (figure 5).

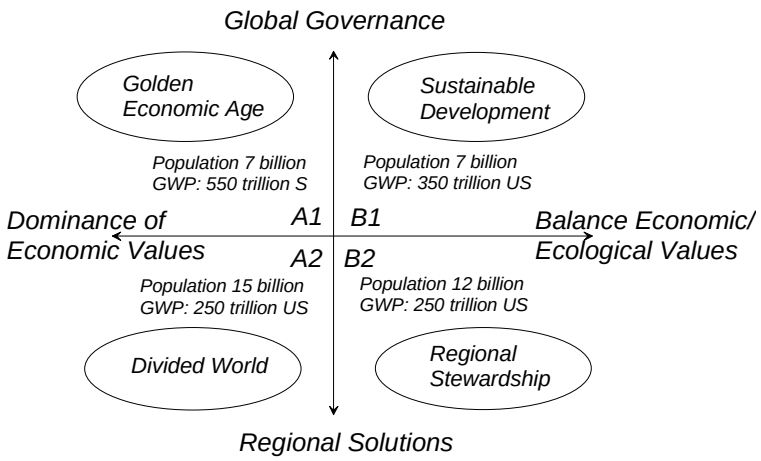


Figure 5. The Climate Change scenarios in a four-field presentation (IPCC 2009, Masui et al. 2001)

World population is projected to grow in all these scenarios in accordance with the UN projections (UN 2009[a], UN 2009[b]). The ways the development of the built environment rises to this grand challenge depend on material, energy and economic resources as well as technological and human capacities. In principle, the growth of the middle class will improve the quality of life, well-being and educational level but it also bears a risk of over-consumption of natural resources.

The World economy is here a background factor that is expected to allow investments to the built environment in the positive scenarios. In a similar way, the sustainable built environment and convenient built environment are foreseen to benefit from an array of intelligent technologies.

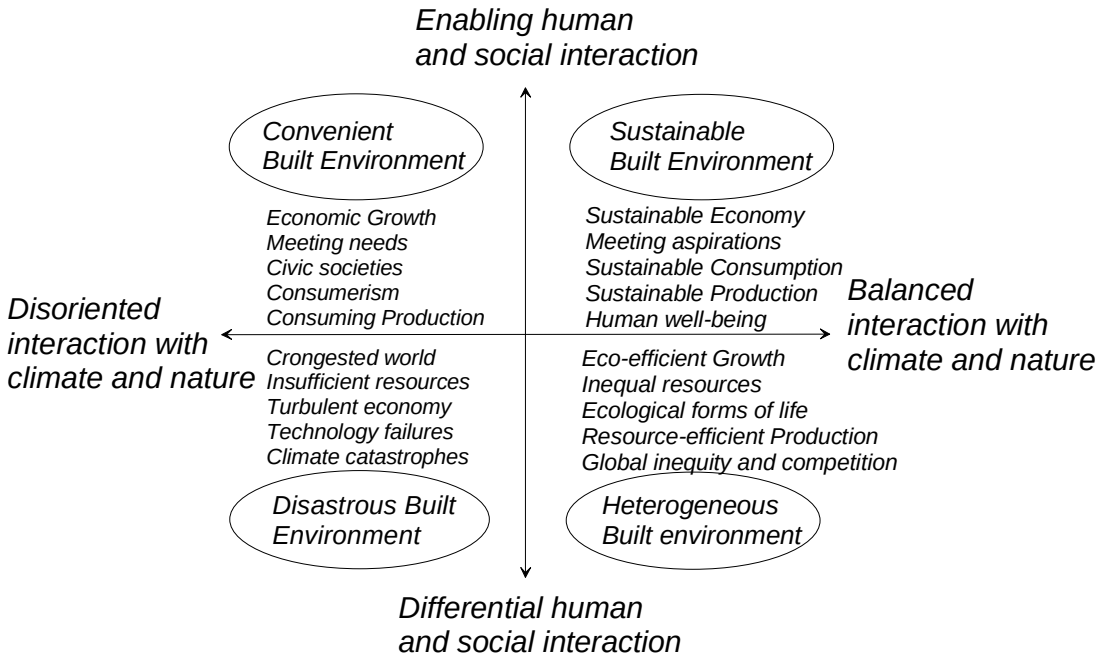


Figure 6. Summary of scenarios for our common built environment (Koukkari 2010).

4.2 *Optimistic transition scenario: sustainability*

The World Business Council for Sustainable Development (WBCSD 2010) has described the pathway to the sustainable development with two phases:

- "Turbulent Teens", from 2010 to 2020, is a period of energy and dynamism for the global vision of sustainability. It is a formative decade for the ideas and relationships that will take place in the 30 years to follow: and
- "Transformation Time", from 2020 to 2050, is a period when traits formed during the first decade mature into more consistent knowledge, behavior and solutions.

In 1999, International Council for Research and Innovation in Building and Construction CIB adopted the goal of sustainable construction as "…creating and operating a healthy built environment based on resource efficiency and ecological principles ". Since that time, efforts to develop methods, tools, technologies and processes to enable a transition in the built environment have been remarkable.

The sustainable development is taking place in the built environment when all its dimensions are taken into account – environmental, economic, social and cultural factors (figure 6).

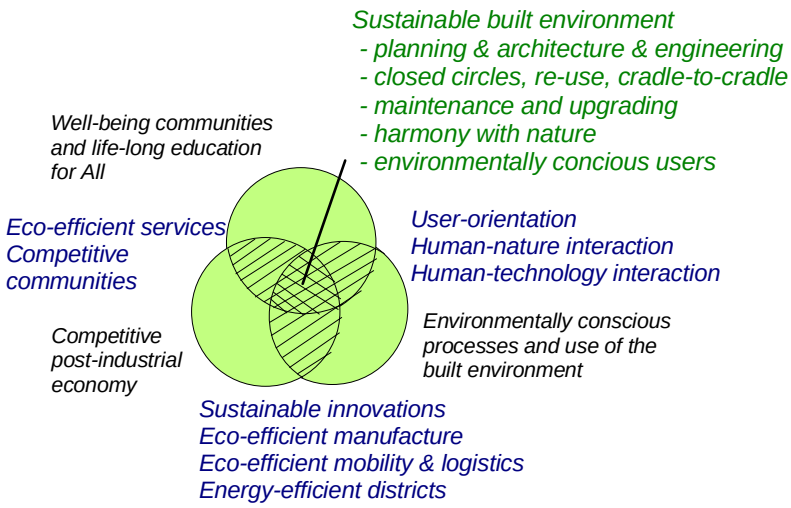


Figure 6. The sustainable built environment results from several dimensions (Koukkari 2010).

5 CONCLUSIONS

In the world scenarios, the position of the built environment is crucial as several global grand challenges are met there. The environmental threats increasingly affect ways the built environment responds to the needs and aspirations of people, society and economy. Awareness of Climate Change and other environmental consequences is rising all over, and steps to improve resource-efficiency and limit impacts are taken everywhere. However, the pace of actions and uptake of novel technologies is crucial for the prospects. The role of the real estate and construction sector is essential in pursuits to balance between circles of nature and resource flows of societies.

The development and concept of the built environment can be studied from various perspectives and applying various theories. In engineering, the history of tools and technology is a natural way to study and explain drivers, factors and phenomena. This is also in accordance with a major line when the current megatrends and their consequences are analyzed. One should however keep in mind that several other domains, like economy, cultures, religions, politics, regulations, affect the development of the built environment as well. Theories of architecture and social sciences deal with the development and interaction of the built environment and societies, economies and individual, and they might give even more plausible descriptions about mechanisms of changes, transitions and innovations. And after all, the complexity of the built environment needs integrated and holistic approaches.

A trial has been made in order to integrate the various world scenarios into a picture that depicts scenarios for the built environment. This kind of approach opens also a new opportunity to indentify and study the dimensions of the sustainable development of the built environment.

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