Sustainability of Constructions

Integrated Approach to Lifetime Structural Engineering

Proceedings of Workshop
Lisbon 13, 14, 15 September 2007
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COST Action C25

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Editors:
L. Bragança, H. Koukkari, R. Blok, H. Gervásio, M. Veljkovic,
Z. Plewako, R. Landolfo, V. Ungureanu, L.S. Silva

COST is supported by the EU RTD Framework Programme and ESF provides the COST Office through an EC contract
The Workshop “Sustainability of Constructions” is the outcome of the first year of activity of COST Action C25 “Sustainability of Constructions - Integrated Approach to Life-time Structural Engineering”.

The COST Action C25 was approved on 29-30 March 2006, during the 164th Meeting of the Committee of Senior Officials for Scientific and Technical Research (COST), and the Kick-off Meeting was held on the 3rd of October 2006 in Brussels. Since its approval, 26 countries (Austria, Belgium, Croatia, Czech Republic, Cyprus, Denmark, Finland, fyr Macedonia, Germany, Greece, Hungary, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovenia, Sweden, Turkey and United Kingdom) and one EC Joint Research Centre joined this project, becoming the Action C25 one of the more participated Actions in the Domain of Transport and Urban Development (TUD).

The main objective of the Action is to promote science-based developments in sustainable construction in Europe through the collection and collaborative analysis of scientific results concerning life-time structural engineering and especially integration of environmental assessment methods and tools of structural engineering.

The Action involves a wide range of experts from a variety of disciplines related to the construction sector. 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. In accordance with the Memorandum of Understanding three Working Groups were created and cover the three main areas of the Action:

In accordance with the Memorandum of Understanding the coordination of C25 activity is being carried out by the MC and three WGs that cover the three main areas of the Action. The coordinators of MC and of WGs are also the organizers of this 1st Workshop on “Sustainability of Constructions”:

Management Committee
Chair – Luís Bragança (University of Minho, Portugal)
Vice-chair – Heli Koukkari (VTT Technical Research Centre of Finland, Finland)

WG1 – Criteria for Sustainable Constructions
Chair – Rijk Blok (University of Technology Eindhoven, Netherlands)
Vice-Chair – Helena Gervásio (GIPAC, Lda., Portugal)

WG2 – Eco-efficiency
Chair – Milan Veljkovic (Luleå University of Technology, Sweden)
Vice-Chair – Zbigniew Plewako (Rzeszów University of Technology, Poland)

WG3 – Life-time structural engineering
Chair – Raffaele Landolfo (University of Naples “Federico II”, Italy)
Vice-Chair – Viorel Ungureanu (Politehnica University of Timisoara, Romania)

Website and Databases
Chair – Luís Simões da Silva (University of Coimbra, Portugal)

The Workshop main topics cover a wide range of up-to-date issues and the contributions received from the delegates reflect critical research and the best available practices in the Sustainable Construction field. The issues presented include:
Criteria for Sustainable Constructions
- Global methodologies
- Assessment methods
- Global models
- Databases

Eco-efficiency
- Eco-efficient use of natural resources in construction
- Eco-efficient materials
- Eco-efficient products
- Eco-efficient processes

Life-time structural engineering
- Design for durability
- Life-cycle performance
- Maintenance and deconstruction

The Organizing Committee wants to warmly thank all the authors who have contributed with papers for publication in the proceedings. Their efforts reflect their commitment and dedication to Science and Sustainable Construction.

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

The organisers hope that this initiative will promote further the sustainability of construction industry and the built environment, consequently, contributing to further sustainable development of the participating countries.

The Organizing Committee and Proceedings Editors

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What is COST

**COST** - the acronym for European COoperation in the field of Scientific and Technical Research - is the oldest and widest European intergovernmental network for cooperation in research. Established by the Ministerial Conference in November 1971, COST is presently used by the scientific communities of 35 European countries to cooperate in common research projects supported by national funds.

The funds provided by COST - less than 1% of the total value of the projects - support the COST cooperation networks, COST Actions, through which, with only around € 20 million per year, more than 30,000 European scientists are involved in research having a total value which exceeds € 2 billion per year. This is the financial worth of the European added value which COST achieves.

A bottom up approach (the initiative of launching a COST Action comes from the European scientists themselves), a la carte participation (only countries interested in the Action participate), equality of access (participation is open also to the scientific communities of countries not belonging to the European Union) and flexible structure (easy implementation and light management of the research initiatives) are the main characteristics of COST.

As precursor of advanced multidisciplinary research COST has a very important role for the realisation of the European Research Area (ERA) anticipating and complementing the activities of the Framework Programmes, constituting a ridge towards the scientific communities of emerging countries, increasing the mobility of researchers across Europe and fostering the establishment of Networks of Excellence in many key scientific domains such as: Biomedicine and Molecular Biosciences; Food and Agriculture; Forests, their Products and Services; Materials, Physics and Nanosciences; Chemistry and Molecular Sciences and Technologies; Earth System Science and Environmental Management; Information and Communication Technologies; Transport and Urban Development; Individuals, Society, Culture and Health. It covers basic and more applied research and also addresses issues of pre-normative nature or of societal importance.
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Chapter 0

SUSTAINABILITY AND INTEGRATED LIFE-CYCLE DESIGN

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The building sector is one of the most important sectors for social and economic activities, being responsible to create, modify and improve the living environment of humanity. On the other hand, construction and buildings have considerable environmental impacts, consuming a significant proportion of limited resources of the planet including energy, raw materials, water and land. Therefore, the sustainability of the built environment, the construction industry and the related activities is a pressing issue facing all stakeholders.

The ecological rucksack of the construction sector is significant, and calls for rapid changes in technologies and processes. The strategic research activities and education of future professionals are of utmost importance for the progress. In this context, COST Action C25 is very timely, and its Memorandum of Understanding shows several topics of science- and research-based response to the global challenge. The Action covers subjects that represent both traditional engineering sciences and modern decision-making theories, but it “concentrates on methodologies that incorporate holistic understanding on the integrated processes and systems that result to the sustainability, quality and performance properties of buildings and built environment”.

Life-cycle has become a new concept known by everybody but not applied so well as a principle to promote sustainability. According to the Standard ISO 14040, life-cycle assessment is defined as a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. The LCA is a methodology for analysing the environmental interactions of a technological system with the environment. It is in general considered part of “sustainability”, although usually sustainability integrates social, economic and environmental objectives.

A variety of construction sector-specific methods and tools have been developed following the framework of the ISO standard. The long lifespan of buildings accentuates the whole lifecycle that includes effects of maintenance and demolishing, too. However, the LCA is most often carried out at the level of materials and components. Generic methods for the building level been developed, but they are still very much changing. The main goal of their developments, at the moment, is to create and implement a systematic methodology to achieve the most appropriate balance between the different sustainability dimensions, which is at the same time practical, transparent and flexible enough to be easily adapted to the different kind of buildings.

In two introductory papers, the state-of-the-art of the LCA methods in the construction sector is presented. In “Assessment of building sustainability”, perspectives of the sustainability assessment of a whole building are presented based on feasibility study on performance analysis and development of extended LCA. The methods to combine functionality (performance) and data-based analyses are introduced. In the paper “LCA databases (EPD vs Generic data)”, the concern is in suitability, reliability, availability and usability of LCA methods, tools and related databases.

The environmental life-cycle assessment is based on engineering data, but as such it is a systematic valuing process. Incorporation this new approach to everyday design and building...
practices needs more integration and communication. The rapid development of information and communication technologies is a basis for integration of modelling and simulation tools to LCA tools, and this evolution brings more opportunities to analyse building projects at different phases. Further, the achievements of the Building Information Modelling open new ways to use the LCA information.

The paper “An approach for an Integrated Design Process focussed on Sustainable Buildings” highlights the expectations and experiences about the LCA from the viewpoints of a world-wide design office. According to the authors, an interdisciplinary planning process is indispensable in order to develop and implement truly sustainable building concepts, and all designers involved in the project should participate at the earliest project phase possible. The paper proposes an approach towards sustainability as the governing factor in the compilation of all specifications and contract documents. The needs of guidelines to ensure a coherent and sustainable design process in all phases of a project are addressed.

It is generally accepted that improvement of sustainability starts with the following actions:

- maximise energy efficiency
- minimise waste in all phases
- maximise water efficiency
- optimise indoor air quality
- minimise embodied energy
- maximise the use of recycled, environmentally responsible materials.

The paper “Energy in the sustainable European construction sector” presents needs and methods to reduce the effects of one important flow in the LCA. The implementation of the Energy-Performance of Buildings Directive EPBD requires changes in design and building methods.

There are important issues related to the life-cycle concept that are a continuation of the engineering traditions in the construction sector: For the sake of safety, usability and comfort, the concepts of durability and serviceability are design criteria. The science- and research-based understanding of the phenomena that affect the duration of the life-cycle is the basis of service-life design methodology. The life-cycle – and phases of the life-cycle – is fundamental for assessments of environmental, economic, social or cultural impacts of components, buildings and other works.

For all kinds of works, durability is a major requirement that is included in all six essential requirements of the Construction Products Directive of the European Community (CPD). In the Guidance Paper related to the Directive, durability has been defined as “the property of lasting for a given or long time without breaking or getting weaker.” Further, durability aspects are linked to the “working life” that means the “period of time during which the performance of the works will be maintained at a level compatible with the fulfillment of the essential requirements.

The widely used ISO Standard 15686 defines durability as the “capability of a building or its parts to perform its required function over a specified period of time under the influence of the agents anticipated in service”. The factors that affect the duration of a life-cycle are the basis for development of service-life design methods.

The scope of the Action include, but is not restricted to, practical building technologies applications to promote sustainability, mathematical modelling, computer and experimental methods in the areas of sustainability assessment and evaluation, construction and design for durability, decision making, deterioration modelling and aging, failure analysis, field testing, financial planning, inspection and diagnostics, life-cycle analysis and prediction, loads, maintenance strategies, management systems, non-destructive testing, optimization of maintenance and management, specifications and codes, time-dependent performance, rehabilitation, repair, replacement, reliability and risk management, service life prediction, strengthening and whole life costing.

The papers prepared in the three Working Groups of the Action C25 give an overview of the research activities in relation to the wide field of the sustainable construction.
Assessment of Building Sustainability

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ABSTRACT: The concept of sustainable building is usually related to environmental characteristics although the social, economic and cultural indicators of the life-cycle impacts are of substantial importance. Any building level assessment method is complex and involves contradictory aspects; emphasizing the qualitative criteria only increases confusion. The R&D and standardization is thus concentrated to transparency and usability of the environmental methods. Other directions of research are aiming at performance-based design and methods to take regional and cultural aspects into account. In this paper, perspectives of the sustainability assessment of a whole building are presented based on the state-of-the art, feasibility study on performance analysis and development of extended LCA for buildings. Based on the case studies of building sustainability assessment using various tools, the environmental indicators were shown to be often of lesser importance than the other, soft ones. At the end, will be presented and discussed the steps to develop a building sustainability assessment method for residential buildings.

1 INTRODUCTION

A building project can be regarded as sustainable only when all the various dimensions of sustainability – environmental, economic, social and cultural ones - are dealt with. The various sustainability issues are interwoven, and the interaction of a building and its surroundings is also important. The environmental issues are in common those which cope with reducing use of non-renewable materials and water, and reducing emissions, waste and pollutants. The following goals for an overall assessment can be found in several agendas: optimization of site potential, preservation of regional and cultural identity, minimization of energy consumption, protection and conservation of water resources, use of environmentally friendly materials and products, healthy and convenient indoor climate and optimized operational and maintenance practices.

The purpose of sustainability assessments is to report information for decision-making during different phases of a new-building project or existing building. This is done in the form of quantified measures of various indicators that tell about the expected impacts during the life-cycle or phases of the life-cycle. The scores or profiles are derived from a process in which the relevant issues are identified, analyzed, categorized and valued. Development of a life-cycle method or tool or use of them should follow the standard series ISO 14040 – 14043.

A variety of sustainability assessment tools is available on the construction market, and they are widely used in environmental product declarations. Several comparative studies on contextual and methodological aspects of tools has also been made, like e.g. by Forsberg and Malmborg (2004).

The majority of the tools is developed based on a bottom up approach, i.e. a combination of building materials and components sums up to a building, and this even though they are designed to consider the whole building including energy demand, etc (Erlandsson & Borg 2003). Allacker and De Troyer (2006) comment that it is not correct to equate a building to a sum of its constituent components due to the influence of the (architectural) design on overall impacts.
Kohler et al (1997) emphasize that only the building level provides a coherent functional unit that leads to the need of modular data. This is because
- buildings have the longest life time of industrially produced goods
- current costs and energy use are in general much larger than the initial investment
- there are complex relations between initial and current costs
- one-of-a-kind character of buildings makes comparisons difficult
- design process is not linear and has many feedback, the same data are used several times with different accuracy.

Tools to support decision-making in accordance with principles of performance based design have also been developed, mainly in research communities. The assessment tools, either environmental or performance-based, are under constant evolution in order to overcome their various limitations. The main goal, at the moment, is to develop and implement a systematic methodology that supports design process of a building. The methodology should result to the most appropriate balance between the different sustainability dimensions, and be practical, transparent and flexible at the same time. It should be easily adaptable to the different kinds of buildings and to the constant technology evolution.

In this paper, approaches to incorporate the three sustainability dimensions within a building project are presented and discussed based on a feasibility study and state-of-the-art. In a more thorough way, the sustainability is dealt with the concepts of eco-efficiency and cost-efficiency that result from a holistic building performance analysis. Then, the potential to introduce the building’s economic and social impacts (“soft indicators”) in the originally environmental LCA methodology is studied, and the new developments and perspectives for the Building Sustainability Assessment (BSA) using global indicators is presented.

2 GENERIC METHODS OF BUILDING SUSTAINABILITY

2.1 General requirements of methods

According to CIB (1999), the relevant issue areas of a sustainable building should include all factors that may affect the natural environment or human health. For a contractor or facility manager, it is important to differentiate between the criteria and tools used to assess technology at the generic or global level, and the approach used at the site specific application or local level (Environmentally Sound Technologies 2003).

Hermann et al (1997) have prepared a list of requirements for generic tools of building sustainability assessment that have been agreed with by many researchers:
- adaptable to building life cycle phases, different actors and different decision levels
- adaptable to different types of impacts and effects
- suit to the usual professional working environment
- scaleable – allowing a zoom.

According to Herman et al (1997), “the evaluation of the design and of the effective performance of a building is always a very complex issue. There is no simple and transparent performance optimum. Multi-criteria methods are of not much help in the real design process. The best evaluation model is probably constraint satisfaction. The target performances of buildings are considered as constraints forming an n-dimensional performance space. The design alternatives must be inside this space and the optimisation depends on aesthetic, cultural, social, psychological qualities.”

2.2 Managing and assessing building sustainability

Building Sustainability Assessment (BSA) methods can be oriented to different scale analysis: building material, building product, construction element, independent zone, building and neighbourhood. Analysing the scope of the most important sustainability support and assessment systems and tools it is possible to distinguish three types:
- Systems to manage building performance (Performance Based Design);
- Life-cycle assessment (LCA) systems;
- Sustainable building rating and certification systems.
i) Managing building performance

Performance Based Building is an approach to building-related processes, products and services with a focus on the required outcomes (the 'end'). This approach would allow for any design solution (the 'means') which can be shown to meet design objectives (Koukkari, 2005).

The comprehensive implementation of the performance approach is dependent on further advancement in the following three key areas: the description of appropriate building performance requirements; methods for delivering the required performance; methods for verifying that the required performance has been achieved.

The main purpose for a generic hierarchical model is to provide a common platform to define the desired qualities of a building and to develop a common language for different disciplines as well as to serve as a basis for development of design and technical solutions. The choice of the objectives in the hierarchical presentation shows also to some extent the values of the developer.

Based on the hierarchy of performance objectives and their targeted qualities, alternate design and technical solutions can be developed. The capability of different solutions to fulfil the performance criteria can be studied with verification methods. Figure 1 represents a generic model of building’s performance analysis. Similar hierarchies are introduced by several organisations.

Figure 1. Example of a generic model of building’s performance analysis (VTT ProP®).

This kind of method is providing some important benefits to both end users and to the other participants in the building process, since it promotes substantial improvements in the overall performance of the building, encourages the use of construction solutions that better fit the use of the building and promotes a better understanding and communication of client and users requirements.

Tools to support decision-making in accordance with principles of performance based design have been developed mainly in research communities. An example is the EcoProp software (Finland).

ii) Integrated Life-Cycle-Analysis of buildings

The complete building sustainability assessment (BSA) comprise the ways in which built structures and facilities are procured and erected, used and operated, maintained and repaired, modernised and rehabilitated, and finally dismantled and demolished or reused and recycled. The life-cycle of a building project starts before any physical construction activities and ends after its usable life. Figure 2 shows an integrated LCA of the building stages.

In the first LCA methods the concept of sustainable construction was confused with the concept “low environmental impact construction”; therefore they failed to enter the mainstream sustainable development discourse. More recent LCA methods include the economic performance analysis in the evaluation. Demand for sustainable construction is influenced by buyer perception of the first costs versus life cycle costs of sustainable alternatives (Kibert, 2003).

The more rigorous the LCA methods are the more data intensive they are, and therefore the assessment process can involve enormous expenses of collecting data and keeping it updated, particularly in a period of considerable changes in materials manufacturing processes. Some data needed for the LCA is expensive and difficult to obtain, and is most often kept confidential by those manufactures that do undertake the studies. According to Pushkar, Becker and Katz (2005), the databases do not include all the needed information for many of the relevant building products and components, nor the construction process itself. Therefore they conclude that
LCA tools that editing of existing variables and adding new ones according to local conditions, is essential.

The goal of some BSA methods is to simplify the LCA for practical use. The simplified LCA methods that currently exist aren’t comprehensive or consistently LCA-based but they play an important role in turning the buildings more sustainable. More accurate BSA tools will integrate environmental assessment, life cycle costs and methods needed to verify if the required performance has been achieved. LCA-based methods are used to compare solutions to help decide which solution corresponds to the best compromise among the different sustainability dimensions.

2.3 Sustainable building rating and certification

The rating and certification systems and tools are intended to foster more sustainable building design, construction, operation, maintenance and disassembly/deconstruction by promoting and making possible a better integration of environment, societal, functional and cost concerns with other traditional decision criteria.

These systems and tools can be used both to support the sustainable design, since they transform the sustainable goal into specific performance objectives and to evaluate the overall performance. There are different perspectives in different sustainable building rating and certification, but they have certain points in common. In general, these systems and tools, deal in one way or another with the same categories of building design and life cycle performance: site, water, energy, materials and indoor environment.

Near all of the sustainable building rating and certification methods are based in local regulations or standards and in local conventional building solutions. The weigh of each parameter and indicator in the evaluation is predefined according to local socio-cultural, environmental and economic reality. Therefore the major part of them can only have reflexes at local or regional scales. However, there are some few examples of global scale methods. This kind of methods are above all used at the academic level since the requisite reference cases have to be constructed and separately assessed for each building type which is a time consuming and expensive process.

There are three major building rating and certification systems that provide the basis for the other approaches used throughout the world: Building Research Establishment Environmental Assessment Method (BREEAM), developed in U.K.; Sustainable Building Challenge Frame-
DEVELOPMENT OF BUILDING SUSTAINABILITY ASSESSMENT

3.1 Scope of the work

The Portuguese building technologies and the indoor environment quality standards are quite different from most European countries. The first situation is mainly related to the fact that Portugal was not involved in the II World while the second is related to the mild climate. This reality normally hinders the use of foreign decision support and sustainability assessment methodologies without prior adaptation of the list of parameters, weights and almost all benchmarks. Another important reason that is clogging the real implementation of the sustainable assessment is the huge amount of parameters that project teams have to deal with: many of the methodologies presented in the sections above embrace hundreds of parameters, most of them not standard in Portugal and difficult to deal with for many project teams.

This study intends to be the basis for the future development of an advanced residential building sustainability rating tool, especially to be suitable in Portuguese traditions, climate, society and national standards. The research aims to cope with the mentioned problems and to real implement building sustainability assessment in Portugal. The name of the methodology that is under development is Methodology for the Relative Sustainability Assessment of Residential Buildings (MARS-ER from the Portuguese acronym).

In this section, steps to establish the methodology are presented. The indicators inside each sustainable dimension and their associated parameters will be presented. Additional it will be discussed how to calculate the weights, based in the local environmental, socio-economic and legal reality and in the type of building that is going to be evaluated.

First of all, system boundaries are presented. Then, the approach can be divided in four major stages: selection of indicators and parameters, quantification of parameters, normalization and aggregation of parameters and representation and the global assessment of a project.

3.2 System boundaries

At a first stage, the methodology is being developed to assess residential buildings. Most of the Portuguese construction market is related with the residential sector and therefore the development of a methodology to support and rate this sector’s sustainability is a priority.

The object of assessment is the building, including its foundations and external works within the area of the building site. The impacts of the building in the surroundings and in urban environment won’t be assessed. Some authors concluded that restricted scales of study (corresponding for a single building for example) are too limited to take into account sustainable development objectives correctly (Bussemey-Buhe, 1997). Although, sustainable urban planning is normally limited to municipalities and regional authorities, therefore, it is more rational and straightforward to limit the physical system boundary to the building itself (or part of it) together with the site. This way, the methodology excludes construction works outside of the site location and construction of the different networks for communication, energy and transportation outside of the site location.

The temporal methodology’s boundary should represent the whole life cycle stages of the building. In a new building it will consider all life-cycle stages, from construction to final disposal and in existing buildings the temporal boundary will start from the moment of the intervention to the final disposal. Besides the time boundary two other important aspects to define are the hours of normal occupation and use and the occupation density.

3.3 Selection of indicators and parameters

After defining the methodology’s time and physical boundaries the next step is to choose the indicators and related parameters within the three sustainable development dimensions that are going to be used to assess the objectives of a project. According to Kurtz et al (2001) a parameters is a sign or a signal that relay a complex message, from potentially numerous sources, in a
simple and useful manner. Therefore the main three objectives of the parameters are: simplification, quantification and communication (Geissler, 2001).

Categories and related parameters are the basis of the methodology, since objectives and results will be conditioned by them.

Figure 3 resumes the parameters that are considered in the methodology under development. Other parameters could be included in further phases of development.

### Assessment Objectives

#### Indicators and Parameters to Assess

<table>
<thead>
<tr>
<th>Environmental Performance</th>
<th>Societal Performance</th>
<th>Economic Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Climate change:</td>
<td>• Hydrothermal comfort:</td>
<td>• Life-cycle costs:</td>
</tr>
<tr>
<td>Global warming potential.</td>
<td>Relative humidity;</td>
<td>Costs before use of the building;</td>
</tr>
<tr>
<td>• Emissions to air, water and soil:</td>
<td>Winter thermal performance;</td>
<td>Maintenance costs;</td>
</tr>
<tr>
<td>Destruct. of the stratospheric ozone</td>
<td>Summer thermal performance;</td>
<td>Operation costs;</td>
</tr>
<tr>
<td>layer;</td>
<td>Air suspension solid particles;</td>
<td>Costs after building use;</td>
</tr>
<tr>
<td>Acidification potential;</td>
<td>Carbon monoxide;</td>
<td>Residual value.</td>
</tr>
<tr>
<td>Eutrophication potential;</td>
<td>Carbon dioxide;</td>
<td></td>
</tr>
<tr>
<td>Formation of ground-level ozone;</td>
<td>Ozone;</td>
<td></td>
</tr>
<tr>
<td>Inert waste to disposal</td>
<td>Formaldehyde;</td>
<td></td>
</tr>
<tr>
<td>Hazardous waste to disposal</td>
<td>Organic volatile compounds.</td>
<td></td>
</tr>
<tr>
<td>• Water efficiency:</td>
<td>• Acoustic comfort:</td>
<td></td>
</tr>
<tr>
<td>Potable water use;</td>
<td>Airborne sound insulation;</td>
<td></td>
</tr>
<tr>
<td>Rain water use.</td>
<td>Impact sound insulation;</td>
<td></td>
</tr>
<tr>
<td>• Resources depletion:</td>
<td>Reverberation time.</td>
<td></td>
</tr>
<tr>
<td>Land use;</td>
<td>• Visual comfort:</td>
<td></td>
</tr>
<tr>
<td>Materials resource depletion;</td>
<td>Natural lighting use;</td>
<td></td>
</tr>
<tr>
<td>Fossil fuel depletion potential.</td>
<td>Illuminances.</td>
<td></td>
</tr>
</tbody>
</table>

#### Integrated Building Performance Analysis

#### Representation and Global Index

Figure 3. Indicators and related parameters considered in the MARS-ER tool.

In the evaluation of the environmental performance it is necessary to analyse the potential effects related not only with the building materials or products but also with the operation of the building. For example, the assessment of fossil fuel depletion for a building’s life cycle is based in its materials or products embodied energy (energy invested in extraction, transport, manufacture and installation), plus the operational energy needed to run the building over its lifetime.

The definition of the environmental indicators and parameters is based in the work that is being carried out in CEN/TC 350 WG1. The methodology uses the same indicators and parameters that the experts found relevant in the building environmental performance assessment.

In societal performance assessment, the methodology only considers the parameters related to the health and comfort performance of buildings during their use and operation. The methodology doesn’t considers parameters that could raise some kind of complexity and subjectivity in the assessment, in order to facilitate its use and understanding by all Portuguese construction market’s actors. The list of societal parameters presented in Figure 1 reflects the functional requirements of a residential building, according to national construction codes.

The economic performance parameters were defined in order to include all costs related to building’s life-cycle, from cradle to grave. The economical performance analysis is not complete unless the residual value is evaluated. The residual value of a system (or component) is its remaining value at the end of the study period, or at the time it is replaced during the study period.
3.4 Quantification of parameters

After selecting the parameters it is necessary to proceed with their quantification. Quantification is essential to compare different solutions, aggregate parameters and to accurately assess the solution. The quantification method should be anticipated. There are several quantification methods: previous studies results, simulation tools, expert’s opinions, databases processing, etc. (Cherqui, 2004).

At the level of the quantification of the environmental parameters, there are some aspects to overcome, mainly in which regards to the availability of fundamental local LCI environmental data for all construction materials and products used in buildings. While there isn’t local LCI it is possible to use the information given in Environmental Products Declarations (EPD’s), and other LCI databases from nearby countries. MARS-RE recommends the use of the Central Europe’s LCI data collected by Berge (Berge 2000). Another way is to use an external life-cycle assessment (LCA) tool to quantify the environmental parameters.

After quantifying the economic parameters listed in Figure 3, the next step is to calculate the sum of the total net present value (NPV) of the different costs. Therefore in the assessment there will be just one economic parameter: life-cycle costs.

3.5 Normalization of parameters and aggregation

The objective of the normalization of parameters 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”. Normalization is done using the Diaz-Balteiro et al. (2004) Equation 1.

\[
\overline{P_i} = \frac{P_i - P_{i*}}{P_{i*} - P_{i**}} \quad \forall i
\]

In this equation, \( P_i \) is the value of the \( i^{th} \) parameter. \( P_{i*} \) and \( P_{i**} \) are the best and standard value of the \( i^{th} \) sustainable parameter. The best value of a parameter represents the best practice available and the worst value represents the standard practice or the minimum legal requirement.

Normalization in addition to turning dimensionless the value of the parameters considered in the assessment, converts the values into a scale bounded between 0 (worst value) and 1 (best value). This equation is valid for both situations: “higher is better” and “lower is better”.

As stated before, building sustainability assessment across different fields and involves the use of numerous indicators and tens of parameters. A long list of parameters with its associated values won’t be useful to assess a solution. The best way is to combine parameters with each other inside each dimension in order to obtain the performance of the solution in each indicator (Allard, 2004).

The methodology uses a complete aggregation method for each indicator, according to Equation 2.

\[
I_j = \sum_{i=1}^{n} w_i \cdot \overline{P_i}
\]

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 \( i^{th} \) parameter. The sum of all weights must be equal to 1.

Difficulties in this method lie in setting the weight of each parameter and in the possible compensation between parameters. Since weights are strongly linked to the objectives of the project and to the relative importance of each parameter in the assessment of each indicator, higher weights must be adopted for parameters of major importance in the project. The possible compensation between parameters is limited inside each indicator.

In what concerns to the weights of the environmental parameters, there aren’t national impacts scores for each environmental parameter, according to its relative importance to overall performance. Although, there are some international accepted studies that allow an almost clear definition. Two of the most consensual lists of values are based on a US Environmental Protec-
tion Agency’s Science Advisory Board study (EPA, 2000) and a Harvard University study (Norberg-Bohm, 1992). Whenever there isn’t a local or regional available data, it is suggested to use SAB’s weights in MARS-RE. Table 1 presents the relative importance of environmental parameters and indicators that is considered in the methodology. Values are adapted from the SAB’s study.

Table 1. Relative importance weights for environmental parameters, adapted from the Science Advisory Board study.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Impact parameter</th>
<th>Parameter’s Weight (%)</th>
<th>Indicator’s Weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate change</td>
<td>Global warming potential</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Emissions</td>
<td>Destruction of the stratospheric ozone layer</td>
<td>15</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>Acidification potential</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Eutrophication potential</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Formation of ground-level ozone (smog)</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inert waste to disposal</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hazardous waste to disposal</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Water efficiency</td>
<td>Potable water use</td>
<td>75</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Rain water use</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Resources depletion</td>
<td>Land use</td>
<td>37</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Materials resource depletion</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fossil fuel depletion potential</td>
<td>26</td>
<td></td>
</tr>
</tbody>
</table>

1 This parameter was connected with the habitat alteration impact category of the SAB study.
2 This parameter was connected with the habitat alteration and ecological toxicity impact categories of the SAB study.
3 This parameter was connected with the water intake impact category of the SAB study.

In spite of being easy to quantify the functional parameters, the way as each parameter influences the functional performance and therefore the sustainability isn’t consensual. This assessment involves subjective rating and depends, above all, on the type of solution and on the valuator’s social-cultural and economic status. This way in a first approach the methodology considers the same weight for all functional parameters. The MARS-RE is being developed in order to accommodate a more consensual distribution of weights.

3.6 Representation and global assessment of a project

One important feature of the methodology is the graphical representation for the monitoring of the different solutions that are analyzed. The representation is global, involving all the considered objectives (indicators).

The tool that is used to graphically integrate and monitor the different parameters is the “radar” or Amoeba diagram. This diagram has the same number of rays as the number of parameters under analysis and is called the sustainable profile. In each sustainable profile the global performance of a solution is monitored and compared with the performance of the reference solution. Furthest to the centre is the solution, better it is. It is also possible to verify the solution that best compromises the different parameters used in the assessment. Figure 4 represents two sustainable profiles that result from the application of the MARS-RE to two hypothetical solutions.

The assessment of a project will come from the visualization of all indicators. Analysing figure 4 it is possible to verify that the solution that best compromises the objectives of the project is the most circular one. MARS-RE is an iterative design method, which is used to identify and to overcome the weaknesses of a project but it could not be used to assess the sustainability of a solution in an absolute way. It is used to compare different solutions in order to recognize the one that best suits the objectives of the project.

After assessing the performance of a solution within all indicators as presented in Figure 2 the next step is to combine the indicators with each other inside each dimension in order to obtain the environmental, societal and economic performance of each solution, as presented in Equation 8 for the environmental dimension.

\[
P_{\text{Env}} = \sum_{i=1}^{n} I_{\text{Env},i} \cdot W_{\text{Env},i}
\]
$P_{Env}$ represents the environmental performance of the solution, $I_{Envi}$ the $i^{th}$ environmental indicator and $w_{Envi}$ is the weight of the $i^{th}$ indicator.

Figure 4. Sustainable profile.

The last step is the quantification of the Sustainable score (SS). SS is a single index that resumes the global performance of a solution. As nearest to 1 is the sustainable score, more sustainable is the solution. The aggregation method used to calculate the sustainable score is presented in Equation 6.

$$SS = P_{Env}.w_{Env} + P_{Sec}.w_{Sec} + P_{Eco}.w_{Eco}$$

Since that the main aim of the sustainable development is the balanced development within the three dimensions, MARS-RE considers as standard an equal weight for each dimension in the integrated assessment. Although, users can use another set of weights, according to specific local priorities. In order to prevent difficulties in sustainability assessment, this unique mark should not be used alone to classify the sustainability because there is the possible compensation between indicators and moreover the solution has to be the best compromise between all different indicator.

4 CONCLUSIONS

Sustainable design, construction and use of buildings are based on the evaluation of the environmental pressure (related to the environmental impacts), social aspects (related to the users comfort and other social benefits) and economic aspects (related to the life-cycle costs).

In this paper it was presented some approaches to the buildings sustainability assessment (BSA) and one tool that is being developed to assist the design teams in the sustainable design. Despite the numerous studies about it there is a lack of a worldwide accepted method to assist the architects and engineers in the design, production and refurbishing stages of a building.

The actual LCA methods and building rating tools have a positive contribution in the fulfillment of sustainable developing aims, but they have their subjective aspects, for example, the weight of each parameter and indicator in the evaluation. For this reason, nowadays, the use of Performance Based Buildings methods, supported in the best construction codes and practices, to guide the design teams in order to archive the performance objectives, continues to be more objective than the use of rating tools.

The sustainable building rating tool that is being developed intends to contribute positively to the sustainable construction through the definition of a list of goals and aims, easily understandable by all intervenient in construction market, compatible with the European construction technology background. Although, there are still two important steps to fulfil before applying the methodology: validation of the list of indicators and parameters and assessment of the societal weights. 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 European countries through thematic interviews and surveys to experts in each dimension of the sustainable development. The weight of each health and comfort related parameter is now being assessed through experimental works and subjective evaluations.

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.

5 REFERENCES

Allacker, K. & DeTroyer, F. 2006. Evaluation of the environmental impact of buildings, including quality and financial cost. 13th of the CIRP Int. Conf. on Life Cycle Engineering.


LCA databases (EPD vs Generic data)

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Daniel Grecea  
*University “Politehnica” Timisoara, Timisoara, Romania*

Guri Krigsvoll  
*Oslo University College/SINTEF, Oslo, Norway*

Helena Gervásio  
*ISISE, GIPAC Ltd, Coimbra, Portugal*

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*Faculty of Architecture, Dokuz Eylul University, Izmir, Turkey*

**ABSTRACT:** Life Cycle Analysis (LCA) is time consuming and this is mainly due to the inventory stage, when data is collected for each unit process in the analysis. Currently there are many databases available, however data regarding the same process can vary from database to database and this can lead to significant deviations in the results of the LCA. Many issues contribute to the differences between data in current databases, namely: definition of the system boundary, cut-off rules, allocation procedures, accurate quantification of data, level of uncertainties in data, different sources of information, reliability of data and source, age of the data, geography of data, etc. Also, the main problem when dealing with data from different databases is the information contained in each dataset. This information is not always clear or is not available. To overcome some of these problems Environmental Product Declarations (EPD) are being developed. The aim of the EPD’s is to standardize data and to make inventory a more reliable and clear process. Unfortunately, for the time being, only a few processes have EDP available and databases are still the mainly resource to conduct LCA. It is the objective of the present paper to (i) present a review of available databases; (ii) describe the typical structure of a LCA database; (iii) perform a comparative evaluation of the outputs of a LCA analysis for steel using various databases; and (iv) to discuss the contribution of the EPD’s towards the standardization of databases.

1 INTRODUCTION

To make a Life Cycle Analyses (LCA) of a product or system it is necessary to create a model that contains the amounts of all the input and outputs of the processes involved over the life cycle. Large amounts of data concerning the inputs (raw materials, energy or other processes) as well as the outputs (products, semi-finished products and emissions) have to be handled. The data collecting and accounting of the processes is called the Life Cycle Inventory. Most of the time specific data, foreground data, still needs to be collected. But a large part of the data, the background data, may be available. For this background data, most assessment tools use a Life Cycle Inventory database.

Because sometimes these LCI databases have been developed together with an LCA tool these databases are more or less incorporated in the tool. With many LCA tools it is not possible to access, add or change, the LCI-data. This makes comparison of separate LCA databases difficult. Other databases however are open source with a clear unit format and available for use in other LCA tools.

Comparisons of LCA calculations show that it is extremely difficult to almost impossible to compare results obtained with different LCA tools. There is a need to harmonize existing LCA methods and LCA tools. At the same time it shows that it will be very hard to reach consensus.
The differences in approaches and outcomes undermine the reliability of LCA calculations and sometimes make the usability of results doubtful. Also the differences in methods and the lack of uniformity might prevent authorities in implementing these methods in the necessary push for a more sustainable construction industry.

In order to achieve more consistency and further harmonization of LCA tools as well as more transparent results, one of the first requirements is harmonization in obtaining and representing the Life Cycle Inventory (LCI) data. The use of ISO 14048 Technical Specification “LCA Data Documentation Format” (at this stage still preliminary) must ensure that sufficient transparency and adequate documentation is achieved.

To overcome some of these problems Environmental Product Declarations (EPD) are being developed. The aim of the EPD’s is to standardize data and to make inventory a more reliable and clear process. Unfortunately, for the time being, only a few processes have EDp available and databases are still the mainly resource to conduct LCA.

It is the objective of the present paper to (i) present a review of available databases; (ii) describe the typical structure of a LCA database; (iii) perform a comparative evaluation of the outputs of a LCA analysis for steel using various databases; and (iv) to discuss the contribution of the EPD’s towards the standardization of databases.

2 REVIEW OF AVAILABLE DATABASES

Different fields of application as well as differences in national approaches have resulted in a large number of different LCA databases with different LCA Tools. Without being exhaustive a number of these LCA databases will briefly be discussed here. The databases listed on the European Platform on LCA of the European commission formed the starting point of this limited investigation (See Table 1). Some questions: which of these databases are suitable for building and construction (The scope of Cost Action 25)? How is their availability: are they commercial or freely available, are they linked to existing LCA tools or not?

Table 1 shows the availability of the databases and the possibility to use it in different LCA Tools. (Some suppliers provide educational/ student versions at reduced cost)

The highlighted databases are considered the most important from the construction point of view because they contain (also) information regarding building (products) and construction industry. Also they have an approach beyond the scope of a national level. Further more their information can be accessed without the use of a specific LCA Tool.

The first database on the list CML IA is really a special kind of database. Unlike most of the others it does not contain information on, for example, production or manufacturing processes but it is a database to be used after the inventories have been made. It contains characterization factors for different (base-line and non baseline) assessment methods. From the Life Cycle Inventory, long lists of substances will be the results. But this (still more or less objective) information has to be evaluated. To do this all substances are sorted in classes according to the effect they have on the environment. To make it possible to aggregate the substances within these classes and to come to an effect score, the substances, or emissions, are multiplied by corresponding weighting factors called characterization factors. CML IA is a freely available database which provides these characterization factors in order to come to effect scores. Examples of effect scores are Human Toxicity, Global Warming or Acidification.

A number of the other databases listed on the European Platform on LCA, are databases for specific areas or fields of application only. They are less suitable for the building and construction industry. For example SABENTO is a databases used for the assessment of biotechnological processes. EIME is developed very specifically for the assessment of electrical and electromechanical products. Eurofer is another, Belgium, database, with a limited field of application, but it is interesting from the construction point of view, because it has data specifically for a number of different carbon and stainless steel products.

Other databases follow a more or less national approach, using information and processes based on nationally obtained statistics. It must be clear whether the used data relate to regional, national, European or world context. For example the IO databases for Denmark 1999 are based on the national Danish statistics of 1999. In general these Input-Ouput, IO, databases use national or regional economy figures of trade between sectors, suppliers and consumers, exports
Table 1 – Availability of databases

<table>
<thead>
<tr>
<th>Database</th>
<th>Supplier</th>
<th>Link to specific LCA tool</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>CML-IA 2.7</td>
<td>Leiden University, Institute of Environment</td>
<td>no</td>
<td>free</td>
</tr>
<tr>
<td>DEAM Impact</td>
<td>Ecobilan - Pricewaterhouse-Coopers</td>
<td>yes</td>
<td>commercial</td>
</tr>
<tr>
<td>DIM 1.0</td>
<td>ENEA – Italian National Agency for Ne</td>
<td>yes</td>
<td>commercial</td>
</tr>
<tr>
<td>Ecoinvent Data v1.3</td>
<td>Ecoinvent Centre</td>
<td>no</td>
<td>commercial</td>
</tr>
<tr>
<td>EIME v8.0</td>
<td>CODDE</td>
<td>yes</td>
<td>commercial</td>
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<tr>
<td>Esu-services database v1</td>
<td>ESU-services Ltd.</td>
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<tr>
<td>Eurofer datasets</td>
<td>EUROFER</td>
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<tr>
<td>GABI databases 2006</td>
<td>PE International GmbH</td>
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<td>GEMIS 4.4</td>
<td>Oeko-Institutt (Institut for Applied Ecology)</td>
<td>no</td>
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<td>IO-database for Denmark 1999</td>
<td>2.-0 LCA consultants</td>
<td>no</td>
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<tr>
<td>IVAM LCA Data 4.04</td>
<td>IVAM University of Amsterdam bv</td>
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<tr>
<td>KCL EcoData</td>
<td>Oy Keskuslaboratorio-Centrallaboratorium</td>
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<td>commercial</td>
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<tr>
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<td>Bundesforschungsanstalt fur Forest</td>
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<td>Option data pack</td>
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<td>Umweltbundesamt</td>
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<td>Sabento library 1.1</td>
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<td>US Life Cycle Inventory Da-</td>
<td>Athena Sustainable Materials Institute</td>
<td>No</td>
<td>free</td>
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<tr>
<td>tabase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waste Technologies Data Centre</td>
<td>UK Environment Agency</td>
<td>yes</td>
<td>free</td>
</tr>
</tbody>
</table>

etc. These data are mostly expressed in financial terms. The environmental data is divided by the added value of a sector. Thus all allocations of environmental loads are based on economic value. This means that it becomes possible to allocate all the environmental loads throughout the whole economy. The advantage is that there are no problems with system boundaries of processes. On the other hand it raises questions on how to deal with, and value the environmental imports, especially from very different economies. Another disadvantage is, is that the information is not very specific. It is not possible to compare materials that come from the same, for example building products, sector.

Some databases are combinations of freely available other databases and information: these databases are dependent on other institutions and other efforts to enlarge and update their information. For example Probas, from the German Umweltbundesamt, includes other freely available databases such as GEMIS (Global Emission Model for Integrated Systems) and information from Plastics Europe Eco-profiles as well as other data from publicly sponsored research. Most of the larger databases are compilations of other databases anyway and are the results of joint efforts of several institutes. Sometimes they combine different IO databases with unit processes and system processes databases.
Probably the most important European database of unit processes and system processes is the Ecoinvent database. Its information is used in many LCA tools and often included in other large databases. The Ecoinvent database is in its turn the result of the compilation and integration of several other databases like ETH-ESU 96 and Buwal250. This way it covers a very broad range of data. This joint effort of many Swiss institutes has provided data on many unit processes and system processes. Extensive background reports with a consistent specification of uncertainty data are available. This large effort, combined in the Ecoinvent centre, ensures regular updates, necessary for reliable information. Most of the other larger databases and the more commonly used LCA Tools include the possibility to use the Ecoinvent data sets.

Besides Ecoinvent, the GaBi and Simapro databases are probably the most important ones. It is a bit confusing, but both Gabi and Simapro include the Ecoinvent data and several other data-sets in their databases. Simapro for example consists of Buwal 250 (packaging), Danish Food data, Dutch input output data, Ecoinvent, ESU ETH data, Franklin USA data, IDEMAT, IO database Denmark 1999, USA input output data, Industry data. The wide range of the data sets of Gabi databases cover many industrial branches like metals (steel, aluminium and non ferrous metals), organic and inorganic intermediate products, plastics, mineral materials, energy supply (steam, thermal energy, power grid mixes), end-of life, coatings, manufacturing and electronics, construction materials, renewable materials, and textile processing.

An important initiative is the US LCI Database project by NREL National Renewable Energy Laboratory and Athena, Sustainable Materials Institute, Canada. It is supported by many, mostly US, institutions. To achieve more consistency and transparency the aim was to develop a single protocol which would be the bases of the data. At this moment, quite a number of different categories, one of which is Building and construction products, are included. The databases can be supplied by data from other sources, such as the Industry as long as the prescribed protocol for adding and changing data is closely followed.

It remains doubtful if recommendations with regard to the preferred use of certain databases could be made at this stage. Because of the enormous amounts and the wide range of the information, as well as the wide variety of the data sources it seems almost impossible to form an opinion with regard to the quality of a database. Within a database there may well be a wide variety in the quality of the data and the way it is presented. Some observations can be made:

Because of the very wide scope of LCA inventory databases, the data has to be obtained from many different sources. Database organizations therefore must cooperate with many different industries, producers and material organizations etc. Also production processes are constantly being optimized. This means that also the relevant data associated with these processes need constant updating. This may be virtually impossible for small commercial initiatives without the cooperation with larger research institutes, universities and industrial organizations.

It may well be more useful to form an opinion on the quality of the database organization, than on the quality of the database itself. The consistent way the information is collected, presented, updated, how much of the background information is available and how transparent are the data become the more important criteria

- Is sufficient meta-data, data about the data, made available, sources, age, what kind of process, measurements, how were calculations made etc.?
- Is sufficient information on the data quality and data uncertainty been made available?
- Is there a standard and publicly accessible protocol on obtaining, maintaining and updating the data?
- Is all the data and documentation ISO 14041 and ISO 14048 compliant?
- Is all the data available in the now standardized EcoSpold data exchange format (based on XML and related technologies)?

Some of these questions are addressed in more detail in the following sections.

3 TYPICAL STRUCTURE OF A LCA DATABASE

3.1 Introduction

The increasing demand on LCA in the industry sector and in policy making has been increasing the pressure on the development of LCA databases in order to comply with those demands.
To perform the life cycle inventory stage of a LCA data should be collected for each unit process included in the system boundary. Data may be obtained in situ by direct measurements or from calculations and estimations based on available data in literature.

The main guidelines to collect data are described in ISO 14040 (2006). According to this standard data can be classified in (i) energy inputs, raw material inputs, ancillary inputs, other physical inputs; (ii) products, co-products and waste; (iii) releases to air, water and soil; and (iv) other environmental aspects.

The quality of data should address the following requirements (ISO14044, 2006): a) time-related coverage: age of data and the minimum length of time over which data should be collected; b) geographical coverage: geographical area from which data for unit processes should be collected to satisfy the goal of the study; c) technology coverage: specific technology or technology mix; d) precision: measure of the variability of the data values for each data expressed (e.g. variance); e) completeness: percentage of flow that is measured or estimated; f) representativeness: qualitative assessment of the degree to which the data set reflects the true population of interest (i.e. geographical coverage, time period and technology coverage); g) consistency: qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis; h) reproducibility: qualitative assessment of the extent to which information about the methodology and data values would allow an independent practitioner to reproduce the results reported in the study; i) sources of the data; j) uncertainty of the information (e.g. data, models and assumptions).

In the following paragraphs two of the most comprehensive databases for LCA are going to be described. A specific database regarding steel products and a more general database regarding several products and services.

3.2 Examples of LCA databases

3.2.1 Worldwide LCI database for steel industry products

The International Iron and Steel Institute (IISI) developed an unified Life Cycle Inventory (LCI) methodology (2002) for steel products worldwide in accordance with the IISI Policy Statement on LCA and related ISO 14040 set of standards. The main goal of this study was to provide high quality LCI data for steel products on a global and regional basis. Further goals were to promote the environmental advantages of steel and to make steel industry more competitive in environmental expertise. The first study was made with data from 1994/95 but actual database is an updated version from 1999/2000 data. The study concerns fourteen products including hot rolled coil, cold rolled coil, hot dip and electrically galvanized sheet, painted sheet, tinplate and tin-free sheet, tubes, sections, plate, rebar/wire rod, and engineering steels.

Data was obtained from 50 sites worldwide operated by 28 companies accounting for 39.7% of global crude steel production outside of the former USSR and China. The LCI resulting values were calculated from an average of the values resulting from each site.

The function unit of the system is the production of 1 kg of steel product at the factory gate, and the boundaries of the system include all the production steps from raw material to finished products ready to be shipped from the steelwork. It does not include the manufacture of downstream products, their use, and end of life and scrap recovery schemes.

Within the LCI study all significant inputs and outputs from steel production are included. In the datasheets supplied by IISI only major articles are shown namely: (i) raw materials, (ii) air and water emissions, (iii) waste, (iv) non-allocated products, and (v) energy reminders. In formation on other articles may be obtained on request. The section referred to as “energy reminders” regards an energy indicator, given in terms of total primary energy, representing the energy derived from material inputs which constitute energy as well as mass inputs (e.g. coal, oil, etc). The total primary energy can be further divided into the following categories (i) non-renewable energy, (ii) renewable energy, (iii) fuel energy, and (iv) feedstock energy.

The allocation procedure selected by the study was the system expansion method mainly for two reasons (i) the method allows to discriminate between alternative recycling routes given “credits” for recycling, and (ii) the mass and element balances of the system are preserved in the LCI study.
All the data obtained was checked according to the goal of the study and in accordance with ISO 14040 standards. The complete study was subjected to an independent critical review panel of LCA specialists to ensure that it was consistent with the standards.

3.2.2 Ecoinvent database

The ecoinvent (Frischknecht et al., 2004) is one of the most comprehensive databases for LCA. It was developed by the Swiss Centre for Life Cycle Inventories with the main goal to provide a set of unified and generic LCI data of high quality.

One limitation of the database regards the geographic scope. The collected data relies mainly on Swiss and western European conditions.

The database (version 1.3) contains more than 2500 datasets of products and services from the energy, transport, building materials, chemicals, pull and paper, waste treatment and agricultural sector. Each dataset describes a life cycle inventory on a unit process level. The functional unit of all these unit processes is either a product or a service. Each dataset gives additional information regarding modeling assumptions for technology, location, date of data, collection method, data treatment, allocation rules, etc.

All products and services are identified by one particular category and subcategory, the latter is only used for informative purpose. An additional feature of the ecoinvent database is that it includes, for some unit processes, information about the amount of infrastructure needed per functional unit (e.g. $10^{10}$ units of a chemical plant per kg chemical output). The LCI results can be calculated including or excluding this information although for the time being the last option is not available.

In the same way, inputs and outputs (the so-called elementary flows) from each unit process are identified by the flow name, the unit, the category and the subcategory. Categories describe the different environmental compartments, air, water, soil and resources use. The first three categories describe the receiving compartment and are used for pollutant emissions whereas the last category “resource” is used for all kinds of resource consumption. Subcategories distinguish subcompartments within these compartments which may be relevant for the impact assessment step.

In ecoinvent, system boundaries are drawn based on expert knowledge (Frischknecht and Rebitzer, 2005) and not based on fixed rules. If no data is available for an expected pollutant than estimates are used in order to identify whether or not the pollutant is environmentally relevant.

Different types of uncertainties may be present in a LCI data and they should be taken into consideration. Regarding the uncertainties due to measurements, process variation, temporal variation, etc, are addressed by ecoinvent, on the level of individual inputs and outputs of unit processes, by the application of a probabilistic distribution.

Regarding the allocation procedure, a cut-off approach is used for recycled materials and for by-products, meaning that neither burdens/impacts nor benefits are granted for any subsequent use of recycled material or by-product. In the case of multi-output processes, the ecoinvent database includes unallocated multi-output processes and their derived single co-products output processes. Allocation factors are recorded separately and may be adjusted according to personal choices or new market situations.

The ecoinvent data was published in the SPOLD data exchange format in order to maximize its usability. The ecoinvent database also contains the characterization damage or weighting factors of various impact assessment methods but this is not addressed in this paper.

In order to comply with quality standards all reports and datasets were internally reviewed or validated.

4 COMPARATIVE EVALUATION OF THE OUTPUTS OF A LCA ANALYSIS FOR STEEL USING VARIOUS DATABASES

In the following paragraphs a comparative analysis of LCA databases is going to be described. The aim of the analysis is to assess the influence on the use of different databases in the result of the LCA analysis. The functional unit considered in the analysis is the production of 1 kg of
steel at the factory gate (cradle-to-gate approach). Two different routes were considered for steel production (i) the blast furnace route, where steel is obtained mainly from raw materials; and (ii) the electric arc furnace route whereas steel is obtained mainly from scrap.

In the LCA analysis only one potential impact is going to be considered for the sake of simplicity in the comparison. Therefore in the analysis only Global Warming Potential (GWP) is accounted for by the use of characterization factors for greenhouse gas emissions developed by the Intergovernmental Panel on Climate Change (IPCC, 2001) representing a 100-year time horizon. The characterization factors allow to calculate a single index, expressed in grams of carbon dioxide equivalents per functional unit of product, that measures the quantity of carbon dioxide with the same potential for global warming over a 100-year period.

For the comparison four databases were used (i) the IISI database, described in previous paragraphs; (ii) the ecoinvent database, also described before; (iii) an US database - Franklin Associates (this database is included in the LCA software tool SIMAPRO), and (iv) databases used in the LCA tool GEMIS. The results obtained from the EAF route and BF route analysis are represented in Tables 2 and 3 respectively.

Table 2 – Global warming potential for the production of 1 kg of steel through EAF route

<table>
<thead>
<tr>
<th>Database</th>
<th>Ref.</th>
<th>Location data</th>
<th>Ref. date</th>
<th>gr CO₂ eq.</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>IISI</td>
<td>1A</td>
<td>Global</td>
<td>2000</td>
<td>462</td>
<td>worldwide average</td>
</tr>
<tr>
<td>Ecoinvent</td>
<td>2A</td>
<td>EU</td>
<td>2006</td>
<td>1320</td>
<td>average technology</td>
</tr>
<tr>
<td>Franklin Associates</td>
<td>3A</td>
<td>US</td>
<td>1998</td>
<td>2010</td>
<td>average technology</td>
</tr>
<tr>
<td>Gemis</td>
<td>4A</td>
<td>Germany</td>
<td>2000</td>
<td>556</td>
<td>new technology</td>
</tr>
<tr>
<td>Gemis</td>
<td>5A</td>
<td>Germany</td>
<td>2000</td>
<td>602</td>
<td>old technology</td>
</tr>
<tr>
<td>Gemis</td>
<td>6A</td>
<td>Luxembourg</td>
<td>1990</td>
<td>627</td>
<td></td>
</tr>
<tr>
<td>Gemis</td>
<td>7A</td>
<td>Czech Republic</td>
<td>1990</td>
<td>3969</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 – Global warming potential for the production of 1 kg of steel through BF route

<table>
<thead>
<tr>
<th>Database</th>
<th>Ref.</th>
<th>Location data</th>
<th>Ref. date</th>
<th>gr CO₂ eq.</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>IISI</td>
<td>1B</td>
<td>Global</td>
<td>2000</td>
<td>2494</td>
<td>worldwide average</td>
</tr>
<tr>
<td>Ecoinvent</td>
<td>2B</td>
<td>EU</td>
<td>2006</td>
<td>1090</td>
<td>average technology</td>
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<tr>
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<td>1998</td>
<td>2820</td>
<td>average technology</td>
</tr>
<tr>
<td>Gemis</td>
<td>4B</td>
<td>Germany</td>
<td>2000</td>
<td>1836</td>
<td></td>
</tr>
<tr>
<td>Gemis</td>
<td>5B</td>
<td>India</td>
<td>1990</td>
<td>1886</td>
<td></td>
</tr>
<tr>
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<td>6B</td>
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<td>1990</td>
<td>2199</td>
<td></td>
</tr>
<tr>
<td>Gemis</td>
<td>7B</td>
<td>China</td>
<td>1990</td>
<td>6853</td>
<td></td>
</tr>
</tbody>
</table>

The same results are shown in Figure 1.

![Figure 1 – Global Warming potential – a) variation in the EAF route; b) variation in the BF route](image)

From Figure 1 a huge variation in the results can be observed particularly in the case of the EAF route, as the BF route has a lesser variation apart from China data. In different electric steel plants different electric arc furnaces are used and obviously this leads to different results in the collected data. The same can be said to blast furnace processes. Data is very much dependent of local technology and of the time period it refers to – old technology or new technology. Therefore, although all the indicated databases referred to the same functional unit, some aspects are different from database to database. For instance, regarding the EAF route all databases use the
electric arc process to melt the scrap and in certain cases pig iron, however the percentage of materials considered differ from process to process. Other differences shown in databases concerned the amounts of total energy, the consideration of different kinds of transports and distances in the collected data, different assumptions of allocation procedures, etc. In Table 4 some of these differences are illustrated.

Table 4 – Comparisons of databases (approximate values)

<table>
<thead>
<tr>
<th>Database Ref.</th>
<th>Materials (%)</th>
<th>Electricity (Kwh/kg)</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Iron Scrap</td>
<td></td>
</tr>
<tr>
<td>1A</td>
<td>0 100</td>
<td>??</td>
</tr>
<tr>
<td>2A</td>
<td>65 35</td>
<td>425x10^-3</td>
</tr>
<tr>
<td>3A</td>
<td>0 100</td>
<td>1.9</td>
</tr>
<tr>
<td>4A</td>
<td>0 100</td>
<td>400x10^-3</td>
</tr>
<tr>
<td>5A</td>
<td>0 100</td>
<td>550x10^-3</td>
</tr>
<tr>
<td>6A</td>
<td>0 100</td>
<td>697x10^-3</td>
</tr>
<tr>
<td>7A</td>
<td>?? ??</td>
<td>6</td>
</tr>
<tr>
<td>1B</td>
<td>100 0</td>
<td>??</td>
</tr>
<tr>
<td>2B</td>
<td>100 0</td>
<td>??</td>
</tr>
<tr>
<td>3B</td>
<td>75 25</td>
<td>747x10^-3</td>
</tr>
<tr>
<td>4B</td>
<td>85 15</td>
<td>14x10^-3</td>
</tr>
<tr>
<td>5B</td>
<td>80 20</td>
<td>??</td>
</tr>
<tr>
<td>6B</td>
<td>?? ??</td>
<td>14x10^-3</td>
</tr>
<tr>
<td>7B</td>
<td>?? ??</td>
<td>??</td>
</tr>
</tbody>
</table>

?? – data not available/unclear

In the above table only two parameters are shown. As seen from this table it is not always possible to check the information contained in databases. Not every database is completely clear regarding the data collected not the unit processes it refers to. The lack of information regarding the data stored in each database and the clear definition of the effective processes included, definition of the system boundary, is a major drawback in the use of databases from different sources and comparisons between data from different databases is in most cases impossible to be performed.

5 THE CONTRIBUTION OF EPD’S TOWARDS STANDARDIZATION OF LCA DATABASES

5.1 Environmental Product Declaration (EPDs) as input to LCA of constructions

The EPD of building products and services are intended to provide information for planning and assessing buildings and civil engineering works. EPD can also be used to compare the environmental impacts of building products under certain conditions. EPD are based on LCA, LCI or information modules. Relevant environmental aspects that have not been covered by LCA are addressed as additional environmental information. The rules for development and use of EPD are described in ISO 21930, and planned European standards (CEN350).

The objective of the Product Category Rules (PCR) is to provide the rules for the LCA, LCI or information modules underlying an EPD in order to obtain verifiable, consistent and comparable data describing their environmental performance as well as their contribution to health and comfort related aspects of a building.

The PCR shall identify and report the goal and scope of the LCA-based information and the rules on producing the additional environmental information for the product category. The PCR shall also determine the life cycle stages to be included, the parameters to be covered and the way in which the parameters shall be collated and reported. Further the principles and procedures set out in ISO 14020 and 14025 should apply.

Where the EPD includes all life cycle stages, such as production, installation into the building, use and maintenance, replacements, demolition, recycling and disposal, the EPD is said to
be “cradle to grave” and becomes an EPD of building products based on LCA. The material and energy flows for an EPD based on LCA are expressed per functional unit, defined in the PCR.

Comparability of EPD relies on using the same PCR for products to be compared. Comparison of building products using EPD shall only be carried out on building level.

The PCR sets rules for data quality requirements, including coverage, precision, completeness, representativeness, consistency, reproducibility, sources and uncertainty.

To ensure the transparency of the EPD the project documentation should address the LCA study including other environmental information performed to produce the EPD, as:

- the input and output data of the unit processes that are used for the LCA calculations
- the documentation that provides the basis from which the process data for the LCA is formulated
- the specification used to create the manufacturer's building product
- referenced literature and databases from which data have been extracted
- documentation that substantiates the chosen life cycle stages of the building product
- the data used to carry out the sensitivity analyses
- the documentation that substantiates the percentages or figures used for the calculations in the end of life scenario
- documentation that substantiates the percentages and figures used for the calculations in the allocation procedure, if it differs from the PCR;
- information showing how averages of different reporting locations have been calculated in order to obtain generic data
- procedures used to carry out the data collection (questionnaires, instructions, informative material confidentiality agreements, etc)
- the criteria and substantiation used to determine the system boundaries
- documentation used to substantiate any other choices and assumptions
- documentation that demonstrate the consistency when using information modules

5.2 Scenarios and Technical information

Scenarios and technical information are necessary for the application of EPD in building assessment. Therefore EPD should include information for the building product about:

- reference service life of the building product, with reference in-use conditions according to ISO/DIS 15686-8
- transportation, construction, use and operation, maintenance, replacements based on the reference service life
- the end of life stage, from de-construction, reuse, demolition, recycling and disposal
- energy-, water-saving etc. and other improvements like acoustical improvement
- energy content of the building product for energy recovery in the end of life
- recycled content (ISO 14021 clause 7.8.1.1) or recycling rates

5.3 Declared Unit and Functional Unit

The declared and functional unit is defined in the PCR, including information of which part of the life cycle that is covered (cradle to grave) and the expected average service life, and if necessary information about number of replacement during the service life of the building. Whether package is included should also be stated.

5.4 System boundaries

The system boundaries have to be stated. An important aspect when using EPDs is that transport should be included, as:

- Transport of raw materials from extraction/supplier to manufacturer.
- Transport of products from plant to wholesaler
- Transport of products from wholesaler to manufacturer
• Transport of building products from manufacturer to building site
• Transport from building site to recycling/incineration and landfill

Information on use, demolition and end of life scenarios should be included.

5.5 EPD databases

Data bases with the EPDs or similar information, as generic or average information for materials or products, simplifies the LCI of buildings of civil engineering work, both in planning stage and for existing constructions. Aggregating the information from the EPDs ensure LCAs where information is treated in a standardised way and that environmental impacts due to transportation, package, maintenance etc are taken into account.

6 CONCLUDING REMARKS

Obtaining and compiling LCI datasets and maintaining databases for LCA require a huge and constant effort. It requires the cooperation and the management of many different contributors. To ensure the quality and transparency of the data and the information, the development of a database must follow the ISO 14000 series standards and a number of clear and transparent guidelines. Benchmarks should be available to test the quality of the databases and the underlying assumptions in LCA Tools.

Transparent and Reliable LCI data are a first requirement for EPD’s, as they should be LCA based with sufficient third party verification. EPD’s are certainly a way forward because they will overcome the problem that many manufacturers are not willing to give full insight in their production processes.

REFERENCES

ISO 21690 Building construction - Sustainability in building construction – Environmental declaration of building products
US LCI Database Project Development Guidelines; NREL Athena; febr 2004
Inter-comparison and benchmarking Tools; Final report PRESCO project; febr 2005.
Introduction to LCA with Simapro; june 2007; Pre Consultants
Several Product websites of databases, as listed on EU platform on LCA: http://lca.jrc.ec.europa.eu
Comparison of life-Cycle Inventory Databases: a case study; S.A. Miller; Chicago USA
Energy in the sustainable European construction sector

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1 ABSTRACT:

Energy use in the construction sector consumes non-renewable resources and adds the greenhouse gases that are the main cause for the Climate Change. In the EU, the residential and tertiary sector buildings consume roughly 40% of total final energy use. Together with environmental pressure, the import dependence calls for urgent measures to reduce energy demand. The consumption tends to increase, especially that of electricity. In order to turn the development, the EU is planning to set the objective of 30% reduction of the final energy use of buildings.

The technologies needed in the construction sector are those that reduce the overall energy consumption of buildings, especially during their operational time, and those that produce electricity and heat in cleaner ways. The alternatives to solve the serious problems should be search from integrated approaches including technical and structural systems and potential of emerging technologies and new materials. Improvement of the energy-efficiency of buildings should be developed parallel with all aspects of environmentally, economically and socially sustainable construction sector. To the objectives, reliability of assessment and user-orientation of planning and design are of great importance.

2 INTRODUCTION

The new EU Action Plan on the energy-efficiency presents a goal to limit the raise of the global average temperature to 2°C, compared to pre-industrial level (EU2007a). To achieve this, the EU is promoting a goal of 30% reduction in greenhouse gas emissions by 2020, compared to 1990 levels, in developed countries. Further, it has made an independent commitment to achieve at least 20% reduction. The targets for various measures up to 2020 in the EU include:

- 20% improvement of energy-efficiency of cars, buildings and appliances, and especially
- 30% reduction of final energy use of buildings
- 20% share of renewable energy in average
- 10% share of biofuels
- ≈0% emissions of new power plants.

The carbon dioxide (CO₂) is dominant among the greenhouse gases (GHG). A major part of CO₂ emissions is related to energy, either to production or use, and combustion of coal and oil fuels is the main emitter. The Kyoto protocol states a goal to reduce the amount of six Greenhouse gases at least by 5% by the year 2012 compared with the year 1990; the EU-15 countries agreed a target of 8%.
According to the communication of Commission of the European Communities (2007), most technologies to reduce GHG emissions either exist or are at an advanced stage of preparation and can reduce emissions (see figure 1). This view concerning the construction sector has been stated by the Intergovernmental Panel on Climate Change, too (IPCC 2007).

Figure 1. Potential of various technologies to affect globally to GHG emissions.

For the EU, reducing overall demand of energy is of great importance due to commercial and political reasons, too. The European Environment Agency calls the situation as “twin-challenges of climate change and energy supply security” (EEA 2006a). Dependence on the external energy sources is expected to grow up to 70% in 2030 when it is nowadays 50% (Commission of the European Communities 2001). In the EU, the residential and tertiary sector buildings consume roughly 40% of total final energy use. Their energy needs are satisfied mainly by oil and gas - around 60% -, whose import dependence e.g. on Russian sources is great.

From the points of views of sustainable construction, the “twin-challenges” are only a part of the picture: the fossil fuel depletion is a serious environmental load. In the Life-Cycle-Analysis of a building, the energy used in the construction process comprises the direct energy used on the construction site and the indirect energy used in the manufacture of the building materials. The indirect energy component known as embodied energy of materials is increasingly being considered as manufacture of construction materials uses about 1/3 of industrial energy.

For all these reasons, improvements in the energy-efficiency of the European construction sector, and especially that of the existing building stock, are important for the sustainability of the construction sector. Among the measures to response the challenges, the EU is expanding the scope of the Directive on Energy performance of buildings and introducing EU performance requirements that promote concepts of very low energy and neutral energy buildings.

The purpose of the paper is to give an overview on the energy consumption and energy-related emissions of the European building stock, and technologies available to respond to the challenge of major savings. Further, the state-of-the-art of methods to verify the energy performance of buildings as a part of a sustainability assessment is studied. The methods of the study are surveys on statistics and literature.

3 ENERGY IN THE CONTEXT OF CONSTRUCTION SECTOR

3.1 Use of energy in operation of buildings

The European Environment Agency EEA has developed a set of 24 energy and environment indicators which serve for communicating about energy issues and are a part of the EU’s indicators for sustainable development (EEA 2006a). These indicators include e.g. final energy consumption by sector, green house gas intensity, and total energy consumption by fuel/energy
source, but do not give combined information. The energy statistics using these indicators is also given by the Directorate General for Energy and Transport about all European countries (EU 2007b). The cross-information of energy-sources to satisfy demands of various sectors by country is presented in the publication “Panorama of Energy” (European Communities 2007b).

The energy consumption is commonly divided into three main categories in statistics that are Industry, Buildings and Transport. The category of buildings excludes industrial buildings, and it consists of two subdivisions: residential and tertiary or household and service sector. The tertiary or service sector includes offices, wholesale and retail trade, hotels, restaurants, schools, hospitals, sport halls, indoor swimming pools etc. In Table 1, the final energy consumption in the EU is presented. (One should take a notice that there are slight differences between various EU documents, and starting from the Eurostat or national statistics is recommended.)

Table 1. The CO₂ emissions and import dependency of gross inland consumption (EU 2007) in relation to energy, final energy consumption of households and services (Eurostat 2007) and share of space heating in the sectors (European Communities 2007) The figures do not take into account the temperature correction (based on heating-degree days, see e.g. European Communities 2007b).

<table>
<thead>
<tr>
<th>Country</th>
<th>Import dependency</th>
<th>CO₂ emissions of all sectors</th>
<th>Final Energy Consumption of households and services in 2005, share of all sectors (Mt Mtoe = million tons of oil equivalent 1 Mtoe = 11630 GWh or 41868 TJ according to IEA)</th>
<th>Space heating alone of all energy sources used in the sector 2004</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Mt</td>
<td>Mtoe</td>
<td>% Mtoe</td>
<td>% Mt Mtoe</td>
</tr>
<tr>
<td>BE</td>
<td>78.9</td>
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<td>CY</td>
<td>94.6</td>
<td>8</td>
<td>0.5</td>
<td>29.4</td>
</tr>
<tr>
<td>LV</td>
<td>63.5</td>
<td>7</td>
<td>2.2</td>
<td>55.0</td>
</tr>
<tr>
<td>LT</td>
<td>48.0</td>
<td>12</td>
<td>2.1</td>
<td>46.7</td>
</tr>
<tr>
<td>LU</td>
<td>98.2</td>
<td>12</td>
<td>0.8</td>
<td>18.2</td>
</tr>
<tr>
<td>HU</td>
<td>60.8</td>
<td>54</td>
<td>10.5</td>
<td>58.0</td>
</tr>
<tr>
<td>MT</td>
<td>100.0</td>
<td>3</td>
<td>0.1</td>
<td>20.0</td>
</tr>
<tr>
<td>NL</td>
<td>30.7</td>
<td>177</td>
<td>21.9</td>
<td>42.4</td>
</tr>
<tr>
<td>AT</td>
<td>70.8</td>
<td>69</td>
<td>10.5</td>
<td>38.5</td>
</tr>
<tr>
<td>PL</td>
<td>14.7</td>
<td>292</td>
<td>28.7</td>
<td>50.2</td>
</tr>
<tr>
<td>PT</td>
<td>83.6</td>
<td>64</td>
<td>6.0</td>
<td>32.3</td>
</tr>
<tr>
<td>RO</td>
<td>30.3</td>
<td>98</td>
<td>10.5</td>
<td>42.9</td>
</tr>
<tr>
<td>SI</td>
<td>52.1</td>
<td>15</td>
<td>1.8</td>
<td>36.7</td>
</tr>
<tr>
<td>SK</td>
<td>67.6</td>
<td>36</td>
<td>4.3</td>
<td>40.6</td>
</tr>
<tr>
<td>FI</td>
<td>54.5</td>
<td>68</td>
<td>8.3</td>
<td>32.9</td>
</tr>
<tr>
<td>SE</td>
<td>36.5</td>
<td>51</td>
<td>12.5</td>
<td>37.1</td>
</tr>
<tr>
<td>UK</td>
<td>5.2</td>
<td>560</td>
<td>62.4</td>
<td>41.2</td>
</tr>
<tr>
<td>All</td>
<td>4005</td>
<td>480.4</td>
<td>39.6</td>
<td></td>
</tr>
</tbody>
</table>

Six countries with the great numbers of populations account for 3024.9 Millions tons of emissions being 70.6% of the total amount of 4286.2 Millions tons of equivalent oil; these coun-
tries are Germany, France, Italy, Poland, Spain and the U.K. The same countries account for 2850 Mt’s of CO₂ emissions that are 71.2 % of the total amount of 4005 Mt’s.

When the efficiency of various energy savings measures is studied, the differences between macro-economic indicators of countries cannot be overlooked, like energy sources used for space heating, green house gas intensities and import dependency. The average European values are more indicative, and give information about trends at the EU level (Table 2).

Table 2. Share of the buildings of final energy demand by fuel in the EU25 in 2002 (Commission of the European Communities 2005). About conversion factors see Table 1 or www.iea.org.

<table>
<thead>
<tr>
<th>Final energy demand by fuel</th>
<th>Buildings (residential and tertiary) Mtoe</th>
<th>Share of energy sources used for buildings</th>
<th>Share of buildings of the total final energy demand %</th>
<th>Total final energy demand in the EU25 % of the total final energy demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid fuels</td>
<td>12.2</td>
<td>2.8</td>
<td>1.1</td>
<td>50.9</td>
</tr>
<tr>
<td>Oil</td>
<td>96.8</td>
<td>22.1</td>
<td>8.9</td>
<td>475.2</td>
</tr>
<tr>
<td>Gas</td>
<td>151.6</td>
<td>34.6</td>
<td>14.4</td>
<td>261.5</td>
</tr>
<tr>
<td>Electricity</td>
<td>121.3</td>
<td>27.7</td>
<td>11.2</td>
<td>218.5</td>
</tr>
<tr>
<td>Derived heat</td>
<td>22.8</td>
<td>5.2</td>
<td>2.1</td>
<td>30.3</td>
</tr>
<tr>
<td>Renewables</td>
<td>29.0</td>
<td>6.6</td>
<td>2.7</td>
<td>46.2</td>
</tr>
<tr>
<td>Total</td>
<td>437.8</td>
<td>100</td>
<td>40.4</td>
<td>1082.6</td>
</tr>
</tbody>
</table>

The CO₂ emissions of residential buildings in the EU25 were 10.1% of all energy-related emissions and those of service sector 5.5% in the 2003. The tons of CO₂ equivalent per a ton of oil equivalent of energy vary according to the energy sources; for more information see e.g. the Report 8 of the EEA (2006).

Reducing growth in electricity consumption will be crucial from an environmental viewpoint, especially for consumption from fossil-fuel based electricity. Two to three units of energy input are needed for producing one unit of electricity form fossil fuels with the rest being lost in the process, unless the heat is recovered in combined heat and power process.

3.2 Embodied energy of buildings

Embodied energy is the energy consumed by all processes associated with the production of a building, from the acquisition of natural resources to product delivery. Example of a component embodied energy is shown in figure 2a). Research has shown that the embodied energy content of a building can be the equivalent of many years of operational energy (see figure 2b). Renovation and maintenance also add to the embodied energy over a building's life. Basic information can be found in literature and databases (Table 3).

Figure 2. a) Example of the breakdown of initial embodied energy in a building. b) Influence of materials and concepts on the overall energy consumption of a building (csiro 2007).
Table 3. Example of embodied energy of a composite steel beam and concrete slab (steeluniversity 2007).

<table>
<thead>
<tr>
<th>Years</th>
<th>Energy, GJ m⁻²</th>
<th>CO₂ Emissions, kg m⁻²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Structure Embodied</td>
<td>2.6</td>
<td>2.7</td>
</tr>
</tbody>
</table>

3.3 Energy indicators of the European building stock

The energy indicators of buildings are related on the other hand to the characteristics of the building stock and on the other hand to social and demographic information. For example, increasing wealth, decreasing size of households and increasing usable area per person indicate that the consumption of households will still increase. The slow replacement of old building stock - only 0.07% in average - is a factor that supports this trend.

In analysis of various retrofitting needs of buildings, it is common to classify the building stock into age groups according to the completing years. This approach is justified due to the similar building technologies. Table 4 gives basic information for energy-related indicators of the building stock. However, the official national statistics should be used in studies because there are differences between sources; the UNECE and Boverket have some great differences.

Table 4. Characteristics of the European building stock related to energy (UNECE 2007, Boverket 2005).

<table>
<thead>
<tr>
<th>Country</th>
<th>Population 2005 x10^3</th>
<th>Dwellings in total</th>
<th>Age distribution of the housing stock (Boverket 2005)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BE</td>
<td>10 446</td>
<td>4.8</td>
<td>86.3</td>
</tr>
<tr>
<td>BU</td>
<td>7 761</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>CZ</td>
<td>10 221</td>
<td>4.3</td>
<td>76.3</td>
</tr>
<tr>
<td>DK</td>
<td>5 411</td>
<td>2.6</td>
<td>109.1</td>
</tr>
<tr>
<td>DE</td>
<td>82 501</td>
<td>38.9</td>
<td>89.7</td>
</tr>
<tr>
<td>EE</td>
<td>1 347</td>
<td>0.6</td>
<td>60.2</td>
</tr>
<tr>
<td>EL</td>
<td>11 076</td>
<td>5.5</td>
<td>82.7</td>
</tr>
<tr>
<td>ES</td>
<td>43 038</td>
<td>20.9</td>
<td>90.0</td>
</tr>
<tr>
<td>FR</td>
<td>60 361</td>
<td>29.5</td>
<td>89.6</td>
</tr>
<tr>
<td>IE</td>
<td>4 109</td>
<td>1.4</td>
<td>104.0</td>
</tr>
<tr>
<td>IT</td>
<td>58 462</td>
<td>26.5</td>
<td>90.3</td>
</tr>
<tr>
<td>CY</td>
<td>749</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>LV</td>
<td>2 306</td>
<td>1.0</td>
<td>55.4</td>
</tr>
<tr>
<td>LT</td>
<td>3 425</td>
<td>1.3</td>
<td>60.6</td>
</tr>
<tr>
<td>LU</td>
<td>455</td>
<td>0.2</td>
<td>125.0</td>
</tr>
<tr>
<td>HU</td>
<td>10 098</td>
<td>4.1</td>
<td>75.0</td>
</tr>
<tr>
<td>MT</td>
<td>4 032</td>
<td>0.1</td>
<td>106.4</td>
</tr>
<tr>
<td>NL</td>
<td>16 306</td>
<td>6.8</td>
<td>98.0</td>
</tr>
<tr>
<td>AT</td>
<td>8 207</td>
<td>3.3</td>
<td>92.9</td>
</tr>
<tr>
<td>PL</td>
<td>38 174</td>
<td>11.8</td>
<td>68.2</td>
</tr>
<tr>
<td>PT</td>
<td>10 529</td>
<td>5.3</td>
<td>83.0</td>
</tr>
<tr>
<td>RO</td>
<td>21 659</td>
<td>8.1</td>
<td></td>
</tr>
<tr>
<td>SI</td>
<td>1 998</td>
<td>0.8</td>
<td>75.0</td>
</tr>
<tr>
<td>SK</td>
<td>5 385</td>
<td>1.7</td>
<td>56.1</td>
</tr>
<tr>
<td>FI</td>
<td>5 237</td>
<td>2.6</td>
<td>77.0</td>
</tr>
<tr>
<td>SE</td>
<td>9 011</td>
<td>4.4</td>
<td>91.6</td>
</tr>
<tr>
<td>UK</td>
<td>60 035</td>
<td>25.6</td>
<td>86.9</td>
</tr>
</tbody>
</table>
The number of dwellings in EU-27 is about 215 millions, of which about three fourths is concentrated in six countries: Germany (18.0%), Italy (12.3%), UK (11.9%), France (13.7%), Spain (9.7%), Poland (5.5%).

There is a significant difference between occupied (treated) floor area and the total area. Again, one should have a real data about the heated area when indicators like consumption per m² or m³ or the potential of energy savings are evaluated. For example, in Finland there is a stock of secondary houses that is more and more used also during the winter time, and thus heated to some extent.

Several European studies have been performed concerning indicators and data needed for the evaluation of the energy performance of buildings. As the most accessible data concerns residential buildings, the work has very much concerned to it. The list of Odyssee project is similar with the indicators used in practical assessments (Odyssee 2007):

- Unit consumption per households (total, for various purposes, per m², with climatic corrections, in useful energy)
- Energy efficiency index
- Specific consumption of new dwellings (per m³, flat, houses)
- CO₂ emissions (direct, total, per dwelling, for space heating)

More and more the information needed to evaluate energy used in the building stock can be found in publications, based on data gathered in several European and international projects and networks, like e.g. IEA (2007), IEE (2007) and COST Actions.

4 ENERGY PERFORMANCE OF BUILDINGS

4.1 Thermal performance characteristics

Knowledge on the energy-performance of buildings is needed for evaluation of the potential of energy-savings of existing buildings and verification of the thermal performance of a new building during design process. The main interest is nowadays in the overall consumption in the context of indoor climate; in other words “energy conversation and thermal comfort”. This approach means that performance and interaction of all systems of a building have to be dealt at the same time (see figure 3).

![Figure 3. Development of calculation methods and requirements in Germany since 1995 for a typical single family house in Germany.](image)

As long as the construction technologies were based on natural ventilation, air leakages and varying indoor conditions, development of thermal performance was concentrating solely to envelopes. For that reason, tested values of thermal and moisture properties of materials and struc-
tural solutions, or calculations based on them, became gradually regulated. In academia, the building physics was applied to thermal performance calculations already in the beginning of 19th century.

Prescribed coefficients for heat transfer, so-called U-values (unit W/m²K) for the building’s envelopes – floor, walls and roof – are used in many countries as the principal criteria for design. Nowadays, there are calculators available in the web. Also, “typical” U-values can be found there. In some countries, a more holistic ‘Energy Performance’ (EP) regulation was used (the calculated energy consumption of the building, usually expressed in kWh/m²).

The year of building construction provides useful insight with regard to the type of envelope construction. On the other hand, the history of U-values is also usable when potential of energy-savings is estimated. U-values as such do not tell about the energy-consumption unless the climatic conditions and the consumption patterns are not taken into account. This hold especially the Southern countries in which only recently the heating and cooling demands have increased. Further, the regulated U-values can in many ways differ from the actual values of buildings, to both directions.

More than half of the existing residential buildings in EU-25 was built before 1970 and about 1/3 of the dwellings were built during the 1970–1990. On an average, new European dwellings are about 60% more energy efficient than the ones constructed before the first oil crisis in the 1970s, and consume 28% less than dwellings built in 1985. Actually, the most significant improvement was observed after 1990 due to the stricter measures taken by several EU member states and the introduction of higher energy standards in the mid-1990s. As a result, dwellings built in 2002 consume 24% less than dwellings built in 1990.

The Directive on Energy Performance of Buildings EPBD (EU 2002) has adopted an integrated approach that is similar to the Construction Products Directive, CPD. In the reasoning of the EPBD, the estimation of the saving potential of 22 % by the year 2010 is based upon savings in all consumption areas, namely heating, hot water, air-conditioning and lighting. The Directive concerns the residential sector and the tertiary sector (offices, public buildings, etc.).

The key points of the Directive concerning structures are:
- Common methodology for calculating the integrated energy performance of buildings
- Minimum standards on the energy performance of new buildings and existing buildings that are subject to major renovation
- Systems for the energy certification of new and existing buildings and, for public buildings.

As a minimum, the Directive requires that the following aspects should be considered:
- Thermal characteristics of the building (i.e. its external envelope/shell and internal walls), including air-tightness
- Heating installations and hot water supply, including their insulation characteristics
- Air conditioning systems
- Mechanical ventilation systems
- Built-in lighting installations (mainly in non-residential buildings)
- Position and orientation of the building, including outdoor climate
- Passive solar systems and solar protection
- Natural ventilation
- Indoor climatic conditions, including the designed indoor climate.

The status of the implementation of the EPBD to the national regulation in the Member States is presented at the EU’s official webpage buildingsplatform.eu, where country reports summarize the development and give links to the national regulations and tools.

4.2 Modelling and simulation

Modelling and simulation based on building physics are sophisticated methods for analysis of components, structures, buildings or even building stock. They are extensively used in calculating the heat loss and surface temperatures in buildings, in order to verify thermal performance during a design process. There are hundreds of software tools and guidelines on the market.

The information for an energy simulation is basically the same as that for simplified energy calculation. Before carrying out the simulation, one must collect information about the local climatic data, building design, air-conditioning system and control method. The local outdoor
climatic conditions over a year are an important piece of information and it is better to have the hourly values of the climatic data. This data is often recorded in a typical year. If the weather data for a particular location is not available, it may take a lot of efforts to collect and establish this data.

The dynamic simulation of building energy consumption focuses on the hourly variations of the outdoor climatic conditions and the indoor design criteria about temperature and humidity. The air-conditioning loads and energy consumption for 8760 hours in a year or for several years are determined. Beside the part-load energy consumption, the maximum load over the year(s) will also be included.

The modelling and methods are used also to analyse the condition of a building stock in an area, suburb, city or a country. In a model, typical buildings are rated for specific annual energy consumption per m², and then the surface of each age-class is multiplied by the specific annual energy consumption to predict the overall consumption (Kohler & Hasler 2002). Validation of these models can be achieved by comparing the sum of estimated consumption to the statistically known building energy consumption.

5 STRATEGIES TO IMPROVE SUSTAINABLE CONSTRUCTION

5.1 Energy in the sustainability assessment methods

The generic methods of Life Cycle Analysis of buildings are under development although there are standards and tools to perform environmental assessments. The LCA methods comprise identification of indicators and their parameters, data collection, calculation of parameters, combination of indicators, evaluation and valuation – in the context of a life-cycle. The phases and tasks of the LCA as an environmental management tool is presented in the standard ISO14040. Considerations of energy in the life-cycle of a building are presented in figure 4.

Figure 4. Aspects of energy in the environmental LCA of a building (Kohler et al, 1997).

The data needed in the inventory phase of an LCA can be got from databanks, measurements, calculations and simulation. It can be expressed as a loss through envelope or primary
energy consumption – depending on the purpose of the evaluation. The sequential phases of LCA involve subjective valuation that is a different approach from the quantitative calculations. In valuation, weighting factors are given to the various qualities. The LCA approach brings other aspects of sustainable construction sector to the valuation process than the consumption figures only. According to Casals (2006), the meaning of embodied energy accumulated in the materials and equipments becomes more critical as building operational energy efficiency is increased.

Current development work of the life-cycle assessment methods concentrates to establishing links between LCA software tools and design tools. The analysis software utilises object orientated CAD data along with life cycle, embodied energy and detailed climatic data to create an individual lifetime profile for a building design (figure 5). Users are able to modify their design to explore different life cycle energy scenarios through material choice, orientation and layout.

![Diagram](Image)

**Figure 5.** Australian development of the interaction of CAD designs and LCA with respect to energy (Drogemuller et al. 2002).

### 5.2 New technologies for energy-efficiency

According to the survey of the IPCC (2007), there is a broad array of accessible and cost-effective technologies and know-how to reduce energy losses during the operation of buildings. Several other projects and political communication are in agreement with this view; for example ENPER– Project (2007) concludes: “With respect to the 2020 horizon, there is a need for innovative concepts in terms of a large-scale market implementation of well-proven technologies (thermal insulation, efficient boilers, heat pumps, energy-efficient ventilation, efficient lighting, use of renewables, etc). No new major technological innovation is required.”

However, at the longer run there are needs of technological innovations. The novel solutions are searched from rapid developments of material sciences and technologies as well as miniturizing of monitoring technologies.

Microprocessors can be used to control solar thermal and photovoltaic systems, heat storage, sun-shading, ventilation and back-up heat, and provide electrical power management. Energy management use computer-based monitoring systems to optimize the performance and interaction of systems, and more often the various systems are interacting as an intelligent building. They integrate monitoring and control of heating and cooling systems, lighting, building envelope shading, elevators, security, fire control systems and many other subsystems.

Recent research has shown that the savings potential of advanced control systems alone is of the order of 190 PJ of primary energy per year in the whole Dutch built environment, and 12 Mtoe CO₂ emission reduction (Opstelten et al. 2007). The control systems are classified as environment-adaptive, user-adaptive and user-educational (interactive), and the latter one is an evolving area. It requires simultaneous simulation and extending the current software tools.
There are several disciplines and industrial branches that are interested and involved in the research and development work aiming at new solutions for the construction sector. The objectives and roadmaps developed among the various European Technology platforms give good introductions to the advanced and alternative technologies. Similar concepts can be found in several European projects (Table 6).

<table>
<thead>
<tr>
<th>Potential</th>
<th>Targeted technical effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modified natural solutions</td>
<td>- increased ventilation&lt;br&gt;- cooling with cold water&lt;br&gt;- passive solar shades</td>
</tr>
<tr>
<td>Advanced materials</td>
<td>- energy storing, dissipation&lt;br&gt;- smart materials, phase changing materials&lt;br&gt;- high-reflectivity, cooling (new hybrids)&lt;br&gt;- use of solar energy (space heating, water heating)&lt;br&gt;- high-efficiency lighting&lt;br&gt;- insulation materials</td>
</tr>
<tr>
<td>Advanced facades and roofs</td>
<td>- reduction of heating or cooling needs&lt;br&gt;- light-weight and free forms&lt;br&gt;- reduction of thicknesses (e.g. vacuum solutions, Hastings 2004)&lt;br&gt;- minimizing or selecting the infiltration of outside air&lt;br&gt;- building integrated photovoltaics (to produce electricity and also act as a building material)</td>
</tr>
<tr>
<td>Advanced windows</td>
<td>- reduction of heating needs (multiple glazing, superior glazing)&lt;br&gt;- control the amount of solar heat that passes through the window glass (electrochromic or &quot;smart&quot; windows)</td>
</tr>
<tr>
<td>Integrated design</td>
<td>- effective use of ambient energy sources and heat sinks&lt;br&gt;- effective control strategies (integrated design of windows and HVAC systems)</td>
</tr>
<tr>
<td>Integrated products</td>
<td>- use of massive structures (floors, facades)&lt;br&gt;- technical services integrated in the core structures&lt;br&gt;- multifunctionality (electricity, heat, aesthetic, structure)</td>
</tr>
<tr>
<td>Intelligent building technologies</td>
<td>- dynamic and adaptive overall management of systems&lt;br&gt;- educational control systems</td>
</tr>
<tr>
<td>Industrialized production</td>
<td>- air-tight and easy-to-assemble connections</td>
</tr>
</tbody>
</table>

5.3 Passive and zero-energy building concepts

The energy-efficiency goals of buildings have been studied in the context of the whole building stock and built environment. There are arguments that only the zero-energy or energy neutral solutions of new buildings will have the desired impact to the needs of absolute savings; less stringent goals of new building means savings of 50-80% in space heating compared the average level of current use. Various concepts have been developed in many countries. For example, NREL participates in the United States in “creation of the technology and knowledge base for cost-effective zero-energy buildings by 2025. A zero energy building is defined in the following way (NERL 2007): “…produces as much energy on-site as it consumes on an annual basis, primarily through energy efficiency with any small remaining loads met by photovoltaics and other solar energy technologies”. The Energy Research Centre of the Netherlands gives a definition of a zero-energy house that “annually the energy demand can be met by locally generated renewable energy” (Opstelten et al. 2007).

A Passive House concept has been under development since the 90ies. The Passive House Institute has given a definition that it is “a building in which the heat requirement is so low that a separate heating system is not necessary and there is no loss of comfort” (Feist 1997). The concept is gaining more and more support among practitioners and stake-holders, as it introduces clear targets for energy-consumption in technical terms. In total, more than 6,000 houses have now been built in Germany and elsewhere in central Europe (for example Austria, Belgium, Switzerland, Sweden) which conform to the Passivhaus standard. The standard funda-
mentally consists of three elements: i) an energy limit; ii) a quality requirement; iii) a defined set of preferred Passive Systems with cost efficiency.

The Passive House has a heating demand of 15 kWh/m² floor area per year, whilst the total primary energy use in the house is restricted to 120 kWh/m² per year (see figure 6).

For the Northern Scandinavia and other countries with cold climates, a more flexible definition of the Passive House concept is set. For Southern climates (<40° latitude), where passive cooling is more dominant, a second addition to the definition should be made:

- Nordic passive houses (> 60° northern latitudes)
- Central European passive Houses (40° - 60° northern latitude)
- Mediterranean passive houses (IEE project Passive-On < 40° northern latitude)

According the most optimistic but still realistic scenario of the potential savings, the passive houses are projected to realize a goal that exceeds the Kyoto target in the new building sector.

![Figure 6. Annual building energy use for space heating (net energy use for heating) for single family houses in Germany.](image)

6 CONCLUDING REMARKS

Life-time engineering aims at translating the requirements of all stake-holders into performance requirements of the technical systems and assuring that those requirements will be fulfilled over the entire design service life, as the Memorandum of Understanding of the COST C25 Action presents. Life-time design or integrated life cycle design implies a new thinking about current design methodologies and it’s highly dependent on aspects such as durability, maintenance, service life prediction.

Life-time engineering supports sustainable construction, but applies different methods of structural service life design. The basis of design service life is knowledge about phenomena affecting durability and serviceability of components. The knowledge about materials and components – including durability - is the basis of LCA methods, too. Life cycle assessments are focused to the impacts on the environment of any product (including buildings) from "cradle to grave", i.e. from obtaining the raw materials from which the product is created to its disposal at the end of its life.

It can be foreseen that LCA methods will increase their importance in planning and design of building projects. The role of energy-related indicators is crucial in evaluation of environmental and economic impacts but also with respect to social aspects of sustainable development. As a consequence, in material and product development, the issues of the LCA will become more important.
REFERENCES


steeluniversity. 2007. E-learning webpage of the University of Liverpool, International Iron and Steel Institute and Matter. www.steeluniversity.org

An approach for an Integrated Design Process focussed on Sustainable Buildings

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ABSTRACT: This paper is a contribution towards an integrated design process focussed on sustainable buildings. It considers the project partners involved throughout the planning progress and responsible for the implementation of a green design. A fully ecological design is achieved by the concept of triple zero which is explained and defined as a principal target. The paper also proposes a new certification procedure offering a comprehensive assessment and classification of buildings.

1 INTRODUCTION

Over the last five years the focus of building design has shifted from predominantly architectural and functional approaches to more exhaustive approaches putting a special emphasis on sustainability. Today investors, building developers, and project managers do specify certain demands for sustainability in first stages of a project. But these demands are simply additional requirements leaving the conventional contract documents and planning process unchanged. Specialist consultants are as yet insufficiently involved in the first design phases, although their contribution is vital for a really ecological design. Moreover, sustainability is often merely used as an argument for architectural competitions and marketing purposes, the final result not matching the promises made at an earlier stage.

In order to develop and implement truly sustainable building concepts, an interdisciplinary planning process is indispensable. All planners involved in the project should participate at the earliest project phase possible. Moreover, coherent guidelines and assessments are necessary to ensure a coherent and sustainable design process in all phases of a project. Sustainability has to be the governing factor in the compilation of all specifications and contract documents. The present paper proposes an approach towards achieving this aim. This approach will hitherto be called integrated design.

Sustainability covers social, ecologic, and economic questions. The social aspect comprises cultural considerations, comfort, social integration, health, ergonomics, and functionality. It is generally taken care of by architects. The economic aspect is assessed by value-engineering and commercial departments. The ecological aspect, however, is often reduced to energy efficiency only. Ecology is thus taken into consideration but to a relatively limited degree. The present paper proposes a much more comprehensive target concept called triple zero – zero energy, zero emission, zero waste.

Last but not least a national certification procedure is presented offering an advanced tool for the classification of structures according to their sustainability. This classification system is about to become be the governing factor for the assessment of buildings, especially for office, retail and residential buildings, in Germany and beyond.

This paper shows a way to successfully fulfil the demands for full sustainability by applying an integrated design process, the triple zero concept, and the new certification procedure proposed by the GeSBC.
2 STATE OF THE ART DESIGN PROCESS

2.1 Representative life-time phases

The life-span of a structure can be divided into four periods, subdivided into several subitems:

1. Preliminary Phase
   - Definition of building task, data collection
   - Architectural and functional concept (possibly defined for a competition)

2. Realisation Phase
   - Schematic design
   - Detailed design
   - Construction design
   - Bidding and contract award

3. Construction
   - On-site activities
   - Re-design

4. Operation Phase
   - Utilisation
   - Conversion

5. Removal Phase
   - Deconstruction
   - Disposal of waste

2.2 Design Groups and Involved Parties

Depending on the extent and type of structure, various disciplines are required for the design process. The following list is a typical compilation of disciplines involved in a larger project.

Developer:
- Principal, Investor
- Project manager
- Project controlling and monitoring

General Design:
- Architect, design engineer

Construction:
- Structural consultant
- Geotechnical engineer
- Special structure consultants (light structures, special foundation, etc.)
- Wind engineer

Building Services/ Physics:
- MEP – Mechanical, Electrical, Plumbing –
- Building Physics consultant incl. Hygrothermie (heat and moist transfer)
- Special consultant on cooling and heating
- Thermal simulation, CFD engineer
- Façade consultant
- Daylighting consultant

Ergonomic and Interior Design:
- Interior architect
- Ergonomic consultants for workplaces, offices, apartments, hotels, wellness, retails
- Acoustic Consultant
- Light planning consultant

Cost Assessment/ Economy:
- Value engineer
- Full life-cycle costs/ Environmental costs consultant
2.3  Traditional Linear Design Process

The traditional linear design process basically follows consecutive planning and design phases shown in figure 1. Architects, engineers, and specialist consultants are successively included in this planning procedure. Often engineers and specialist consultants participate only to a limited extent in the early phases of a project. However, the first two phases of a project are of the highest importance, as here the effect of measures aiming at sustainability and cost-efficiency is strongest. The rare examples where specialist consultants are involved from the very beginning of a project demonstrate the validity of this argument [5].

As a typical example, structural engineers, MEP, and lighting consultants often become involved in the schematic or detailed design. Therefore these experts are often acting only in a passive way, because the main design has already been determined before. In the later planning phases major changes or innovations are more difficult and less efficient. The frame in which the consultants search for solutions gets narrower the more advanced the design already is [4]. Within the old-fashioned linear planning process, the active involvement of these specialist consultants in the preliminary design is more or less impossible.

Figure 1. Traditional Linear Design Process

2.4  Sustainable Guidelines and Standards

The existing guidelines and standards, e.g. [1], [2] or [3] on sustainable designs are focussing on the final performance of the building. These codes are measuring the sustainability of a building against various design categories (e.g. energy/CO₂, water, waste, health and well-being etc.). In [1] and [3] the rating is performed using a table of points awarded for a variety of criteria (e.g. in [3] sustainable sites, water efficiency, atmosphere, material & resources, indoor environmental quality, innovation & design process), whereas the structure is considered as a whole package. Although very good checklists and references to special codes are given, e.g. in [2], the design process itself is not mentioned in these guidelines.

There is a number of recent buildings in Europe showing a good sustainable performance such as the headquarter of DEW21/Dortmund, EnergyBase/Vienna, R&D centre of Festo/Esslingen, headquarter Telefónica/Madrid, Kolumbus-Centre/Vienna or BMW-World/Munich. In all these buildings, various techniques were taken into consideration (and later on implemented) at a very early stage of the design. These techniques include intelligent double facades, solar-powered cooling, geothermal energy systems, absorption cooling, thermal storages, PCM, plasters with microcapsule including paraffin or silicate gel, photovoltaic, thermally activated structural members and air-conditioning based on heat exchangers. Future projects may use even more advanced techniques currently being prepared for maturity phase [6].
3 INTEGRATED DESIGN PROCESS FOCUSED ON SUSTAINABLE BUILDINGS

3.1 Integrated Design

Sustainable design requires a holistic approach, where the specialist consultants from various disciplines are included from the very beginning of a project. These specialist consultants have to be able to understand the needs and intentions of the other disciplines. This process is herein after called integrated design.

Within the integrated design process all parties involved are considered throughout the representative life-time phases according to 2.1 and 2.2. Figure 2 and 3 give an illustration and a matrix of the integrated design process. The relevant experts are involved from the first outline of the project until the removal phase. Therefore they acquire a better understanding of the various demands and performances of the various disciplines. Finally the building set-up is a common development.

Architectural, formwork, and reinforcement drawings are commonplace. The authors of the present article propose to create “member drawings” as well. Every structural and finishing member shall get a special barcode as an identification number. The members shall be marked with this barcode on site or already in the prefabrication plants. The member drawings shall include a list of members and be linked to a member databank. This databank shall contain detailed information on average life-span and costs as well as instructions on deconstruction and disposal of waste.

The whole integrated design process has to be focused on sustainability. The key elements of design and construction have to be assessed with regard to their social, ecologic and economic impact on the building. Improvements and innovations shall be supported, negative impacts excluded.

The basic objective underlying integrated design is the triple zero concept described in the following chapter.

Figure 2. Integrated Design Process
<table>
<thead>
<tr>
<th>Life-time phases</th>
<th>Developer</th>
<th>General Design</th>
<th>Construction</th>
<th>Building Services/Physics</th>
<th>Ergonomic and Interior Design</th>
<th>Cost Assessment/Economy</th>
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</thead>
<tbody>
<tr>
<td>Preliminary Phase</td>
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<td>Definition task</td>
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<tr>
<td>Architectural Concept</td>
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<tr>
<td>Realisation</td>
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<td>Schematic Design</td>
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<td>X</td>
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<tr>
<td>Detailed Design</td>
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<td></td>
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<tr>
<td>Construction Design</td>
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<td>X</td>
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<tr>
<td>Bidding and Contract Award</td>
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<td>Construction</td>
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<td>On-Site Activities</td>
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<td>X</td>
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<tr>
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<td>X</td>
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<tr>
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<td>Utilisation</td>
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<td>Conversion</td>
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<td>Deconstruction</td>
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<td>X</td>
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<tr>
<td>Disposal of Waste</td>
<td>X</td>
<td></td>
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<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Figure 3. Matrix of design groups and life-time phases for an Integrated Design Process
3.2  *The Triple Zero Concept*

Triple Zero is a comprehensive approach covering all ecological aspects of sustainability:

a) Zero Energy

- reduction of the energy consumption in the operation of a building (lighting, heating/cooling, ventilation)
- avoidance of fossil fuels
- use of renewable energy sources

b) Zero Emission

- reduction of emissions (energy use emissions, particulate matter, plasticizer, scent etc.) throughout the life-cycle of a building (design, construction, operation, reuse, demolition)
- design of flexible and reusable buildings
- use of ecological and local materials to avoid long transport and high grey energy use as well as sick-building-syndrome

c) Zero Waste

- recycling of all materials used in a building
- avoidance of composite materials which cannot be separated at the end of their life-cycle
- easily demountable constructions
- creation and use of a member databank

The Triple Zero concept is to be used as the central guideline underlying the whole integrated design process.

4  CERTIFICATION

4.1  *Existing Certification Systems*

Various countries have already implemented a certification system for sustainable designs, e.g.:

- USA: U.S. Green Building Council     Leed – Certification System
- France : Association HQE     HQE – Certification System
- Great Britain: U.K. Green Building Council     BREFAM – Certification System
- Japan: Japan Sustainable Building Consortium     CASBEE – Certification System

All these certification activities are coordinated and supported by national Green Buildings Councils (GBC). The umbrella organization is the World Green Building Council describing its activities as ‘the peak global not-for-profit organisation working to transform the property industry towards sustainability through its members national GBC’.”
In several European countries an ‘energy passport’ for buildings will be introduced soon. For example, in 2007 the Energy Performance Certificates will be introduced in Great Britain under the Energy Performance of Building Directive (EPBD). The EPBD requires that all new, sold or released homes have an Energy Performance Certificate. The key information in this certificate is energy efficiency measured as carbon performance using the same calculation method as the Code for Sustainable Homes [1].

4.2 Proposal for a Certification System of the German Sustainable Building Council

The German Sustainable Building Council (GeSBC) has recently been established. The mission of the GeSBC is to promote and support a fully sustainable design, realisation, usage and disposal of buildings. The aims pursued by the GeSBC are:

- Protection of resources
- Preservation of natural environment
- Health, comfort and well-being of habitants
- Protection of environment and public goods
- Preservation of values

The main objective of the GeSBC is the configuration of a national certification system making the above-mentioned aims “protection targets” for the assessment. Contrary to other certification procedures such as [3], the GeSBC Certification clearly specifies the main objectives and not individual measures. Specific means are deliberately left undefined so as to allow for an open and innovation-friendly sustainable design process.

The GeSBC certificate defines a number of aspects necessary for full sustainability, e.g. thermal insulation, comfort, impact on environment, social aspects etc. Only for some of these aspects numeric indicators can be used, e.g. for carbon performance, total primary energy supply etc. Therefore expert groups will work out a procedure how the assessment can be performed using these new comprehensive indicators.

In order to achieve maximum acceptance, a certification system has to be highly transparent and coherent. It also has to be adapted to the national culture of each country taking into consideration national building traditions, codifications, and social aspects.

As a result of its current deliberations, the GeSBC will introduce in the near future a certification system with five stars and gold as well as silver rating. The assessment starts with the individual target definition and accompanies the design process until the final award. A five star classification is an exclusive distinction which will only be given to truly outstanding projects.

5 SUMMARY

The conventional and traditional way of linear planning is not compatible with the demands of a sustainable building design process. The stepwise involvement of specialist consultants at a relatively late stage of the project hinders a mutual understanding of the various disciplines and prevents true sustainability.

A tripartite approach is proposed to overcome this difficulty. Firstly, an integrated design process allows involving engineers and other specialist consultants already at a very early stage of a project. This allows for an optimum of innovation and cost-efficiency. Secondly, the triple zero concept covers all ecological aspects of sustainability. Thirdly, the certification procedure proposed by the GeSBC permits a holistic assessment of a building, measured by the achievement of five clearly specified targets.
6 REFERENCES

Chapter 1

CRITERIA FOR SUSTAINABLE CONSTRUCTIONS

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INTRODUCTION

The construction sector has a great responsibility in the achievement of global sustainable development. The construction industry is Europe’s largest industrial employer, accounting for 7.5% of total employment and 28.1% of industrial employment in the EU. Construction activities consume more raw materials by weight (as much as 50%) than any other industrial sector. The built environment, moreover, accounts for the largest share of greenhouse gas emissions (about 40%) in terms of energy end usage. Measured by weight, construction and demolition activities also produce Europe’s largest waste stream, (between 40% and 50%) most of which though, is recyclable. Over the past century, a stable trend of increased consumption of construction materials, energy (increasing levels of energy consumption per square meter) and accumulation of construction waste is noted, leading to the constant increase of global environmental impacts. It is further predicted that the built environment will continue to expand destroying and/or disturbing natural habitats and wildlife. The way forward for the construction sector is to develop an integrated approach where the environmental issues are taken alongside the safety and functional requirements usually in a cost-based approach. This integrated approach, also known as Sustainable Construction, aims to balance the social, economical and environmental impacts of construction activities in the present time and in the future. The ways structures are erected, operated, maintained and finally dismantled and/or demolished constitute the complete cycle of sustainable construction activities. Thus, sustainable construction requires a multidimensional, life-cycle approach, where all impacts and stages are considered throughout the whole design life of a construction.

It is the main objective of Action C25 “to promote science-based developments in sustainable construction in Europe through the collection and collaborative analysis of scientific results concerning life-time structural engineering and the integration of environmental assessment methods and tools for structural engineering”. In the pursuit of this goal, the role of Working Group 1 is to deal with general criteria for sustainable construction, gathering information and expertise from participating countries, identifying main methodologies and available databases and providing further scientific bases towards an integrated approach for a sustainable assessment of the built environment. This chapter is the result of the work done by Working Group 1 members over the first year of the Action.

As already referred, a life-cycle sustainability analysis of constructions must integrate, in a “cradle to grave” approach, ecological, economical and socio-cultural aspects. The environmental performance is usually measured using an Environmental Life-cycle Assessment (LCA). This approach is based on the belief that all stages in the life of a product generate environ-
mental impacts and must therefore be analysed. These include raw materials acquisition, product manufacture, transportation, installation, operation and maintenance, and ultimately, recycling and waste management. The strength of environmental life-cycle assessment lies in its comprehensive and multi-dimensional scope. In the following, a review of the general methodology to conduct a LCA is introduced and further developments are discussed. As the implementation of current methodologies varies from country to country, as an example, the present situation in Greece is presented and discussed.

Although many developments are being made within the scientific community in order to improve the framework of LCA, this approach has been used since the end of the 60’s. Thus, after the presentation of the LCA framework a review of the state-of-the-art of LCA methodologies is presented, including a brief historical review of LCA, and the main LCA methodologies currently available are introduced and discussed.

In regard of LCA methodologies in the construction sector, two major classes of assessment tools for the built environment can be identified. While LCA follows a more quantitative approach, an alternative type of assessment tool is a criterion based methodology, often used as a ranking system for the environmental classification of buildings. The criterion based methodologies are more qualitative, although some indicators may be quantified. This kind of approach, also known as Voluntary Building Environmental Assessment Systems, is presented in this chapter, where main available methodologies are introduced and compared and further developments are discussed.

Standardization has given LCA a major push for world wide acceptance. The need for standardization in environmental reporting became clear, in the end of the 1980s, when environmental reports on similar products often contained conflicting results because they were based on different methods, data and terminology. Therefore a part of this chapter is dedicated to an overview of existing and planned national and international standards. Within this section examples are given on how to use the standards as framework for development of methods and tools for the environmental assessment.

The economical performance is best assessed using a Life-cycle Cost Analysis (LCCA). In a LCCA, all construction-related costs occurring at the different stages over the life-time of the construction are considered and discounted to their present value as the base data of the analysis, before being combined into the LCCA performance score. The chapter also gives an overview on the use of LCC in construction. It is the purpose of this section to show at which stages in the construction process (from idea to operation and demolition) LCC is an adequate decision support tool, and on what level (main design to system to product) decisions and analysis are done. This section ends with a presentation of some few databases currently available at building or construction level to conduct LCCA.

Socio-cultural aspects are of a much fuzzier nature and consequently they are much more difficult to take into account. These aspects are however crucial and often impose choices that contradict the better environmental and economical solutions. As for the other two aspects, socio-cultural aspects should also follow a life-cycle methodology. This part of a sustainable analysis is not yet covered in this working group.

Although the scope of Action C25 is at the construction level, a complete sustainable analysis of the built environment cannot be performed without the consideration of the surrounding envelope of the construction, either in an urban or rural area. Thus this chapter ends with an overview of different approaches to evaluate urban infrastructures from a sustainable point of view. In this context urban infrastructure covers transportation, energy, water, sewage and information networks as well as waste management and blue-green infrastructure, in terms of supply and demand side. In this section parts of the work developed in other actions and projects are also presented, showing the link between the present action and other research groups. Therefore, a guidebook for decision makers in local authorities for the evaluation of sustainability, prepared within COST C8, is presented. Information about best practice projects in sustainable urban infrastructure is also given and illustrated with an overview of identified cases. In addition the FP6 project PETUS is briefly presented aiming to give a complete survey of tools for evaluation of urban sustainability.
1 INTRODUCTION

Since the beginnings of the 1960’s the awareness that mankind has a significant influence on its environment has grown. The idea that man may well be the cause of many environmental problems arising, now and possibly in the future, has been widely accepted. Together with this awareness the need for modelling, calculating and evaluating these influences has grown. Life Cycle Assessment studies have gradually developed from general calculations, to predict the effects of world’s changing populations on the demand for finite resources, to methods that can be used to evaluate for example different product solutions and processes or to identify weak points that can be improved.

2 LCA AND SUSTAINABILITY

Besides the environment also social and economic issues should be incorporated in thriving for more sustainable solutions. Social issues however can be very wide ranging, for example from working conditions, access to clean drinking water up to political choices. There is no ISO standardization on these social issues. Although several Tools try to incorporate them, there is little consensus on how to deal with social and economic aspects. To include economic aspects and come to integrated Life Cycle Costing LCC seems obvious but still proves to be difficult. Many difficulties still need to be overcome. This paper will focus on the LCA with regard to environment.
3 STANDARDIZATION FOR LCA

A big step forward (also to prevent inappropriate use of LCA’s in misleading marketing claims) has been the standardization of LCA methodology in the ISO 14000 series.

The two ISO standards for LCA are ISO 14040: Principles and Framework and ISO 14044: Requirements and Guidelines (the new 14044 replaces 14041, 14042 1n 14043 with minor differences in content). Deviating from these standards is possible but might have consequences for the reliability of the LCA.

4 MODELLING

Of course, LCA involves modelling; it is never a “complete image of the real world”, (although sometimes it may seem to be as complex as the real world). A lot of decisions with regard to this modelling have to be made, for example whether to include or exclude certain effects, on the data reliability, the boundaries to be set, cut-off rules, interpretation etc. Because very different aspects are included in the LCA modelling it is important for the reliability and the transparency that decisions and uncertainties are well documented.

5 FRAMEWORK OF LCA

5.1 General foundations of LCA

According to SETAC, Society of Environmental Toxicology and Chemistry, Life Cycle Assessment is an objective process to evaluate the environmental burdens associated with a product process or activity by identifying energy and materials used and wastes released to the environment, and to evaluate and implement opportunities to affect environmental improvements. In this context, environmental impacts, including relevant safety, health, and social factors are quantified and summed up across the product or service life cycle.

An LCA identifies and quantifies material usage, energy requirements, solid wastes, and atmospheric and waterborne emissions throughout the product life cycle (i.e. cradle-to-grave).

The International Standards ISO 14040 (2006) and 14044 (2006) specify the general framework, principles and requirements for conducting and reporting life cycle assessment studies. Regarding these standards, life cycle assessment shall include definition of goal and scope, inventory analysis, impact assessment, and interpretation of results, as illustrated in Figure 1. The various phases are interrelated.

![Figure 1. Life cycle assessment framework according to ISO 14040.](image-url)
5.2 Goal and scope of the LCA

The first requirement for an LCA is to define and carefully document the purpose and application. The ISO standards deal with this. A clear statement of the objectives possibly in terms of the questions that need to be answered should be one of the first steps. Once these goal(s), and the scope of the LCA is set and documented, decisions on the appropriate modelling as well as other issues regarding the modelling can be based on this (and if necessary adapted):

- The definition and choice of the product with its system boundaries, its life cycle and the function it fulfils.
- The choice of the environmental parameters to be included, choice of aggregation and evaluation method.
- Definition of the basis for comparison (functional unit), in case two products need to be compared
- The data requirements
- Allocation problems
- Assumptions and limitations

An LCA according to ISO 14040 is defined as a compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product through its life cycle.

5.3 The inventory (LCI, Life Cycle Inventory)

The LCI is a rather objective accounting of environmental and economic inputs and environmental and economic outputs of the system. Which emissions will occur, which raw materials/energy are used during the life of a product? To do the calculations a lot of LCA tools have been developed. In a lot of these LCA Tools datasets of many processes which have already been investigated, are included and stored in the LCI databases of the Tool. Unit processes have transparent and big process trees with much detail. Sometime it is simpler to use system processes. They are basically models like black box, with only the input and output of the system available.

5.4 The assessment

What are the impacts of these emissions and the depletions of the raw materials?

To determine this, classification and characterization (obligatory according to ISO 14042) is performed. The emissions and substances are classified into effect classes according to the effect they have on the environment. Examples of these classes are: Carcinogen, Energy use, Ozone layer depletion. Some substances have more effect in a category than others; this is why weighting, with so-called characterization factors, is applied. The results become effect scores per category. It now becomes possible to compare for example the environmental effects in a certain category of two different products.

5.5 Normalisation

It becomes more difficult if we want to assess the importance of effects in different categories. What is the relative importance of one impact category compared to others?

To evaluate the relative influence of a score in an impact category a normalization step can be applied. It shows the relative contribution of the system to each already existing effect by comparing it to a normalized value, for example the same effect caused by an average European in the year 2000. Also impact categories with a very small contribution can now be left out. In the evaluation phase it is possible to multiply normalized effect scores by a weighting factor, representing the relative importance of the effect. Normalisation is optional, according to the ISO
standards. But for a comparison of products, which is to be publicly presented, the ISO standards do not allow normalisation ranking, grouping or weighting.

5.6 Life Cycle Impact Assessment (LCIA) methods

It may be clear that, while the LCI, Life Cycle Inventory phase, is still rather objective, the assessment phase involves a lot of, more or less, subjective decisions. There are a large number of different impact assessment methods (LCIA methods) which have each defined different impact categories. Usually the methods use approximately 10 to 20 impact categories. The choice of the method and the corresponding impact categories should be made in relation to the goals of the LCA. For example the impact category noise may proof to be of less value in the comparison of two building products, but in the comparison of two engines or tires noise might be extremely important.

ISO recommends first to select and define so-called endpoints: The main categories of environmental concern, for example Extinction of species, Depletion of resources are called endpoints. From there impact categories (midpoints) can be selected that have a clear and described linked to the endpoints. For example the midpoints, or impact categories, Eco-toxicity and Land-use have a (in a model) described link to the endpoint extinction of species. Of course LCA experts do not have to design their own impact assessment methodology. There are a number of existing methods. CML 92, or ECO-indicator 99 are examples of methods with different impact categories. CML 92 is a midpoint method. The results stay relatively close to the inventory result. ECO-indicator 99 on the other hand is an endpoint method. It uses the unit DALY: Disability Adjusted Life Years, used by the WHO and World Bank to evaluate health statistics. From the inventory of the substances (LCI) the concentrations to air water and soil are calculated, resulting in a certain exposures, causing different human disabilities which are weighted and then expressed in DALY. Also it is a damage oriented method. Because it calculates the impact categories in only three different units it becomes possible to add them into three final endpoints: Resources (expressed in MJ Surplus Energy) ecosystem quality expressed in PDF*m2*yr and Human Health, expressed in DALY.

5.7 Weighting

Finally with some endpoints methodologies the results can be expressed in single score, such as Eco-indicators, EPS scores or Swiss Ecopoints. This may be a very clear but also vary subjective way of representing the results. Some other methods for weighting can be followed, for example the use of an expert panel. Sometimes however the number of indicators is rather large and it becomes difficult to explain the meanings of the indicators to the panel. Use of panels also can have interfering social behaviour effects. Sometimes political reduction targets are suggested to be used as weighting factors. Sometimes monetarisation is suggested: to express all damages in a monetary unit. Willingness to pay, future extracting costs etc. are different cost of which it is assumed that they are representative and that they can be added. An interesting method to represent LCA outcomes for comparisons of two products is the triangle concept of Hofstetter (1999). It shows for which weighting sets there is no difference in choice, or for which weighting sets product A is favourable and for which sets product B is favourable.

5.8 Interpretation

The ISO standards describe a number of checks which have to be made in order to see if the reliability of the outcome is sufficient and the conclusions are sufficiently supported by the data and the model. To assess the influences of these aspects, checks on incompleteness etc. sensitivity, consistency and contribution analyses must be made.

5.9 Limitations

The “holistic” nature of LCA is maybe its major strength but it may be also its limitation. The analysis of the complete life cycle of a product can only be achieved by the simplification of
some aspects in the overall analysis. Therefore the main limitations of a LCA methodology may be listed as the followings (LCA, 2001):

i) LCA does not address impacts that are locally dependent;
ii) LCA is typically a steady-state and it does not take into account time aspects;
iii) LCA is a tool based on linear modelling of environmental problems;
iv) LCA focuses on the environmental aspects of products and says nothing about their economic, social and other characteristics.

A more general limitation regards the availability of data to conduct a LCA. Databases are being developed in various countries, and the format for databases is being standardized. But in practice, data are frequently obsolete, not reliable and of poor quality.

6 BEYOND THE SCOPE OF ISO 14040

The ISO standards are not an easy step by step cooking book with a guaranteed recipe. The requirement of sufficient documentation in the standards is very clear and the way the standards are written means that many different solutions and ways to perform an LCA are kept open. This means that developed LCA tools can follow their own approach. This may be positive but it also means that results are often not compatible and are difficult to compare. For both LCA experts as well as non experts there are still a number of issues on which more detailed guidance could be very helpful.

7 BUILDING AND CONSTRUCTION

For building and construction the evaluation for recycling as well at the start of the building life cycle as the end should be included. This can be done in various ways. The discussion of the methods goes beyond the scope of this paper, but harmonisation in the methods is desirable. The implementation of LCA in Building and construction varies from country to country. Implementation of legislation still awaits further harmonisation in methods. A short overview with regard to the situation in Greece is given.

7.1 Use of LCA Tools in Greece

In Greece, the efforts to adapt exiting methods to the national conditions and to encourage the use of the corresponding tools, even at the level of integration of sustainability principles in every day practice, are at an early stage. The main problem seems to be the lack of sufficient support of the necessary mechanisms and substructures. The experience derived from some attempts to use rather analytical tools for the buildings’ environmental performance assessment in Greece has revealed gaps, and in some cases the complete lack, of databases, national regulations and statistics relative to environmental issues. Those gaps have been identified and some, at the time crude, proposals for solutions, for the systematic approach of those problems, have been made (Giarma & Bikas 2005).

In the following paragraph, the results provided and the conclusions derived from some attempts to use a method for buildings’ environmental performance in Greece are described. At this point, it should be noted that the previously mentioned problems, that almost jeopardized the reliability of those studies, were overcome with the help of some experts in the various fields examined.

7.2 Application of an environmental performance assessment tool for buildings in Greece -The conclusions drawn and the future prospects emerging

The method applied for the buildings’ environmental performance was Green Building Challenge method that is expressed through GBTool. GBTool is designed to assess the performance of a building in what regards a broad range of performance issues (such as resources consump-
GBTool was initially used to evaluate an office building’s performance, in the design and construction of which special measures were applied for the building to be friendlier to the environment. The assessment conducted showed a considerable improvement in almost every side of the building’s environmental profile in comparison to the conventional buildings of its type (Giarma & Koimtsidou 2002, Giarma et al. 2003).

The same building was taken as the reference case to study the impact of integrating photovoltaic elements on the environmental profile of the building. The results of several cases were analysed (use of PV elements on the northern, southern, eastern, western façade of the building, on its roof, etc.). The conclusion was that the use of PV elements can lead to a, at least, detectable improvement of a building’s environmental profile, especially in countries such as Greece, where the energy provided by the sun is of considerable amounts (Bikas et al. 2005).

GBTool was also used for the investigation of urban context’s impact on the environmental performance of buildings (Tsikaloudaki & Giarma 2005). In this parametric study the variables were the density and the geometry of the urban context, expressed as a range of view angles of the surrounding buildings. GBTool was used for the evaluation of the building’s environmental performance in each case.

The conclusions derived from those attempts to use GBTool for the environmental performance assessment of buildings in Greece are manifold. On the one hand, the lack of the relevant substructures has become obvious. On the other hand, the fact that the application of such tools can prove the alterations in a buildings’ profile (even in what regards practical matters such as the energy consumption) is encouraging, since it provides a strong argument for the persuasion of practitioners to include such methods in every day practice.

8 LIFE TIME

Perhaps one of the most important issues that remain unsolved in LCA is the parameter Life time. Products are modelled as systems with clear inputs and outputs but the differences in service lives between products or parts of products are seldom taken into account, let alone that the service lives are modelled stochastically. Solutions are needed, in particular in the building and construction industry. If we would like to make an LCA of a whole building or bridge, instead of a single product, there are many differences in life time. For reliable comparison of solutions, these differences need to be taken into account. The situation becomes even more complex if we want to compare or make assessments of possiblerestorations or upgrading of existing buildings and constructions.

9 DISCUSSION

LCA performed according to the ISO standards can be a very useful tool to model and study differences in environmental impacts of products and materials (systems). The ISO standards do not yet incorporate solutions for the inclusion of social and economic assessments.

Perhaps the most important aspect of LCA is clearly defining the goal(s) and scope of the LCA. Other decisions regarding various problems (with the inventory or impact assessment) can than be made in the light of this goal. These decisions should be carefully documented to ensure transparency.

With regard to the application of LCA in building and construction still a number of problems need to be solved. One of the most important issues in the implementation of LCA in building and construction are the differences in service lives of the various building elements and components.
REFERENCES


Conference CD, article code nr 01-123.


Goedkoop M., De Schrijver A, Oele M. Introduction To LCA with Simapro Pre Consultants, Delft Netherlands


Peuportier B., Putzeys K., Practical recommendations for sustainable construction; PRESCO Final report WG1


ABSTRACT: Life Cycle Assessment (LCA) is the most comprehensive approach to deal with impacts of material goods on their environment. The method entails compiling an inventory of relevant inputs and outputs (flows) for a system and then evaluating the potential environmental impacts associated with those flows. Although many developments are being made within the scientific community in order to improve the framework of LCA, this approach has been used since the end of the 60’s. It is the purpose of this paper to review the state-of-the-art of LCA methodologies and discuss further developments.

1 INTRODUCTION

The environment has become a major concern to everyone from developed industrial countries to so-called 3rd world countries, although with different kinds of problems. Air and water pollution, global warming, acidification, etc, are only part of the environmental problems that we have to deal in the present and to take into account for the future, so that future generations can live in this planet with, at least, the same conditions as we do today. However a sustainable development is a multi-dimensional concept taking into account not only the environmental aspect, but also social, political, economic, cultural and spiritual dimensions.

Regarding the environmental aspect, one of the tools developed to deal with the problem is the Life Cycle Environmental Assessment (LCEA) or simply Life Cycle Assessment (LCA). LCA takes into account all the environmental burdens of a product or a system from cradle to grave, that is, from the extraction of the raw materials necessary to fabricate the product, to the final disposal of those materials, taking into consideration all the phases in between.

Currently there is not a single globally accepted approach to deal with LCA. A conceptual LCA is still in development and many problems and limitations are being considered in different ways among the existing methodologies.

The first part of this paper will present a brief history of LCA and the general framework of the methodology. Then in the second part, the main available methodologies are presented followed by a discussion on the further developments.

2 BRIEF HISTORICAL REVIEW

The first steps on developing a method for assessing a product's environmental impacts were taken in the 60s by Rachel Carson in *Silent Spring* (1962) where various environmental problems created by human activities were discussed. These methods were however, restricted to
calculate the energy requirements and solid waste, neglecting the evaluation of the potential environmental effects.

The energy crisis of the 1970s and the publication of *Limits to Growth* (Meadow et al. 1972) had a major influence on general environmental awareness. One of the results was a detailed system for analyzing the energy required to manufacture individual products. Again, these first methods were mainly restricted to calculate the energy requirements and solid waste, neglecting the evaluation of the potential environmental effects.

The United Nations played a major role in the global environmental concern. In a report published in 1987, the Bruntland Report (Our Common Future) (Bruntland, 1987), the critical and globally threatening environmental problems resulting from the poverty in the South and excessive consumption in the North were stressed out. The report called for strategies for an environmentally sound economic development – a Sustainable Development. Sustainable development is an approach that aims to balance the social, economic and environmental impacts of all our actions, now and in the future. This well known worldwide concept has increased interest in LCA in two ways: first, methods have been developed for quantifying product impacts on different categories of environmental problems (such as global warming and resource depletion); secondly, LCA studies have started to become more widely available for public use.

An association of industries created in 1992, the Society for the Promotion of Life Cycle Development (SPOLD), developed a database network to stimulate the development of LCA as an accepted management tool for the necessary restructuring of company policies towards sustainable development. The widespread need within the LCA community for reliable inventory data was addressed by SPOLD with the development of the SPOLD format (Weidema, 1999). This common format for exchange of life cycle inventory results allowed data to be understood compared and exchanged, disregarding how it was stored in their original database. The SPOLD format for life cycle inventory data has found wide acceptance and can be found in many databases and software.

Standardization has also given LCA a major push for wider acceptance. The need for standardization in environmental reporting became clear, in the end of the 1980s, when environmental reports on similar products often contained conflicting results because they were based on different methods, data and terminology. Starting in 1990, the Society of Environmental Toxicology and Chemistry (SETAC) took the lead in LCA development. Their efforts resulted in the first international formulation of a Code of Practice for LCA (1993) and it represented a fundamental step for the following standardization carried out by the International Organization for Standardization (ISO) Technical Committee. Since then ISO took over the leadership in standardization and the first international standards on LCA were developed: (i) ISO 14040 - Principles and framework (1997), (ii) ISO 14041 – Goal and Scope (1998), (iii) ISO 14042 – Life Cycle Impact Assessment (2000) and (iv) ISO14043 – Interpretation (2000). In 2006 these standards were replaced by updated versions: ISO 14040 – Principles and framework (2006) and ISO 14044 – Requirements and guidelines (2006), the latter substituting the 14041, 14042 and 14043 standards.

Over the last years the European Commission has been promoting the use of life cycle environmental approaches in their strategies for a Sustainable Development. In the EC’s communication on Integrated Product Policy (COM(2003)302) it was concluded that Life Cycle Assessments provide the best framework for assessing the potential environmental impacts of products currently available. This documented underlined the need for more consistent data and consensus on LCA methodologies. To address these problems the EC launched in 2005 the project “European Platform of Life Cycle Assessment” (http://lca.jrc.ec.europa.eu/). This project is a joint project between the European Commission's Environment Directorate-General Environment and the Commission’s Directorate-General Joint Research Centre (JRC-IES).

Today, knowledge on how to carry out an LCA is improving rapidly. The value of the technique is being increasingly recognized and it is being used for strategic decision making in the framework of sustainability by the industry and the public sector. LCA is also used to improve the competitiveness of the industry and industries’ products and in communication with governmental bodies. Information from LCA can also support public policy making in eco-design criteria setting, in green public procurement and in environmental product declarations (EPDs).
3 FRAMEWORK OF LCA

3.1 General foundations of LCA

According to SETAC, Life Cycle Assessment is an objective process to evaluate the environmental burdens associated with a product process or activity by identifying energy and materials used and wastes released to the environment, and to evaluate and implement opportunities to affect environmental improvements. In this context, environmental impacts, including relevant safety, health, and social factors are quantified and summed up across the product or service life cycle.

A LCA identifies and quantifies material usage, energy requirements, solid wastes, and atmospheric and waterborne emissions throughout the product life cycle (i.e. cradle-to-grave).

The International Standards ISO 14040 (2006) and 14044 (2006) specify the general framework, principles and requirements for conducting and reporting life cycle assessment studies. Regarding these standards, life cycle assessment shall include definition of goal and scope, inventory analysis, impact assessment, and interpretation of results. The various phases are interrelated.

3.1.1 Definition of goal and scope

The goal of an LCA Study shall clearly state the intended application, the reasons for carrying out the study and the intended audience, i.e. to whom the results of the study are intended to be communicated.

In the scope of an LCA Study the main issues to be considered and clearly described are the functional unit, and the system boundaries.

3.1.1.1 Function and functional unit

The scope of an LCA Study shall clearly specify the functions of the system being studied. A functional unit is a measure of the performance of the functional outputs of the product system.

The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of LCA results. Comparability of LCA results is particularly critical when different systems are being assessed to ensure that such comparisons are made on a common basis.

3.1.1.2 System boundaries

The system boundaries determine which unit process shall be included within the LCA.

Several factors determine the system boundaries, including the intended application of the study, the assumptions made, cut-off criteria, data and cost constraints, and the intended audience.

The selection of inputs and outputs, the level of aggregation within a data category, and the modeling of the system should be modeled in such a manner that inputs and outputs at its boundaries are elementary flows.

3.1.2 Life cycle inventory analysis

Inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. These inputs and outputs may include the use of resources and releases to air, water and land associated with the system.

The qualitative and quantitative data for inclusion in the inventory shall be collected for each unit process that is included within the system boundaries.

Data collection can be a resource-intensive process. Practical constraints on data collection should be considered in the scope and documented in the study report.
3.1.3 Life cycle impact assessment

The impact assessment phase of LCA is aimed at evaluating the significance of potential environmental impacts using the results of the life cycle inventory analysis. In general, this process involves associating inventory data with specific environmental impacts, and is made of two parts (i) mandatory elements, such as classification and normalization; and (ii) optional elements, such as normalization, ranking, grouping and weighting.

The classification implies a previous selection of appropriate impact categories, according to the goal of the study, and the assignment of LCI results to the chosen impact categories. Characterization factors are then used representing the relative contribution of an LCI result to the impact category indicator result.

Normalization is usually needed to show to what extend an impact category has a significant contribution to the overall environmental impact. In the weighting step the normalized indicator results for each impact category are assigned numerical factors according to their relative importance. Weighting is based on value-choices rather than natural sciences, thus the ISO standard 14044 distinguishes between internal and external applications, and if results are intended to be compared and presented to the public, than weighting should not be used. Three weighting methods can be used in LCA (Finnveden, 1999) (i) methods based on monetary values; (ii) methods based on (government) standards or targets; and (iii) methods based on the judgment of an authoritative panel.

Grouping is an optional step of life cycle assessment in which impact categories are aggregated into one or more sets. According to ISO standard 14042, two possible procedures can be used: sorting of the category indicators on a nominal basis and ranking of the category indicators on an ordinal scale.

3.1.4 Life cycle interpretation

Interpretation is the phase of LCA in which the findings from the inventory analysis and the impact assessment are combined together. The main aim of this stage is to formulate the conclusions that can be drawn from the results of the LCA. In addition, the results of previous stages of LCA and the choices made during the entire process should be analyzed, namely the assumptions, the models, the parameters and data used in the LCA should be consistent with the Goal and Scope of the study.

4 LCIA METHODOLOGIES

4.1 Introduction

Life Cycle Impact Assessment (LCIA) methods aim to connect life cycle inventory results to category indicators and to category endpoints. According to ISO 14042, category indicators may be chosen anywhere along the environmental mechanism between intervention and endpoint. LCIA methods are usually grouped into two main types of approaches (i) problem-oriented methods, determining environmental impact category indicators (e.g. global warming potential) and (ii) damage-oriented methods aiming to determine environmental damage indicators or “endpoints” at the level of the ultimate societal concern (e.g. damage to human health). The first approach is also called mid-point methods while the latter is called end-point methods.

The classical, problem-oriented methodology developed by SETAC (1993) comprises for each category indicator, a characterization model and characterization factors derived from the model. In this method impact categories are linear functions, i.e. characterization factors are independent of the magnitude of the environmental intervention, as given by expression (1):

\[
impact_{\text{cat}} = \sum_i m_i \times \text{charact}_{\text{factor}}_{\text{cat},i}
\]
where, $m_i$ is the mass of the inventory flow $i$ and $\text{charact\_factor}_{\text{cat}, i}$ is the characterization factor of inventory flow $i$ for the impact category.

In the problem-oriented approach a list of impact categories needs to be defined. A default list of impact categories may be given by (LCA, 2001) (i) depletion of abiotic resources, (ii) impacts of land use, (iii) climate change, (iv) stratospheric ozone depletion, (v) human toxicity, (vi) ecotoxicity, (vii) photo-oxidant formation, (viii) acidification, (ix) eutrophication. Other categories can be included depending on the goal and scope of the LCA. A problem-oriented approach is mass oriented, emissions are taken into consideration independently of the site or the time of release. Therefore potential environmental impacts are evaluated instead of “real” impacts (Krewitt et al., 1998). Another drawback of this method is the unclear environmental importance of the impacts, making the subsequent weighting step difficult. A review of the most representatives mid-point approaches is presented in paragraph 4.2.

In a damage-oriented approach, interventions are assessed according to their modeled potential damage to the environment. The damage categories may be defined according to several grouping criteria: (i) biotic (living organisms in nature), abiotic (non-living elements of nature), human population and also man-made environment (Jolliet et al., 2003); or (ii) human health, natural environment, natural resources and man-made environment. In a final step these damage indicators may be aggregated to a single (eco) index. In either case the resulting number of damage indicators is less than the number of impact categories, which makes the weighting step easier. A review of this kind of approaches is given in paragraph 4.3.

Damage indicators may be defined by impact pathways. An impact pathway (EC, 1995), see Figure 1, consists of linked environmental processes expressing the casual chain of relationships from the pollutant emission through transport and chemical conversion in the atmosphere to the impacts on various receptors, such as human beings, ecosystems, building materials, etc. According to Krewitt et al. (1998) a detailed impact pathway approach allows to quantify the “actual” effect resulting from the exposure to a burden at a specific place and time, rather than estimating a “potential” impact.

![Figure 1. General Impact pathway](image)

The impact pathway approach may also be used for environmental monetary valuation, transforming the welfare losses resulting from impacts into monetary values. In an EU project on External Costs of Energy (ExternE) (EC, 1995) an impact pathway analysis was developed to support the quantification and valuation of environmental impacts resulting from electricity generation technologies.

Because these methods were initially developed with the aim of reducing the number of categories to be weighted they are also referred to as top-down approaches. On the opposite problem-oriented approaches are also called bottom-up approaches. However, a drawback of a top-
down approach is that the definition of impact categories is not a free choice. Both types of approaches are represented in Figure 2.

In regard of Figure 2, the arrows linking inventory flows to environmental impacts (mid-point) are subjected to several kinds of uncertainties due to current limits of scientific knowledge. The level of uncertainties tends to rise towards the end-point categories as current available information regarding the impact pathways to the damage level is even more uncertain or with lack of agreement. Lenzen (2006) made a quantitative analysis regarding the implications of uncertainty using a mid-point or an end-point approach towards a decision making process. He concluded that if endpoint information is too uncertain to allow for a reasonable confidence decision, then it is preferred to make the assessment in midpoints terms taking into consideration stakeholders’ subjective judgments.

As a result of a joint project between the United Nations Environment Programme (UNEP) and SETAC, a LCIA approach was proposed (Jolliet et al., 2004) combining the two types of methods described above. This LCIA midpoint-damage approach aims to become a widely acceptable LCA framework providing a common and consistent basis for further development of mutually consistent impact assessment methods. This approach offers the practitioner the choice to use either midpoint or damage indicators, depending on modeling uncertainty or an increase in results interpretability. Paragraph 4.3 reviews a current mid-end point approach.

In the following the main currently available mid and end point approaches are briefly described. A more general description can be found in the webpage of the UNEP/SETAC Life Cycle Initiative (http://www.lci-network.de/cms/content/LCIAcorner).

4.2 Mid-point approaches

4.2.1 EDIP97

EDIP97 is a midpoint approach developed in 1997 by a joint effort from the Technical University of Denmark, the Danish Environmental Protection Agency and several Danish industrial companies. The method covers most of the emission-related impacts, resource use and working environment impacts (Wenzel et al., 1997, Haushchild and Wenzel, 1998). It also includes normalization factors based on person equivalents and weighting factors based on political reduc-
tion targets for environmental impacts and working environment impacts, and supply horizon for resources.

4.2.2 CML 2001 - Dutch Handbook on LCA

The Dutch Handbook on LCA (Guinée et al. 2001), published in 2001 by the Center of Environmental Science of Leiden University (The Netherlands), describes the procedure to be applied for conducting a LCA project according to the ISO standards. The method follows a midpoint approach and for most impact categories a baseline and a number of alternative characterization methods is recommended. In this guide a comprehensive list of characterization factor and normalization factors are supplied.

4.2.3 TRACI (The Tool for the Reduction and Assessment of Chemical and other environmental Impacts)

TRACI (Bare et al. 2003) is an impact assessment methodology developed by the U.S. Environmental Protection Agency that facilitates the characterization of environmental stressors that have potential effects, including ozone depletion, global warming, acidification, eutrophication, tropospheric ozone (smog) formation, ecotoxicity, human health criteria-related effects, human health cancer effects, human health noncancer effects, and fossil fuel depletion. The methodologies underlying TRACI reflect state-of-the-art developments and best-available practice for life-cycle impact assessment (LCIA) in the United States.

4.2.4 Comparison between mid-point approaches

The main mid-point environmental categories and other characteristics of the reviewed approaches are represented in Table 1.

<table>
<thead>
<tr>
<th>MID-POINT CATEGORIES</th>
<th>LCIA METHODOLOGY</th>
<th>EDIP97</th>
<th>Dutch LCA Handbook</th>
<th>TRACI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming</td>
<td>CO₂ eq./kg emission</td>
<td>CO₂ eq./kg emission</td>
<td>CO₂ eq./kg emission</td>
<td></td>
</tr>
<tr>
<td>Stratospheric ozone depletion</td>
<td>CFC-11 eq./kg emission</td>
<td>CFC-11 eq./kg emission</td>
<td>CFC-11 eq./kg emission</td>
<td></td>
</tr>
<tr>
<td>Human health/ Human toxicity</td>
<td>Via air</td>
<td>m3 air/g emission</td>
<td>Cancer</td>
<td>Benzene eq./kg emission</td>
</tr>
<tr>
<td></td>
<td>Via water</td>
<td>m3 water/g em.</td>
<td>Noncancer</td>
<td>Toluene eq./kg emission</td>
</tr>
<tr>
<td></td>
<td>Via soil</td>
<td>m3 soil/g emis.</td>
<td>Criteria pollutants</td>
<td>DALYS/kg emission</td>
</tr>
<tr>
<td>Ionising radiation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photo oxidant formation</td>
<td>Ethylene eq./kg emission</td>
<td>kg ethylene eq./kg emission; kg formed ozone/kg emission</td>
<td>NOₓ eq./kg emission</td>
<td></td>
</tr>
<tr>
<td>Acidification</td>
<td>SO₂ eq./kg emission</td>
<td>SO₂ eq./kg emission</td>
<td>H⁺ moles eq./kg emission</td>
<td></td>
</tr>
<tr>
<td>Eutrophication</td>
<td>Combined potential</td>
<td>NO₃⁻ eq./kg emi.</td>
<td>kg PO₄³⁻ eq./kg emission; kg NO₃ eq./kg emission (average Europe)</td>
<td>N eq./kg emission</td>
</tr>
<tr>
<td></td>
<td>Separate N potential</td>
<td>N eq./kg emi.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Separate P potential</td>
<td>P eq./kg emi.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chronic in water

Acute, chronic, in water

Ecotoxicity

<table>
<thead>
<tr>
<th>Component</th>
<th>Chronic in water</th>
<th>Acute, chronic, in water</th>
<th>kg 1,4 DCB eq. /kg emission (emitted to fresh water, sea water or industrial soil)</th>
<th>2,4-D eq. / kg emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource depletion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-renewable</td>
<td>kg</td>
<td>Land</td>
<td>Fossil fuel</td>
<td>Surplus MJ/kg</td>
</tr>
<tr>
<td>Renewable</td>
<td>m³</td>
<td>Abiotic resources</td>
<td>Kg antimony eq.</td>
<td>Land</td>
</tr>
<tr>
<td>Waste/land filling</td>
<td>kg waste</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Malodours air</td>
<td></td>
<td>m³ air</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work environment</td>
<td>h</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Normalization

<table>
<thead>
<tr>
<th></th>
<th>Yes, at the European level</th>
<th>Yes, at the Nether-lands level, Western Europe level or World level</th>
<th>Yes, at the U.S. level</th>
</tr>
</thead>
</table>

Weighting

|                | Yes, based on scientific, political and normative considerations | No | No |

4.3 End point approaches

4.3.1 EDIP2003

EDIP2003 is an update version of EDIP 97 methodology (Hauschild and Potting, 2004) which follows an end-point approach for most impact categories. This new version of the methodology supports spatially differentiated characterization modeling which covers a larger part of the environmental mechanism than previous methodology. This part of the general method development and consensus programme covers investigations of the possibilities for inclusion of exposure in the life cycle impact assessment of non-global impact categories (photochemical ozone formation, acidification, nutrient enrichment, ecotoxicity, human toxicity, noise). This new approach was also developed with the aim of making easier and operational the introduction of working environment in LCA. For the assessment of the working environment the following impact categories were included: fatal accidents, total number of accidents, CNS function disorder, hearing damages, cancer, musculo-skeletal disorders, airway diseases (allergic), airway diseases (non-allergic), skin diseases and psycho-social diseases. Normalization and weighting procedures are done in a similar way as previous version.

4.3.2 Eco-Indicator 99

Eco-indicator 99 (Goedkoop et al. 1999) is an end-point approach developed in The Netherlands by Pré Consultants with the aim of simplifying the weighting step. Thus only three environmental damages categories (endpoints) were chosen: human health, ecosystem quality and resources. Damage models were developed to establish the links between inventory data and damage categories. Thus important concepts were developed and introduced in the methodology such as the DALY approach, the introduction of the PAF and PDF approach, as well as the surplus energy approach. Normalization is made using European normalization values. The management of subjective choices and weighting is made by the use of cultural perspectives leading to different versions, each with a different set of choices.

A limiting assumption is that all emissions and land uses are occurring in Europe and subsequent damages occur in Europe, apart from global impacts.
4.3.3 **Environmental Priority Strategies (EPS) 2000**

The Environmental Priority Strategies in Product Development System, the EPS System, was developed by the Swedish Environmental Research Institute, taking an economic approach to assess environmental impacts (Steen, 1999a, 1999b). In this approach category indicators are chosen to represent actual environmental impacts on any or several of five safeguard subjects: human health, ecosystem production capacity, biodiversity, abiotic resources and recreational and cultural values. The characterization factor is the sum of a number of pathway-specific characterization factors describing the average change in category indicator units per unit of an emission. Characterization factors are given for emissions defined by their, location, size and temporal occurrence. Weighting factors for the category indicators are determined according to people’s willingness to pay to avoid one category indicator unit of change in the safeguard subjects. The final result of the EPS system is a single number summarizing all environmental impacts.

4.3.4 **Swiss Ecoscarcity Method (Eco-Points)**

The method of environmental scarcity – sometimes called Swiss Eco-Points method – allows a comparative weighting and aggregation of various environmental interventions by use of so-called eco-factors (Brand et al., 1998). The method was first published in 1990 by the Swiss Federal Office of Environment, Forests, and Landscape, but current updated version is from 1997. The method supplies characterization factors (eco-factors) for different emissions into air, water and top-soil/groundwater as well as for the use of energy resources. These factors are based on the annual actual flows (current flows) and on the annual flow considered as critical (critical flows) in a defined area (country or region). Eco-Points are thus calculated for a product, using the Eco-Factor determined for each inventory flow The Eco-Points for all inventory flows are added together to give one single, final measure of impact.

4.3.5 **LIME**

LIME is a damage assessment approach developed by LCA National Project of Japan. LIME can be used to evaluate the damage on endpoints such as human health and ecological risk caused by 11 impact categories, including global warming, human toxicity and resource consumption. In the framework of LIME (Itsubo et al., 2004, Hayashi et al. 2006), damage functions are defined as the quantitative relationships between an inventory of causative substances or activities and potential effects on each category endpoint. The approach includes characterization, damage assessment and weighting. A damage factor (DF) of certain impact categories is defined as the sum of damage function for individual safeguard subjects, i.e. human health, social assets, biodiversity, and primary productivity. The results of the weighing step can be expressed as monetary values.

4.3.6 **Comparison between end-point approaches**

The main end-point environmental damage categories and other characteristics of the reviewed approaches are represented in Table 2.

Table 2 – Main characteristics of end-point approaches

<table>
<thead>
<tr>
<th>LCIA METHODOLOGY</th>
<th>Eco-indicator 99</th>
<th>EPS 2000</th>
<th>LIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human health</td>
<td>DALYs</td>
<td>Person yr</td>
<td>DALYs</td>
</tr>
<tr>
<td>Natural environment</td>
<td>PDF/m2/yr</td>
<td>kg</td>
<td>EINES (Expected Increase in Number of Extinct Species)</td>
</tr>
<tr>
<td>Natural resources</td>
<td>MJ surplus</td>
<td>kg</td>
<td>NPP (Net Primary Productivity) (kg)</td>
</tr>
</tbody>
</table>
4.4 Mid-End Point approaches

4.4.1 IMPACT 2002+

The IMPACT 2002+ life cycle impact assessment methodology developed at the Swiss Federal Institute of Technology, in Lausanne (EPFL) proposes a feasible implementation of a combined midpoint/damage approach, linking all types of life cycle inventory results (elementary flows and other interventions) via fourteen midpoint categories to four damage categories (Jolliet et al., 2003b). For IMPACT 2002+ new concepts and methods have been developed, especially for the comparative assessment of human toxicity and eco-toxicity. Human Damage Factors are calculated for carcinogens and non-carcinogens, employing intake fractions, best estimates of dose-response slope factors, as well as severities. All midpoint scores are expressed in units of a reference substance and related to the four damage categories human health, ecosystem quality, climate change, and resources. Normalization can be performed either at midpoint or at damage level.

5 ECONOMIC INPUT/OUTPUT LCA

One of the reasons for current LCA being criticized regards the difficulty of knowing where to draw the boundary around the analysis. Practical use of LCA involves drawing a boundary that limits consideration to a few producers of interest in the chain from raw materials to consumers. Researchers at Carnegie Mellon have found that limiting the analysis in this way may lead to consideration of only a fraction of the total environmental discharges associated with the product or process. Therefore, they used models of industrial activity (input-output tables) to develop an economy-wide LCA technique by linking the economic input-output tables with environmental databases (conventional pollutants, TRI, energy use, ore use, fertilizer use, global warming potential, and ozone depleting potential, etc.). The method is called Economic Input-Output Life Cycle Assessment, or EIO-LCA (Hendrickson et al., 1998).

The input-output analysis technique that forms the basis of the model was developed by Leontief (1986). Leontief assumed that the complicated interactions within an economy can be approximated by proportionality relationships.

Input-output analysis has been used extensively for planning in the USA and throughout the world. Many countries collect and publish input-output tables for their economies. The tables are used to calculate the resources and supply chain requirements required to support an increase in the demand for output of specific sectors.

The main advantages of EIO- LCA tool over other LCA techniques is that it can be used to examine the total direct and indirect economy-wide effects (effects of suppliers) on emissions and energy consumption resulting from changes in production; and it uses the entire country economy as the boundary for the analysis.

The approach has also limitations. The amount of desegregation in economic sectors may be insufficient for the desired level of analysis. EIO-LCA models include sectors of the economy rather than specific processes. Detailed analysis of the environmental impacts of the activities of
the individual members of the supply chain will require more traditional LCA techniques. The use and disposal phases of certain products may be too difficult to analyze with EIO-LCA.

6 UNCERTAINTIES AND VARIABILITIES IN LCA

There are major uncertainties about the extent to which outcomes of LCAs reflect real-life environmental impacts. The implementation of the uncertainties (related to lack of knowledge) and variabilities (related to the quality of data) in LCAs is needed in order to make the results of such analysis much more precise and reliable.

There are many ways of classifying uncertainty; according to Huijbregts (2001), the following types of uncertainty and variability may be distinguished:

1) parameter uncertainty – imprecise measurements, incomplete or outdated measurements, and general lack of data in the inventory analysis and in the models;
2) model uncertainty – spatial and temporal characteristics are forgotten in the inventory analysis, simplified and linear (instead of non-linear) models;
3) uncertainty due to choices – choice of the functional unit, allocation procedure, characterisation methods, weighting, etc;
4) spatial variability – variability across locations, such as physico-chemical and ecological properties of the environment, background concentrations of chemicals and human population density, is generally not taken into account;
5) temporal variability – differences in emissions over the time
6) variability between objects/sources – variability caused by different inputs and emissions of comparable processes in a product system, due to the use of different technologies in factories producing the same material, for instance.

Many kinds of approaches aimed to reduce uncertainty in the analysis. The statistical approach (Monte Carlo analysis or fuzzy set theory) aims to explicitly incorporate uncertainties in the analysis. An intensive review of approaches to deal with uncertainties in LCA can be found in Reinout and Huijbregts (2004).

7 LCA IN THE CONSTRUCTION SECTOR

Construction is responsible for a major proportion of environmental impacts in the industrial sector. During the last years there has been an increasing interest in the environmental assessment of the built environment. LCA methods described in the previous paragraphs can be directly applied to the building sector. However, due to its characteristics there are additional problems in the application of standard LCA methods to buildings and other constructions. The main causes may be listed as (IEA, 2001): (i) the life expectancy of buildings is long and unknown and therefore subjected to a high level of uncertainties, (ii) buildings are site dependent and many of the impacts are local, (iii) building products are usually made of composite materials which implies more data to be collected and associated manufacturing processes, (iv) the energy consumption in the use phase of a building is very much dependent on the behavior of the users and of the services, (v) a building is highly multi-functional, which makes it difficult to choose an appropriate functional unit, (vi) buildings are closely integrated with other elements in the building environment, particularly urban infrastructure like roads, pipes, green spaces and treatment facilities, and it can be highly misleading to conduct LCA on a building in isolation. Nevertheless, several LCA methodologies and tools have been developed over the last years focusing on the environmental assessment of the built environment and they are described in the following.

Currently there are two major classes of assessment tools for the built environment (Reijnders and van Roekel, 1999): (i) qualitative tools based on scores and criteria and (ii) quantitative tools using a quantitative analysis of inputs and outputs using a life cycle approach. Within the first group of tools there are systems such as LEED (in the US), BREAM (in the UK), GBTool (International Initiative for a Sustainable Built Environment (iISBE)), etc. These methods, also known as rating systems, are usually based on auditing of buildings and on the assignment of
scores to pre-defined parameters. Although mainly qualitative some parameters may also be quantitative and even use LCA (mainly in the quantification of material credits). Usually these systems are used to obtain green building certifications and eco-labels. This kind of tools is outside the scope of this paper, thus in the following the focus will be on the second group of tools, which are based on LCA.

Regarding the second type of methods another distinction is made between LCA tools developed with aim of evaluating building materials and components (e.g. BEES (Lippiatt 2002)) and LCA approaches for evaluating the building as a whole (e.g. Athena (Trusty WB, 1997), Envest (Howard et al., 1999), EcoQuantum (Kortman et al., 1998)). The latter tools are usually more complex as the overall building performance depends on the interactions between individual components and sub-systems as well as interactions with the occupants and the natural environment. The selection of an appropriate tool depends on the specific environmental objectives of the project.

The precision and the relevance of LCA tools as a design aid was analyzed in a project developed in the frame of the European thematic network PRESCO (Practical Recommendations for Sustainable Construction) (Kellenberger, 2005). In this project, several LCA tools were compared, based in case studies, with the global aim of the harmonization of LCA based assessment tools for buildings. Other comparative analysis regarding tools for environmental assessment of the built environment may be found in Jönsson (2000) and Forsberg & von Malmberg (2001).

8 FURTHER DEVELOPMENTS IN LCA

8.1 Improving the environmental impact assessment

One of the main limitations in current LCA methodologies is due to the lack of spatial and temporal details in the analysis. Regarding spatial differentiation in LCA, although a lot of work has been done (Potting et al. 2006, Bellekom et al. 2006) further research is needed in order to make it feasible for practical applications in LCA.

Other improvements are foreseen in the development of more accurate non-linear models for impact characterization and in the consideration of new impacts in LCA (e.g. noise).

8.2 Extending the scope of life cycle analysis

In the pursuit of the aims of the sustainable development other aspects, apart from the environment, should be considered. To fulfill the needs of this holistic concept the social and the economic aspects need also to be considered in a life cycle approach. The importance of both subjects has been acknowledged by SETAC and a working group had been created which is dedicated to Life Cycle Costing and its integration and compatibilization with LCA Information on the activities of the working group can be found in Rebitzer and Seuring (2003).

Life cycle cost analysis is not a new methodology, in fact it has been using as a stand-alone approach for a long time and standards for LCC will be available soon (Klopffer, 2006). An introduction to LCC analysis and application can be found in Fuller and Peterson (1995). LCC methodology as a stand-alone tool can be found in several programs, for example BridgeLCC 2.0 (2003), a software for the preliminary design of bridges or BLCC 5.0 (1995), a software for the evaluation of long-term costs and savings of energy and water conservation and renewable energy projects. Currently there are also available LCA tools integrating LCC: BEES (www.bfrl.nist.gov/oae/software/bees.html), Envest (http://www.bre.co.uk/service.jsp?id=52), Legep (Ecoinvent http://www.legep.de), EcoEffect (www.ecoeffect.tk), etc.

Societal assessment is commonly referred to as the third pillar of measuring sustainable development and the assessment of life cycle social aspects is a critical future issue for life cycle approaches in general. However social impacts are not easily quantifiable and, contrary to LCC, social LCA is a more recent topic and therefore further research is needed. Nevertheless, several papers have been published over the last years focusing on the problem. O’Brien et al. (1996)
identified social and political factors that contribute to environmental issues and emphasized the connection between them. In order to enhance LCA as a tool for decision-making a framework for Social Life Cycle Impact Assessment (SLCA) is being developed by Dreyer et al., (2006). This new framework is intended to support informed business decisions in a company which aims at minimizing harmful impacts on peoples’ lives from the activities in the company’s product chains. Hunkeler (2006) suggests a preliminary methodology for mid-point based societal life cycle assessment for comparative product assertions and applies it to a case study comparing two detergents in terms of labour hours. Input-output modeling may also be used to characterize the effects of changes in economic demands on social indicators (Hutchins and Sutherland, 2006) and the methodology is applied to a case study regarding a change in a supplier in the US and the corresponding effect in a social indicator - the infant mortality.

8.3 Integration with other tools (TOOlBOX)

Another strategy to improve and to overcome some limitations in current LCA methodology proposed by some authors (Udo de Haes et al., 2004) is to use other types of approaches in combination with LCA – use of a toolbox. Among other advantages, the use of a toolbox allows the possibility to consider spatial and temporal aspects and the integration of other types of impacts into the combined analysis.

When information regarding local impacts is important the use of LCA together with environmental risk assessment can be more practical than downscaling LCA to the local level (Barnthouse et al., 1997). Several methods to integrate risk assessment in LCA can be found in Mathews et al. (2002).

The use of a LCC together with LCA to integrate the economical perspective in a life cycle assessment was already discussed in the previous paragraph. These two tools share a similar framework providing many synergies and thus enhancing the application of life cycle approaches for decision making. Another proposal to integrate economic and social perspectives into LCA is discussed by Weidema (2006) regarding the combined analysis of LCA with a cost-benefit analysis.

9 FINAL REMARKS

Over the last decades LCA has been gaining increasing recognition and acceptance as an environmental assessment tool aiding in decision making processes, however a better understanding of its applicability deserves more research.

To achieve a higher responsibility in the framework of sustainable development the integration with other equally important dimensions (social, economic) is needed in order to enhance wide-scale implementation.

REFERENCES


Bruntland, G (ed). 1987. Our Common Future: The World Commission on Environment and Develop-


Kellenberger D. 2005. Comparison and benchmarking of LCA-based building related environmental assessment and design tools. EMPA Dubendorf, Technology and Society Laboratory, LCA group.

Klopfier, W. 2006. The role of SETAC in the development of LCA. In: Int J LCA 11 (Special Issue 1) 116-122.


Voluntary Building Environmental Assessment Systems and LCA

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ABSTRACT: Voluntary Building Environmental Assessment Systems (BEAS) are increasing. Nevertheless the average of LCA criteria in these systems are one criteria with LCA requirements and that their weight inside each system varies from 0% and 6.9%, being the average for all the considered systems of 0.03%. BEAS could improve, namely walking in the path towards sustainability, with special focus at performance orientations, enlarging their scope, considering in their assessments the entire life cycle. A useful way to get these is to increase LCA approach into BEAS in a multi-approach witch could also be seen as a way to promote more practical LCA solutions.

1 BUILDING ENVIRONMENTAL ASSESSMENT SYSTEMS

Building Environmental Assessment Systems (BEAS), such as BREEAM\(^1\), LEED and similar, where firstly developed with the role of establishing an objective, articulated and structured base for stakeholders in the education, health and construction sectors, to assess and communicate the enhanced environmental performance measurements of their products, goods, materials and buildings, regarding the evaluation of resource use, ecological loadings, indoor environmental quality and other aspects. It also functioned, although not being its main goal, as a platform to discuss and debate buildings environmental performance, bringing the subject to the front line. As stated by Cole (Cole et al., 2005), environmental assessment methods had a major contribution “to furthering the promotion of higher environmental expectations, and have directly and indirectly influenced the performance of buildings”.

Initially, with the BREEAM development, the first with market presence, these building environmental assessment methods (or systems) had the main purpose of evaluating “green” performance (Cole, 1999 in Cole, 2005). According to Cole (2005) in order for a system to be considered a fully environmental building assessment, it had to comply with certain characteristics:

1. Technically framed and emphasize the assessment of resource use, ecological loadings, health and comfort in individual buildings;
2. Primarily concerned with mitigation: reducing stresses on natural systems by improving the environmental performance of buildings;
3. Assess performance in relation to explicitly or implicitly declared benchmarks and, as such, measure the extent of improvement, rather than evaluate the proximity to a defined, desired goal;
4. Assess design intentions and potential as determined through prediction rather than actual real world performance;
5. Structure performance scoring as a simple additive process and use explicitly or implicitly declared weightings to denote priority;

\(^1\)BREEAM – Building Research Establishment Environmental Assessment Method; LEED – Leadership in Energy and Environmental Design
Offer a performance summary, certificate or label, that can be part of leasing and promotional documents;

Operate primarily through the use of ‘hard’ copies of performance requirements in the form of published manuals and ‘hard’ copies of submittal requirements as voluntary, market place mechanisms, by which owners striving for improved performance would have a credible and objective basis for communicating their efforts.

Presently, although the building environmental assessment methods are concentrating most of the attentions from stakeholders, there are other ways to evaluate and assess environmental performance. In this area of expertise we highlight the developments made by the research community in the Life Cycle Assessment (LCA) area.

With the growing awareness and diversification of all the methods and tools that currently exist, some confusion has emerged and the interchangeably of the designation for methods and tools is increasing, when they are so different. Nowadays two main separate notions have emerged (even though they are not mutually excluded): one developed by Cole and the other by Trusty. These are two different ways on how to catalogue the existing techniques.

Cole (2005) separates them into two categories: (1) Assessment Tools and (2) Assessment Methods. For him an assessment tool “is a technique that predicts, calculates or estimates one or more environmental performance characteristics of a product or building”. In this category are included LCA tools, such as Athena or Envest. On the other hand an assessment method “is a technique that has assessment as one of its core functions but which may be accompanied by third-part verification before issuing a performance rating or label, includes reference to or use of a number of tools, and may offer supporting educational programmes for design professionals”.

Trusty (2004) defends a slightly different approach on this subject, pointing out that there are three levels of tools, as follows:

- Level 1 tools – the ones that “focus on the individual product or simple assembly level (e.g., floor coverings or window assemblies) and are used to make comparisons in terms of environmental and/or economic criteria”. The author stated examples may be BEES and GreenSpec Directory, especially relevant for architects;
- Level 2 tools – these ones specially “focus on the whole building, or complete assemblies, providing decision support in specific areas of concern such as life cycle costs, operating energy, or life cycle environmental effects. They are data-oriented and objective, and apply from the conceptual through detailed design stages. Operating energy simulators and daylighting analysis tools fit in this category, along with life cycle costing”. An example is Athena;
- Level 3 tools – the systems or frameworks that perform whole building assessment encompassing a broader range of environmental, economical and social concerns or issues considered relevant to sustainability. “They use a mix of objective and subjective inputs, leaning on Level 2 tools for much of the objective data — energy simulation results, for example. All use subjective scoring or weighting systems to distill the information and provide overall measures, and all can be used to inform or guide the design process”. Currently BREEAM, LEED, LiderA or GBTool, for example, stand in this category.

Despite all the methods, tools or techniques that may be used to assess environmental performance there is, as mentioned by Cole (2005), an undergoing “shift in emphasis toward sustainability” which is already starting to “transform further the structural and operational requirements of such methods”. This change is crucial, in order to enforce methods and tools for the next level towards sustainability. Apparently the assessment methods are the best positioned for affecting change. However, this strength may also be a weakness, because it is sourced on the fact that presently assessment methods are the sole focus of the current debate on sustainability and environmental performance in buildings, which could underpin the debate and does not provide the needed changes (Cole, 2005).

So, the main purpose is to assess the present role and limitations of the existing environmental building assessment systems and tools, expose their emerging roles, and equally examine if LCA and environmental assessment methods are rival or complementary in this pursuit of
change of environmental assessment performance in the construction, or if there are other dynamics involved.

At a current stage, Cole (2005) identifies two main areas of investigation, regarding the building environmental assessment area: (1) seeks to develop greater refinement and rigour in performance indicators, weighting protocols and, where appropriate, the potential incorporation of LCA approaches to refine the constituent measures”; (2). has provided numerous side-by-side comparisons of the more notable methods and tools (e.g. BREEAM, LEED and GBTool) to illustrate areas of convergence and distinction, typically as a starting point for generating applicable methods in other regions or countries seeking to develop new assessment schemes.

Regardless the means used, the end is, without any doubt, to minimize the flows for and from nature, throughout the buildings whole life-cycle, either they are solid, liquid or gaseous or affect land, water, air and living creatures, and we must never loose this from our sight.

2 PRESENT LCA AND BUILDING ENVIRONMENTAL ASSESSMENT

As previously presented the role and needs of the building environmental assessment systems are changing, but exactly what is happening and what are the current drivers? Raymond Cole (2005) believes that it’s not a single issue but an array of subjects:

(1) Assessment methods have moved beyond voluntary market place mechanisms. Performance thresholds in the assessment methods (e.g. LEED Silver) are increasingly being specified by public agencies and other organizations as performance requirements, and are being considered as potential incentives for development approval, bonus density and other concessions;
(2) Building environmental assessment is increasingly being recognized by banking, financial and insurance companies as a basis for risk and mortgage appraisals and real estate valuations; With more widespread adoption of assessment tools, compliance with performance requirements increasingly affects associated manufacturing industries. While some industries use this as an opportunity to re-evaluate production processes, others become increasingly resistive;
(3) The range of building types seeking certification is increasing and this, in turn, is creating the need either to develop generic systems that can recognize distinctions on an as-needed basis for specific situations, or to create a suite of related methods and tools, each of which uniquely addresses a particular building type;
(4) The need to permit easy access to tools and methods, and to enable assessments to be made quickly and cheaply, is spurring the increased deployment of Web-based methods and tools (e.g. ABCplanner (Denmark) and PromisE (Finland)) or attendant software support tools (e.g. Calculator and Letter Templates within LEED (US));
(5) The aggregate effect of individual buildings has an enormous consequence for community infrastructure design and operation. This, together with the inherent limitation of analyzing individual buildings as the basis to understand ecological impacts, has generated interest in creating and linking assessment methods and tools across a variety of scales;
(6) Increased awareness of the inevitability of climate change has extended the approach from solely considering the need for mitigation, to embrace new adaptation to changing conditions and the conscious restoration of previously degraded natural systems.

Besides all this, the International Standard Organization (ISO) is defining standardized requirements for building environmental assessment methods (e.g. ISO TG59/SC17 – Sustainability in Building Construction), and so a technical standard (ISO/PDTS 21931) will provide a general framework to improve the quality and comparability of building assessment methods (Cole, 2005), that is followed by CEN TC 350.

Different opinions are emerging and it is fundamental that new approaches are considered. The two focus of debate, in order to “shift in emphasis toward sustainability”, are the use of LCA tools or the assessment methods. Considering the performed research the main reasons that lead different authors to consider the need of using LCA, instead the current assessment methods are that:
- criteria present in the assessment methods are prescriptive and solutions are oriented to, instead of assessing, performance. The system induces the use of determined solutions, the ones that are presented in the criteria and that may not be the most environmentally adequate. For ex-
ample, advise the use of 100% of recycled material may not translate itself in environmental enhancement because, for example, the energy needed for recycling may be higher than the energy needed to manufacturing other kind material with 0% recycled content, and yet that can be environmentally more acceptable (with regard of the energy example). It all depends on the materials, their extraction, manufacturing, transport or other inherent processes. Each case poses itself as isolated and must be analyzed considering its life-cycle (from cradle-to-grave). So, the focus must be on performing designs that actually result in reduced environmental loadings and impacts. (Huang et al., 2003; Watson et al., 2005; Pitcher, 2005; Bowyer et al., 2005; Trusty & Horst, 2002; Cole et al., 2005);

- the majority of systems don’t range the entire life-cycle inherent to construction (planning, design, construction, commissioning, use and maintenance, renovation, demolition, etc.) and even fewer consider the stages previous to building planning (extraction, processing, transportation, etc.), and consequently environmental assessed impacts are very narrow, when considering the whole process associated with the construction of buildings (Watson et al., 2005; Cole, 2005; Seo, 2002)

- the considered environmental impact categories are not wider enough and as a result of that numerous environmental impacts, usually are not being assessed by the systems, such as ecological toxicity, human toxicity and others (Seo, 2002; Pitcher, 2005; Lavagna, 2006).

In the opposite side, LCA stands as an alternative to the mentioned systems. It is unquestionably a very powerful tool with an outstanding ability for the evaluation of environmental impacts throughout the entire life-cycle. However some authors defend that there still are restrictions for the use and application of LCA assessment tools. Among these we highlight the following:

- LCA needs a strong and vast database and information background (an adequate and proper Life Cycle Inventory, LCI) associated with the LCA. These data have to be gathered near the industry professionals regarding products, goods, services and materials for construction and the problem is that the great majority of those producers aren’t ready to provide the needed data (Trusty & Horst, 2002; Seo, 2002);

- another striking question is the need to develop case studies of different types of conventional buildings in different regions that can serve as benchmarks. After the reference cases are developed, assessment system developers will have to determine how to score results for a specific building relative to the reference case(s) (Trusty & Horst, 2002; Seo, 2002).

But at what extent environmental assessment systems are trying to incorporate and perform changes? Are they remaining isolated from the LCA technique or are they trying to consider it in their assessments? But even more important, is this the way?

From the table 1 and 2 is possible to verify that LCA is almost absent from the building environmental assessment systems. The system that incorporates the larger amount of LCA practices and methods is GBTool, which inclusively considers Life Cycle Cost (LCC) assessment. Despite its general absence, the main concern of the few existing LCA demands, in the analyzed systems, are in the materials or resources area and criteria. The main purpose is to assess the environmental performance of the products, materials or goods used in the building and therefore include the environmental impacts of extraction, production, transport, use, recycling and final disposal. There is also present some complete LCA assessments, as in the case of LEED-EB or GBTool. The average of LCA criteria in the systems is of 1 criterion with LCA requirements and that their weight inside each system varies from 0% and 6,9%, being the average, for all the considered systems, of 0,03%.

In LiderA there is only one criterion which explicitly accepts LCA assessment (environmental low impact materials), representing 2% from the total, although the system itself is organized in order of knowing much more than other systems, because it comprises many stages in the life cycle of a building (planning, design, construction, operation, renovation and demolition).

LEED is probably the system that less uses LCA methods or practices, and so is the one that requires a more rapid intervention and update. After analyzing the used LCA methods it is possible to conclude that the most common used functional unit is 1 m² of building. Finally, only GBTool considers the sustainability aspect of economy and none of them considers explicit life cycle assessment of social aspects.
Table 1 – LCA in some Building Environmental Assessment (BEA) System (1/2)

<table>
<thead>
<tr>
<th>System</th>
<th>Range</th>
<th>Version</th>
<th>Area and Criteria</th>
<th>LCA scope</th>
<th>LCA range</th>
<th>Functional Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>BREEAM</td>
<td>Schools, Industrial fitted</td>
<td>2006</td>
<td>Materials and Waste - Hard landscaping &amp; boundary protection</td>
<td>environmental impacts of materials during their life cycle (Indicators)</td>
<td>manufacture, use, maintenance, renovation (during a 60 year period) and demolition</td>
<td>1 m² to satisfy building regulations, in particular a U value of 0.45 W/m².K</td>
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<tr>
<td></td>
<td>Industrial Speculative</td>
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<td></td>
<td>Buildings</td>
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<tr>
<td></td>
<td>Retail</td>
<td>2006</td>
<td>Energy - Building services whole life performance</td>
<td>quantitative analysis of the life cycle energy consumption and CO₂ emissions</td>
<td>At least: use, maintenance, renovation over a 60 year building life cycle</td>
<td>-</td>
</tr>
<tr>
<td>CASBEE</td>
<td>Offices, Schools, Retailers,</td>
<td>2004</td>
<td>Reliability - Water Supply &amp; Drainage</td>
<td>LCA environmental impacts</td>
<td>Manufacture, use, recycling</td>
<td>The label Eco-mark is issued</td>
</tr>
<tr>
<td></td>
<td>restaurant, halls, hospital,</td>
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<td></td>
<td>hotels, apartments and factories</td>
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<td>(Preliminary Design &amp;</td>
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<td></td>
<td>Execution Design and</td>
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<tr>
<td></td>
<td>Construction Completion Stage</td>
<td></td>
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</tr>
<tr>
<td>GBTool</td>
<td>For Total building, all</td>
<td>2005</td>
<td>Energy and Resources consumption – predicted non renewable primary energy</td>
<td>Embodied energy in materials (with LCA software)</td>
<td>Life cycle analysis</td>
<td>GJ/m² or MJ/m².year (life time span 100 years, optional)</td>
</tr>
<tr>
<td></td>
<td>sizes in office, retail and</td>
<td></td>
<td>embodied in construction materials</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>total project (design phase)</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>For Total building, all</td>
<td></td>
<td>Energy and Resources consumption - Water embodied in materials (not active)</td>
<td>net amount of potable water embodied in materials</td>
<td>processing, manufacturing or installation of major construction materials</td>
<td>L/kg or L/kg.person.year (life time span 100 years, optional)</td>
</tr>
<tr>
<td></td>
<td>sizes (design phase)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>For Total building, all</td>
<td></td>
<td>Environmental Loads - GHG emissions embodied in construction materials</td>
<td>Climate change, GHG emissions (not active)</td>
<td>extraction, fabrication and transportation of materials and components in the building.</td>
<td>GJ/m² or Kg/m².year (life time span 100 years, optional)</td>
</tr>
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<td></td>
<td>sizes in office, retail and</td>
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<td></td>
<td>For individual occupancies,</td>
<td></td>
<td>Social and Economic Aspects – Life Cycle Cost (indicator)</td>
<td>Life Cycle Cost (indicator)</td>
<td>Design, construction and operation (25 years period)</td>
<td>Capital cost USD/m², euro/m², yen/m², peso/m² or CAD/m²</td>
</tr>
<tr>
<td></td>
<td>all sizes in office and</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>retail (design, construction</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>and operation)</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

1 Considered impacts: climate change, fossil fuel depletion, ozone depletion, freight transport, human toxicity, waste disposal, water extraction, acid deposition, ecotoxicity, summer smog and minerals extraction.

2 Considered impacts: climate change, fossil fuel depletion, ozone depletion, freight transport, human toxicity, waste disposal, water extraction, acid deposition, ecotoxicity, summer smog and minerals extraction.
## Table 2 – LCA in some Building Environmental Assessment (BEA) System

<table>
<thead>
<tr>
<th>System</th>
<th>Range</th>
<th>Version</th>
<th>Area and Criteria</th>
<th>LCA scope</th>
<th>LCA range</th>
<th>Functional Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>HQE</td>
<td>Services (Qualité Environnementale du Bâtiment (QEB)) (construction or design)</td>
<td>2006</td>
<td>Integrated choice of constructive products, procedures or systems – Construction materials choice, with the purpose of diminish construction environmental impacts</td>
<td>Several LCA environmental impacts 4 of materials</td>
<td>Manufacture (raw materials extraction to product production), transport, application in construction, use, disposal</td>
<td>/m2.year (considering 100 years base for calculus)</td>
</tr>
<tr>
<td></td>
<td>EB – Existing Building</td>
<td>V2 (2005)</td>
<td>Materials and Resources - Sustainable Cleaning Products and Materials</td>
<td>Life cycle analysis 5</td>
<td>material extraction, continuing with manufacturing and use, and ending with recycling and disposal.</td>
<td>Green seal label</td>
</tr>
<tr>
<td>LiderA</td>
<td>Residential, services and tourism (planning, design, construction, operation, renovation and demolition)</td>
<td>R - V1.2 (2007) T – V1.2 (2007)</td>
<td>Resources - Certified or low environmental impact of materials</td>
<td>LCA environmental impacts of materials (software is accepted)</td>
<td>Life Cycle analysis</td>
<td>/m².year</td>
</tr>
<tr>
<td>NABERS</td>
<td>Commercial and Residential (Design and operation)</td>
<td>2001</td>
<td>Materials - Cost of building per m² of building floor area.</td>
<td>Embodied energy (indicator)</td>
<td>Considering the energy required to make and deliver to the site all the materials from which a building is constructed</td>
<td>Cost in dólares/m2 or EE (embodied energy) em GJ/m2</td>
</tr>
<tr>
<td></td>
<td>Materials - Materials types for structure, walls, floors and roofs. (for buildings under 3 years old)</td>
<td></td>
<td>Best materials choice (qualitative)</td>
<td>Extraction, production and recycling level</td>
<td></td>
<td>Qualitative assessment (best choice to worst choice)</td>
</tr>
</tbody>
</table>

4 Considered impacts: energetic resources consumption, resources, resources exaustion, water consumption, climatic change, atmospheric polution, solid waste, water polution, stratospheric ozone destruction, photochemical ozone formation and atmospheric acidification.
5 Considered impacts: Toxicity; Prohibition of Carcinogens, Mutagens, and Reproductive Toxins; Skin and Eye Irritation; Skin Sensitization; Aquatic Toxicity; Aquatic Biodegradability; Eutrophic Agents; Air Pollutants; Other Prohibited Ingredients; Combustibility; Fragrances; Animal Testing; And some packaging requirements.
During the research made was also possible to confirm that considering structure, way of assessment and scope of the present rating systems, the integration of LCA tools will have to be a gradual process, that will mainly take place in the plan and design phases, since it is in these two phases that all is defined and decided for the whole building life cycle. In order to make this gradual transition happen it was defined (Trusty et al., 2006), in LEED’s case, that the main areas of concern and short term intervention should be energy and materials and resources and that later on the process, LCA assessment should be integrated into other areas. Using this approach it is expected that the professionals who normally use LEED may have enough time to be familiarized with the requirements of LCA, accepting it gradually and without any reserves, validating its benefits. For LEED’s specific case, working groups concluded that some of LEED criteria may never be able to be assessed by LCA (for example, heat island effect).

It is also highlighted that the systems currently presented in the market, in many countries represent tools with broad acceptance and use in construction. These represent techniques that were able to create a proper space of collaboration among field professionals, of understanding and discussing the environmental impacts caused by construction activities and the need to minimize and control those impacts. In some cases these systems acquired an almost legislative dimension (as referred by Cole) that must not be neglected, being that through the integration of LCA in these methods, one may achieve a faster and better use of LCA tools when design projects and during the decision making process of stakeholders.

Regarding Cole’s (2005) vision on the re-contextualization of assessment methods, he considers that it is “increasingly necessary to cast building performance and its assessment within an overarching dictate of sustainability”. As such, the relationship between an assessment method and other complementary mechanisms assumes considerable importance.

In one of the highlights, Cole (2005) point out “an increasingly cited notion is that building environmental assessment methods would be significantly enhanced if LCA methodologies were deployed as underpinnings of relevant performance criteria. A key issue in this paper, however, is that this is simply not a matter of introducing more rigorously developed criteria. More important is the recognition and resolution of fundamentally different assessment cultures: those that are uncompromising in their search for accuracy and precision in describing and reporting results and those are shaped by the reconciliation of a number of stakeholder interests.”

“Currently none of the existing simplified building environmental assessment methods are comprehensively or consistently LCA-based, nor do they necessarily need to be given their primary role in market transformation. While some performance criteria in these methods are increasingly based on conventional LCA data, their strength lies in bringing a broader range of considerations to the assessment process while being respectful of simplicity and practicality to make them widely accessible (Cole et al., 2005).

Generically Cole (2005; Cole et al., 2005) and Seo (2002) pointed out the need to truly engage and incorporate the wider agenda of sustainability in construction, where true sustainability can only be attained when its three components are taken in account: social, economical and environmental. So, for them it is mandatory that the assessment of buildings sustainability embraces these components: LCA, LCC and LCS (Life Cycle Sociability).

Only in this way it will be possible to fully address sustainability (Bowyer et al., 2005; Pitcher, 2005; Cole, 2005; Trusty & Horst, 2002).

An alternative solution that is presented by some other authors is the elimination of the current used systems (assessment methods) and their replacement with more advanced ones, totally incorporating LCA, functioning as support tool for the decision making process, also allowing comparison between different building designs. Among all the existing tools we can present as an example the LCADesign. This is a tool which is an integrant part of a much wider platform, the LCADevelop, which includes: LCADefine, LCADesign, LCADetails, LCADeliver and LCADeconstruct, for each phase, ranging the construction entire life-cycle. (Watson et al, 2004)

Another approach is proposed by Trusty and Horst (2002) standing for a “half way”, complement, solution. According to them, and as presented earlier, the existing techniques can be cate-
organized into three different levels. BREEAM, LEED and similar methods are level 3 tools, which have to be complemented with level 2 tools (Athena or similar) and level 1 tools (BEES or similar). They believe that with this there will be a much more strong and solid assessment that satisfies everyone’s needs.

4 CONCLUSIONS

First it is possible to see that BEAS can improve the walk in the path towards sustainability with special focus at performance orientations, enlarging their scope, considering in their assessments the entire life cycle. A useful way to get these is to increase LCA approach into BEAS. One of the main conclusions to withdraw from the previous analysis is that compromised solutions will be needed, as well as an interaction with a multi-approach.

We must not forget that BEAS has, nowadays an extremely strong market presence, and, in some cases, they are even starting to be a requirement to project approval. So, this market trust and receptivity construction stakeholders must be use to increase the applications of LCA approaches to perform building assessments.

5 REFERENCES

- Trusty, W. et al (2006). Integrating LCA into LEED, Working Group A (Goal and Scope), Interim Report #1, for the USGBC.
National and international (ISO and CEN) standardisation relevant for sustainability in construction

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**ABSTRACT:** Sustainability in construction has a short history in terms of principles, standardisations and applications. From the Brundtland Report “Our Common Future” (UN WCED, 1987) in which the concept of sustainable development was coined, the term “sustainability” was used more and more, by industry and common people, and also in the construction field. The new vision of the resource deficits and climate impacts, and the social responsibility between North-South as well as between generations, gave growth to the idea of sustainable design and construction. The need for analyses, assessments and comparison where noticed by the international, and consequently national, organisations for standardisation, which started to develop standards for the application of sustainable principles, mainly environmental aspects, in construction. The paper is giving an overview of existing and planned standards, and giving examples on how to use the standards as framework for development of methods and tools for assessment.

1 INTRODUCTION

“If there were no standards, we would soon notice. Standards make an enormous contribution to most aspects of our lives - although very often, that contribution is invisible. It is when there is an absence of standards that their importance is brought home. For example, as purchasers or users of products, we soon notice when they turn out to be of poor quality, do not fit, are incompatible with equipment we already have, are unreliable or dangerous. When products meet our expectations, we tend to take this for granted. We are usually unaware of the role played by standards in raising levels of quality, safety, reliability, efficiency and interchangeability - as well as in providing such benefits at an economical cost” (AA.VV., 2007). This explanation of what if standards did not exist is useful to understand the why of this work.

Sustainability and, in particular, sustainability in construction have a short developing history in terms of principles, standardisations and applications. From the Report of the World Commission on Environment and Development: Our Common Future (UN WCED, 1987) in which the concept of sustainable development was coined (by Brundtland, the Prime Minister of Norway), the term “sustainability” was used more and more in many fields, from the industry to the common people. The focus on environmental aspects increased in an exponential manner from when, for instance, the reports of the United Nations Framework Convention on Climate Change (UNFCCC) showed that almost one third of bear energy is used for constructions and the writing of the Kyoto Protocol. Also in the construction field the need for changes was accepted.
Thus, the new vision of need for more sustainable products, design and construction processes were noticed by the international, and consequently national, organisations for standardisation and these organisations started to analyse and develop new standards for the application of sustainable principles in the field of construction. The basic idea of the standardization work for sustainability in construction is that all construction works must fulfil functional and technical performance requirements, but additionally the environmental, social and economic performances. An important issue is that every product or element involved in a construction work has to be considered in the assessment of those performances. Thus, the standardisations for production, transport, building process, use and end of life have to be considered together.

While the challenge of sustainable development is global, the strategies for addressing sustainability in building construction are essentially local and differ in context and content from region to region. These strategies will reflect the context, the preconditions and the priorities and needs, not only in the built environment, but also in the social environment. This social environment includes social equity, cultural issues, traditions, heritage issues, human health and comfort, social infrastructure and safe and healthy environments. It may, in addition, particularly in developing countries, include poverty reduction, job creation, access to safe, affordable and healthy shelter and loss of livelihoods.

2 NATIONAL AND INTERNATIONAL STANDARDISATION WORK RELATED TO SUSTAINABILITY

The International Organization for Standardization (ISO) has several Technical Commissions to analyze and then develop singularly standards for these sectors, for instance, ISO/TC43 (Acoustics), ISO/TC59 (Building Construction), ISO/TC146 (Air quality), ISO/TC163 (Thermal performance and energy use in the built environment), ISO/TC205 (Building environment design), etc.. In a very similar manner the European Committee for Standardization (CEN) examines and establishes, many time following the ISO Standards, the standards for the same sectors, for instance, CEN/TC89 (Thermal performance of buildings), CEN/TC126 (Acoustic properties of building elements and of buildings), CEN/TC156 (Ventilation for buildings), CEN/TC 169 (Energy performance of buildings), CEN/TC350 (Sustainability of construction works) etc. Finally the national standardisation body may make the international standard a national standard, sometimes the standards are translated and fitted for the national characteristics (for instance the Italian UNI EN 12354 and UNI TR 11175:2005 - Building acoustics), in other cases translating exactly the international standard (for instance the Italian UNI EN ISO 13788:2003 - Hygrothermal performance of building components and building elements).

ISO/TC207 (Environmental Management) was established in 1993 with the scope "standardization in the field of environmental management tools and systems". ISO/TC 207 does not set limit levels or performance criteria for operations or products; instead, its activities are based on the philosophy that improving management practices is the best way to improve the environmental performance of organizations and their products. SC3 (Environmental labels and declarations) is the subcommittee that establishes guiding principles for the development and use of environmental labels and declarations (the ISO 14020-21-24-25), while SC5 (Environmental management – Life Cycle Assessment) is the sub-committee that established standards for the applications of LCA methods (the ISO 14040-44-47-48-49).

The ISO Technical Management Board (TMB) decided in June 2007 to establish a task Force of TMB Members with the task to develop an appropriate communication to ISO Committees on ISO and sustainability, carry out an inventory of ISO work relevant to sustainability, and to develop proposed terms of reference for a possible Strategic Advisory Group (SAG). This resolution is based on the fact that sustainability is not the exclusive domain of any one ISO TC or activity but in fact all ISO’s work programme contributes in some manner to sustainability.

Using the term sustainability the building industry was forced not only thinking of energy efficient buildings or good indoor environment, but also have in mind other aspects. For construction as such, sustainability still is regarded equivalent to environmental efficient or “green”.

1.36
ISO/TC59/SC17 (Building construction - Sustainability in building construction) is the first ISO committee addressing sustainability in its work, but many already existing standards, and standards under preparation have considerable influence on the work. Mainly to be named are international standards in the field of environmental management (ISO 14000), environmental life cycle assessment (ISO 14040), environmental declaration (ISO 14025) and international standards on service life planning (ISO 15686 series). This sub-committee is developing specific series of standards for building construction (the ISO 15392, 21929-30-31-32).

In Europe the main important Technical Committee for the sustainability in construction field probably is the European CEN/TC350 (Sustainability of construction works). It is aiming at the development of voluntary horizontal standardised methods for the assessment of the sustainability aspects of new and existing construction works and for standards for the environmental product declaration of construction products as part of implementation of European policy. It points out that in every Technical Committee the Life Cycle Analysis (the process for evaluating the environmental effects associated with a product or service) is considered one of the best tool, because it examines the full range of impacts over all the phases of a building's useful life, instead of focusing on any particular stage (Kotaji, 2003).

The previous section is a brief description of the state of art of the current standard situation for sustainability in construction. In the next sections some more detailed information will be discussed about this field in terms of principles and their practical applications.

3 THE PUBLISHED INTERNATIONAL STANDARDS RELATED TO ENVIRONMENTAL MANAGEMENT

The International Standards Organization has worked with many countries and organisations to bring the 14000 standards forward for the world as a whole. According to the Quality Network (1996), "A set of international standards brings a world-wide focus to the environment, encouraging a cleaner, safer, healthier world for us all". Moreover these standards were created to give countries at least a minimum environmental standard to shoot for. Within ISO, TC207 has responsibility for the development of environmental management standards, including those dealing with LCA. In particular, some recent changes have been made to the ISO norms that standardise the methodology for life cycle assessment (LCA), for process or service over the course of its entire life cycle. It’s come a long way since the 1960s where its roots took shape as the result of the need for energy optimisation within industry.

The first “multi-criteria” study was carried out by Coca-Cola around 1969. The process was further developed at a SETAC conference in Vermont in 1990, which included inventory, interpretation and improvement.

ISO later standardised the methodology with the publication of ISO 14040 – Life Cycle Assessment Principles and Framework) in 1997, which was later added to in 1998 (14041 – Goal & Scope Definition and Inventory Analysis) and 2000 (14042 – Life Cycle Impact Assessment, 14043 – Life Cycle Interpretation). These are the standards that have been revised, cancelled and re-placed by the publication of ISO 14040:2006 outlining LCA principles and framework and ISO 14044:2006 for requirements and guidelines. The ISO LCA standards have established a worldwide set of rules to ensure that LCA studies are conducted in a consistent, reproducible fashion. The standards define what should be considered in setting the goal and scope of the study, what data are needed, how to evaluate the quality of the data, what impact assessment categories will be used (and why), how the results can be interpreted for improvement, what information should be included, and when different levels of review are necessary (Fava, 2005). Another published international standard is the ISO 14025 - Environmental labels and declarations - Type III environmental declarations - Principles and procedures. It is the environmental declaration providing quantified environmental data using predetermined parameters and, where relevant, additional environmental information (the predetermined parameters are based on the ISO 14040 LCA series of standards which is made up of ISO 14040 and ISO 14044; the additional environ-mental information may be quantitative or qualitative).
4 THE PUBLISHED INTERNATIONAL STANDARDS RELATED TO SUSTAINABILITY OF CONSTRUCTION

4.1 ISO/TC59/SC17 “Sustainability on building construction”

ISO/TC59/SC17 "Sustainability in building construction" was established in 2003 as a result of preliminary work conducted since 1999 by WG12 on Sustainability in ISO/TC59/SC3 “Functional/user requirements and performance in building construction”. For the past eight years, substantial work on international standardisation related to sustainability in building construction has been undertaken within ISO/TC59’s SCs 3 & 17, based on the formative work and international activities in International Council for Research and Innovation in Building and Construction (CIB).

SC17 is working to develop a suite of standards covering all aspects related to Sustainability in building construction. In the SC17 there are both the Participating Members (that come from 18 nations) and the Observer member (that come from 9 nations). The main field of the standardisation is the sustainability of the built environment; in particular the environmental, economic, and social aspects of sustainability are included as appropriate. The ISO/TC59/SC17 has the following structure:

- WG 1 “General principles and Terminology”
- WG 2 “Sustainability indicators”
- WG 3 “Environmental declarations of building products”
- WG 4 “Framework for assessment of environmental Performance of Construction works”.

SC 17 has published:
- ISO/TS 21931-1 Sustainability in building construction -- Framework for methods of assessment for environmental performance of construction works

These technical specifications and other work items in SC17 are described in the next chapter.

5 THE INTERNATIONAL STANDARDS UNDER DEVELOPMENT OR REVISION RELATED TO SUSTAINABILITY OF CONSTRUCTION

The standardisation process should be a consensus-building and a participatory process. ISO standards relates to other standards, while CEN standards relates to directives or policies. Important issue is to harmonise existing approaches and being performance based rather than prescriptive.

5.1 ISO/TC59/SC17 “Sustainability on building construction”

The WGs in SC17 have to develop standards according to the Work Programme that foresees the “General principles” (AWI 15392), Terminology (CD 21932), Framework for the development of indicators for buildings (CD 21929), Environmental declaration of building products (CD 21930), and Framework for methods of assessment for environmental performance of construction works – Part 1: Buildings (CD 21931). In the next part the main detailed news about the AWI (Approved Work Item) and the different CD (Committee Draft) will be discussed.

Taking into account that ongoing standardisation work is covering buildings (SC under TC59 Building construction) a new work item, Development of a framework for sustainable indicators for civil engineering works/infrastructures, is proposed for decision in the coming SC17 meeting in October 2007.

5.1.1 ISO/FDIS 15392 Sustainability in building construction – General principle

This standard identifies and establishes general principles for sustainability. It is based on the concept of sustainable development as it applies to buildings and other construction works, from
their inception to the end of life, understood as their “life cycle”. The standard is applicable to buildings and constructions individually and collectively, as well as to the materials, products, services and processes related to the life cycle of construction.

The standard is not intended to provide the basis for assessment of organisations or other stakeholders, and does not provide levels (benchmarks) that can serve as the basis for sustainability claims. The principles established in this standard are intended to be applied broadly in the context of construction. Specific applications are the subject of other related international standards. Buildings are designed to meet numerous requirements, expressed and established in national and international standards. None of these requirements is replaced or changed by this standard.

5.1.2 ISO/TR 21932 Sustainability in building construction – Terminology

This Technical Report gives the terminology used in the suite of standards.

5.1.3 ISO/TS 21929-1 Sustainability in building construction – Sustainability Indicators - Part 1: Framework for the development of indicators for buildings

ISO/TS 21929-1 provides a framework, makes recommendations, and gives guidelines for the development and selection of appropriate sustainability indicators for buildings. The aim of this part of ISO/TS 21929 is to define the process that shall be followed when addressing the economic, environmental and social impacts of a building using a common framework and a set of indicators. In particular the ISO/TS 21929-1:

- adapts general sustainability principles for buildings
- includes a framework for the assessment of economic, environmental and social impacts of buildings
- shows indicators as examples
- shows how to use sustainability indicators with regard to buildings and shows the process of using sustainability indicators
- supports the process of choosing indicators
- supports the development of assessment tools
- defines the conformity with this specification.

5.1.4 ISO 21930 Sustainability in building construction – Environmental declaration of building products

ISO 21930 provides the principles and requirements for Type III environmental declarations of building products. It gives guidelines for the development and implementation of such declarations based on the Life Cycle Assessment. The standard contains specifications and requirements for the EPD (environmental product declaration) of building products. Where this standard contains more specific requirements, it complements ISO/FDIS 14025 for the EPD of building products.

ISO 21930 provides a framework for and basic requirements for Product Category Rules, PCR, as defined in ISO/FDIS 14025 for Type III environmental declarations of building products. Type III environmental declaration for building products as described here are primarily intended for use in business to business communication, but their use in business to consumer communication under certain conditions is not precluded. The standard does not define requirements for developing Type III environmental declaration programmes. This kind of requirement declaration programmes are found in ISO/FDIS 14025.

The working environment is not included in this ISO 21930 because it is normally a subject for national legislation.

In the practice of developing Type III environmental declarations, programmes or their declarations are referred to by various names such as Eco-Leaf, eco-profile, environmental declaration of product, environmental product declaration (EPD), environmental profile, etc.

ISO/TS 21931-1 provides a general framework for improving the quality and comparability of methods for assessing the environmental performance of buildings. It identifies and describes issues to be taken into account when using methods for the assessment of environmental performance for new or existing building properties in the design, construction, operation, refurbishment and deconstruction stages.

The building is the object of the assessment defined in this part of ISO/TS 21931, and this encompasses the building itself, the site and the associated facilities on the site. It is recognized that environmental performance is only one of a number of significant factors in a building’s overall performance.

This part of ISO/TS 21931 is intended be used in conjunction with, and following the principles set out in, the ISO 14000 series of International Standards.

5.2  CEN TC350 "Sustainability of construction works"

The TC350 shall be responsible for the development of voluntary horizontal standardised methods for the assessment of the sustainability aspects of new and existing construction works and for standards for the environmental product declaration of construction products. The standards will be generally applicable (horizontal) and relevant for the assessment of integrated performance of buildings over their life cycle. The standards will describe a harmonized methodology for assessment of environmental performance of buildings and life cycle cost performance of buildings as well as the quantifiable performance aspects of health and comfort of buildings.

In order to assess the integrated performance of buildings it is necessary to regard a building as a whole with required performance and functions to fulfil. Consequently, during its life cycle from raw material supply of building products to the final disposal of building components, a building has environmental and economic impacts as well as impacts on the health & comfort of the users. To get an overall picture on the integrated performance of a building, these impacts must be analysed with the building as an object of the assessment of environmental performance, economic performance and health & comfort performance of building.

The standards of the TC350 will provide the means for the quantification of the impacts of the Construction Industry and for understanding the results of its decisions. The standards will provide essential elements in a strategy leading to the mitigation and possibly, e.g. avoidance of climate change through understanding the effects of decisions taken in the Construction Industry. The TC350 standards will be available by 2007-2010 and will create a set of horizontal European standards in this field. Work item 3, 5, 6, and 7 have not started.


This standard will provide the general principles and requirements for the methodologies for the assessment of environmental performance, life cycle cost performance and health & comfort performance of buildings. The standards will be generally applicable (horizontal) and relevant for the assessment of integrated performance of buildings over their entire life cycle. The standard defines the system boundaries for the assessment of the integrated performance of buildings in terms of its quantifiable impacts. This standard also provides the core indicators for the assessment of environmental performance, life cycle cost performance, and health & comfort performance of buildings and describes how they are treated in the overall assessment.

5.2.2  WI00350002 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation methods.

The standard will provide a framework for calculation methods applicable to all buildings and methodology for the assessment of the environmental performances of a building. This assess-
ment is mainly based on the result of the Life Cycle Assessment for each of the environmental aspects over the life cycle of the building in the framework of the integrated performance of buildings. The standard describes the calculation methods for environmental core indicators defined in the framework standard according to the type of the building and various stages of the building life cycle. The standard describes the system boundaries for LCA and the European rules for LCA outcome for each aspect in order to allow for aggregation, and describes the assessment of data quality for LCA-data and the effect of data quality on the results of the LCA.

The object of the assessment is the building itself, including its foundations and external works within the area of building site, and the source of impacts over its life cycle. The physical and temporal system boundary for the assessment shall be defined in the goals of the assessment. The physical system boundary for the assessment shall exclude impacts of non-building related appliances. Non-building related appliances are domestic, commercial and industrial appliances and other non-building related goods, e.g. entertainment electronics, washing machines, refrigerators, cooking appliances, office electronics and appliances of industrial processes. Assessment of the building shall be presented with a focus on different stage of the life cycle of the building (i.e. construction stage, operation stage and end of life). The standard describes:

- The calculation methods for environmental core indicators defined in the framework standard according to the type of the building and various stages of the building life cycle.
- The system boundaries for LCA and the European rules for LCA outcome for each aspect in order to allow for aggregation.
- The assessment of data quality for LCA-data and the effect of data-quality on the results of the LCA for buildings.

The calculation method should be according to ISO/TS 21931-1.

5.2.3 WI00350003 Sustainability of construction works – Use of environmental product declarations

This standard is applicable to cradle to grave as well as modular environmental product declarations (EPD) of building products, processes and services. It describes the requirements placed on any EPD when it is to be applied in combination with other EPD for the assessment of the environmental performance and health & comfort performance of a building in the framework of the integrated performance of buildings. This standard gives the rules for converting the product, process or service related information, from an EPD supplying the information as related to the performance in the building. The information includes environmental and health and comfort aspects. The conversion will take account of the need to avoid data gaps, data overlaps and double counting. It also includes checking consistency, completeness and comparability as well as equivalence in quality of applied data derived from different EPD.

5.2.4 WI00350004 Sustainability of construction works – Environmental product declarations – Product category rules for construction products

This standard is applicable to building products, processes and services. The product category rules specify requirements for all building products in accordance with ISO 21930 and ISO 14025 for the intended audience whether business or consumers. This standard supports the application of environmental product declarations for the assessment of the environmental performance of buildings and for the assessment of the health & comfort performance of buildings in the framework of the integrated performance of buildings.

5.2.5 WI00350005 Sustainability of construction works – Environmental product declarations – Communication formats.

This standard is applicable to all building products, processes and services. It defines and describes the communication formats of an environmental product declaration dependent on the intended audience; business or consumers.
5.2.6 **WI00350006 Sustainability of construction works – Environmental product declarations – Methodology and data for generic data.**

This technical report describes the sources and methodology to be used when preparing generic data for environmental product declarations. The methodology complies with the requirements of ISO 14044. The report supports the development of the product category rules for environmental declarations of building products, processes and services addressing the use of generic data.

5.2.7 **WI 00350007 Sustainability of construction works – Description of the building life cycle.**

This technical report is meant to describe the building life cycle within the framework standard. In order to complement other work items, this technical report focuses on processes and scenarios related to the building life cycle, and describes items such as service life, technical performance and performance requirements. This technical report expressly serves the demands of that framework standard rather than being a stand-alone document on the description of the building life cycle. This work item is not started, but awaiting decisions from EC and CEN.

6 **CONCLUSION**

The ongoing international standardisation work related to sustainability in construction will make assessments of the sustainability aspects of new and existing construction works more transparent and the results more comparable than what is possible with today’s methods. Standards for the environmental product declaration of construction products will make it easier for actors to decide which products, but also which systems, to use in construction.

An increased interest for using the standards, and the information given according to the standards, will aid the actors to more sustainable constructions. The described standards will give companies a reliable business environment and enable the exchange of sustainability information related to internationally traded products and services.

**REFERENCES**


ISO/FDIS 15392 Building construction – Sustainability in building construction – General Principles

ISO/TS 21929 Building construction - Sustainability in building construction – Sustainability indicators - Part 1 - Framework for development of indicators for buildings

ISO 21930 Building construction - Sustainability in building construction – Environmental declaration of building products


ISO/TR 21932 Building construction - Sustainability in building construction – Terminology

ISO/CD 14025 Environmental labels and declarations - Type III environmental declarations - Principles and procedures

ISO/CD 14040 Environmental management - Life cycle assessment - Principles and framework.

ISO/CD 14044 Environmental management - Life cycle assessment - Requirements and guidelines
Sustainability of urban infrastructure

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ABSTRACT: The scope of the paper is to give an overview of different approaches to evaluation of urban infrastructure sustainability. In this context urban infrastructure covers transportation, energy, water, sewage and information networks as well as waste management and blue-green infrastructure, in terms of supply and demand side. A common effort of partners in COST C8 in defining the methods, indicators and criteria for evaluation of sustainability, summarized in a guidebook for decision makers in local authorities, is presented. The information about best practice projects in sustainable urban infrastructure is given and illustrated with an overview of identified cases. COST C8 project was focused rather on technical view of infrastructure than on social and economical, although the later were not neglected. In addition the FP6 project PETUS will be briefly presented. It aims at giving a complete survey of tools for evaluation of urban sustainability, with respect to the particular scope and level of the analysis.

1 INTRODUCTION

Various urban projects contribute to development of urban infrastructure. They encompass a very broad group of projects, covering urban planning, urban design and architecture, transport studies, economics, ecology, geography, sociology, water management and engineering, waste management, energy engineering and economics, landscape planning and building architecture. The municipalities need methods and tools for evaluation of project sustainability. It is important for decision makers to achieve a common understanding on sustainability and related criteria for decision-making in urban planning and design dealing with infrastructure. Thus the communities create the arguments for sustainable decisions and initiate long term benefits from saving non-renewable resources and creating more economic, sound and livable communities.

The effort of researchers in provision of sustainability evaluation criteria applicable at municipal level was joined in COST C8 project “Best Practice in Sustainable Urban Infrastructure”. The result of the action was a book summarizing the questions, methods and tools for assessing sustainability of the development of urban infrastructure and presenting 46 different good practice cases from 15 EU countries and Canada. The book is a basic information source for planners and designers, civil servants and developers, decision-makers and lay-people dealing with urban development when assessing the sustainability of different alternatives of infrastructure.

COST C8 action initiated also a comprehensive in-depth survey of the evaluation tools for urban sustainability elaborated in FP5 PETUS project “The Practical Evaluation Tools for Urban Sustainability” (http://www.petus.eu.com). The tools focus on different levels relevant for urban sustainability: building component, building, neighbourhood, city and regional level and may cover one or more sectors: waste, energy, water, transport, green-blue infrastructure as well as building and land use. The results are presented as a website tool for people who are involved with, or affected by, building and infrastructure to consider impacts on the environment, society
and the economy. The website includes information that can be used to analyse and improve the sustainability of urban infrastructure.

2 COST C8

2.1 Background and aims

Urban areas are growing fast and consequently, the urban infrastructure has to meet rapidly increasing users' needs. Technical infrastructure, like transportation, energy, water supply, sewage and information networks, represents the skeleton of the city. It provides the end-users with materials, energy and information. But on the other hand urban infrastructure has broad and long term impact on sustainable development of the area. COST C8 action focused on identification of methods and tools for assessment of sustainability in the above cases (Lahti 2001). Primarily, the task was to define the possible indicators of urban infrastructure sustainability. Apart from a well known Brundtland definition of sustainable development, it has been commonly accepted, that sustainable urban infrastructure focuses on prevention of unnecessary consumption of natural resources (especially non-renewable ones) and mitigation of harmful emissions. Moreover, every project may be evaluated in terms of environmental, economic and social aspect of sustainability, where accordance of all three dimensions is needed for overall sustainability (Fig. 1).

The research within COST C8 project covered a broad scope of urban infrastructure sustainability, i.e. all three dimensions – social, environmental and economical one; infrastructural projects on local, regional and global level; and besides the analysis of methods and tools and good practice cases it reflected also to a theory of evaluation. The urban infrastructure was understood as a technical and social one. The technical (physical) infrastructure includes different technical networks needed for transportation of water, energy, materials, people and information, together with the related production plants and demand side conditions. Also blue-green infrastructure (parks, gardens, water areas) and buildings (as the final part of the network) are considered in the frame of the project. Social infrastructure covers various services defining the relations between stakeholders. The focus of COST C8 research is oriented rather at technical infrastructures than at social ones, and it primarily covers local projects with emphasize on environmental issues (Fig. 2).

![Figure 1. Three basic dimensions of sustainability, needed to be considered to attain overall sustainability of a project.](image-url)
The assessment methods with environmental focus appropriate for urban infrastructure evaluation as recommended by COST C8 are summarized in the Table 1 together with the methods with an economic and social focus. In the investigation it was concluded that the methods show diverse degrees of sustainability for a comprehensive assessment of sustainability. Some methods are more appropriate for project appraisal (e.g. EIA), others are meant to deal with strategic policy decisions. Some methods are specific for a particular type of economic, social or environmental analysis, while others allow a more integrated appraisal. There is no single, most appropriate method to deal with a specific case study; the choice for method depends on many criteria, in practice last but not least on material and financial resources and staff expertise. The study gives a brief description of each method and comments on strengths and weaknesses.

Table 1. Assessment methods for sustainable urban infrastructure.

<table>
<thead>
<tr>
<th>Environmental focus</th>
<th>Economic focus</th>
<th>Social focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Impact Assessment (EIA)</td>
<td>Cost-Effectiveness Analysis (CEA)</td>
<td>Social Impact Assessment (SIA)</td>
</tr>
<tr>
<td>Strategic Environmental Assessment (SEA)</td>
<td>Cost Benefit Analysis (CBA)</td>
<td>Socio Economic Impact Assessment (SEIA)</td>
</tr>
<tr>
<td>Life Cycle Analysis (LCA)</td>
<td>Multi-criteria decisions aid (MCDA)</td>
<td></td>
</tr>
<tr>
<td>Ecological Footprints (EF)</td>
<td>Environmental Accounting (EA)</td>
<td></td>
</tr>
<tr>
<td>The Ecological Rucksack (ER)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The Green Poster (GP)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. Scope and focus of “best practice in sustainable urban infrastructure” in COST C8 (Lahti et al. 2006).
Usually the practical problem is to reduce the number of sustainability indicators used in assessment. COST C8 study gives a list of tips in how to select relevant indicators for particular project, like importance and relevance of the indicator for the project, available time and human resources and data for calculation of indicators, uncertainty of the indicator obtained, relevance of indicator for comparison across time and geographical area. Some indicators, like CO₂ emissions, have gained a common relevance in EU context. In most cases indicators are aggregated and weighted by one of weighting techniques (i.e. distance to target methods, economic methods or consensus based method).

Due to the need of a holistic assessment of sustainability of 46 urban infrastructure cases an assessment matrix was developed. Its aim was to correspond to a need for evaluation of many dimensions and many impacts of sustainability, as well as to cover most relevant aspects in a compact space. The matrix uses verbal and visual information and allows additional explanation to the colored arrows indicating the direction and strength of the approach to sustainability. This tool is suggested as a practical way to assist infrastructure planner or decision-maker to assess different alternatives. The “key questions” represent preliminary ideas of the areas where to find perhaps the most relevant indicators of sustainability.

<table>
<thead>
<tr>
<th>Ecology</th>
<th>Economy</th>
<th>Social aspects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Are emissions to air, water and soil within the restrictions set locally and internationally? Are the emissions decreasing?</td>
<td>Is the cost/effectiveness and/or cost/benefits of the system reasonable compared to other systems? Compared to other needs in the city and to political goals?</td>
<td>Has the planning and decision-making for the infrasystem been done in a democratic and participative way?</td>
</tr>
<tr>
<td>Is the use of natural resources reasonable compared to other comparable systems? Is the use decreasing? (e.g. fossil fuels, water, phosphorus, potassium)</td>
<td>Are the citizens willing to pay for the services offered? Are the services affordable to all citizens?</td>
<td>Is the function and the consequences of the system transparent to and accepted by the citizens? Is the system promoting a responsible behaviour by the Citizens?</td>
</tr>
<tr>
<td>Is the system allowing a reasonable bio-diversity with regard to the kind of area studied? Is the bio-diversity increasing?</td>
<td>Is the organisation(s) that finance, maintain and operates the system effective?</td>
<td>Is the system safe to use for the citizens? (hazards, health, well-being)</td>
</tr>
<tr>
<td>Is the system more or less sustainable than a conventional system regarding ecology?</td>
<td>Is the system more or less sustainable than a conventional system regarding economy?</td>
<td>Is the system more or less sustainable than a conventional system regarding social aspects?</td>
</tr>
</tbody>
</table>

Figure 3. The Assessment Matrix Model developed in COST C8 Action for rapid assessment of alternative solutions of urban infrastructure (Lahti et al. 2006).

2.3 _Good practice cases of sustainable urban infrastructure_

The aim of collecting the case studies in COST C8 was to explore the ways in which sustainability projects are realized in practice and to demonstrate the type of applications already in use throughout Europe. The target audience for the case studies is urban planners and engineers, and others who are involved in the decision making processes associated with initiating sustainable development in the urban context. The cases were distributed in six categories (Tab. 2):
Table 2. Case of sustainable urban infrastructure collected and assessed in COST C8 (http://www.cardiff.ac.uk/archi/programmes/cost8/).

<table>
<thead>
<tr>
<th>GREEN/BLUE</th>
<th>TRANSPORT</th>
<th>ENERGY</th>
<th>WATER/SEWERAGE</th>
<th>WASTE</th>
<th>HOLISTIC</th>
<th>ASSESSMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rever (Reseau vert europeen/european green network) crossing – Brussels, BELGIUM</td>
<td>• Urban space zoning, AUSTRIA</td>
<td>• Vienna Climate Protection Programme, KLIP, AUSTRIA</td>
<td>• The Kolding Pyramid, DENMARK</td>
<td>• Strategic environmental assessment (SEA) for the Viennese Waste Management Plan, AUSTRIA</td>
<td>• Urban ecological renewal of the Hedebygade Block, DENMARK</td>
<td>• The use of checklists to support spatial planning in Graz, AUSTRIA</td>
</tr>
<tr>
<td>Rennes Urban Greenspace Differentiated Management, FRANCE</td>
<td>• Lyon Urban Mobility Master Plan, FRANCE</td>
<td>• The Christophorus House - a multi purpose office building with low-energy consumption, AUSTRIA</td>
<td>• Digital diagnostics system for sewer pipes, FINLAND</td>
<td>• Soil remediation programme, FINLAND</td>
<td>• Viikki Eco Neighbourhood Blocks, FINLAND</td>
<td>• Radiation solar comfort early analysis in high density urban context, BELGIUM</td>
</tr>
<tr>
<td>Green Poster Fredrikstad, NORWAY</td>
<td>• Meckenheim’s Motto: Interference wanted, GERMANY</td>
<td>• Middelgrunden Windfarm, DENMARK</td>
<td>• Storm water management “Porte des Alpes” site in the Lyon suburbs, FRANCE</td>
<td>• Pneumatic Waste Collection, SPAIN</td>
<td>• Ferrara – the Children’s city, ITALY</td>
<td>• Energy and Environmental Prediction Model, UK</td>
</tr>
<tr>
<td>Stockholm’s Green Infrastructure, SWEDEN</td>
<td>• The re-organisation of the railway system in the Florentine metropolitan area, ITALY</td>
<td>• Tervola Small Scale CHP Bio Energy Plant, FINLAND</td>
<td>• Sustainable Housing Estate Eva-Lanxmeer, NETHERLANDS</td>
<td>• Construction Waste Minimisation, UK</td>
<td>• Ecosystem fragmentation assessment for the Trento-Rocchetta road project, ITALY</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Ecosystem fragmentation assessment for the Trento-Rocchetta road project, ITALY</td>
<td>• Two million marks for Da Di, GERMANY</td>
<td>• The sustainability of conventional versus nature based sewerage systems, NORWAY</td>
<td></td>
<td>• The Bronna Biogas Plant, Stockholm, SWEDEN</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Buga, the free riding bicycle of Aveiro, PORTUGAL</td>
<td>• The Emporium Case, NETHERLANDS</td>
<td>• Separating waste water system, SWEDEN</td>
<td></td>
<td>• The Bromma Biogas Plant, Stockholm, SWEDEN</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• The mobility program as the link of the interventions of Porto 2001 - Baixa District, PORTUGAL</td>
<td>• Green Municipality, Green Electricity, NETHERLANDS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Escalators to access Toledo’s Historic Core, SPAIN</td>
<td>• City District Heating and Cooling, NETHERLANDS</td>
<td></td>
<td></td>
<td>• The Path (POT) – a circular memorial park around Ljubljana, SLOVENIA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• City of Zurich, SWITZERLAND</td>
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</tr>
</tbody>
</table>

Many cases were assessed using the above matrix but it was not applicable in all cases due to the lack of data or major differences from the core scope of urban infrastructure project. The evaluation data were not always available in a form allowing easy (and comparable) assessment. A need for better benchmarking data for the cases studies was expressed, and due to the big variety in cases more qualitative benchmarks might allow at least some level of comparison of sustainability. The drivers for the sustainable urban infrastructure projects were in most cases environmental, while in the holistic cases there was a strong influence of social aspect.
One of the important conclusions referred to the need for more structured evaluation, flexible
to accommodate different types of cases, allowing combination of quantitative and qualitative
methods as appropriate and covering all three aspects of sustainability. This was a complex task,
that later became a core idea of FP5 PETUS project.

Figure 4. A holistic case “The path (POT)”, from Slovenia, describes a construction of a circular memo-
rial park around the city of Ljubljana, bringing into a circle individual natural landscape features and
green areas in the city. The path offers over 40 km of sports routes (walking, running, cross-country ski-
ing, recreational cycling, relaxing in nature...), it acts as an area of significant environmental value and
maintains a historic memory of a World War II Ljubljana, occupied and entirely fenced in by barbed
wire. (Grgic & Lenardic 2006)

3 PETUS PROJECT

3.1 Aim

The Practical Evaluation Tools for Urban Sustainability (PETUS) Project is aimed to provide a
framework of practical evaluation tools that can be used to analyze and improve the sustainabil-
ity of urban infrastructure projects. PETUS project contributes to bridge the existing gap be-	ween theoretical frameworks and practical approaches applied in everyday practice to evaluate
urban sustainability when building and managing urban technical infrastructure. The process in-
vestigates the opportunities for comparability in evaluating urban projects realized under differ-
ing spatial, cultural, social and economic context (http://www. petus.eu.com).

3.2 PETUS website

The role of PETUS Framework is to identify sustainability problems of urban infrastructure pro-
jects, to clarify the concept of sustainability between all stakeholders, apply the appropriate
method and tool for assessment of sustainability.

To be able to share all the information that has been collected among the project, a web-site
has been developed. The aim of the website is to help people who are involved with, or affected
by building and infrastructure, to consider impacts on the environment, economy and society.
This website therefore includes information that can be used to analyze and improve the sus-
tainability of infrastructure, and includes:

- Case study projects from all around Europe, that illustrate where sustainability has been
  considered.
- Methods and tools that can be used to guide and analyze consideration of sustainability in
  a practical way,
- EU legislation that has to be followed in member countries,
• a monitoring process enabling the tracking for inclusion of sustainability in a respective project.

The case studies were dealing with Energy, Water and Sewage Sustainability Projects, as well as with Transport, Green-blue infrastructure and Building & Land use, which can give useful information for those who are involved with sustainability of infrastructures. The case studies were:

• Energy case studies, like Nord Hoyle Offshore Wind Farm, Awel Aman Tawe Community Energy Project, Middelgrunden Wind Farm, Municipal Energy Efficiency Programme, that give information about type of the activity, tools that specialize on energy, tools that include energy, information on energy legislation.

• Water and Sewage Case Studies: Projects that give information about improving water quality and availability, assisting with water and sewage management in cities. (Jones 2005).

Tools that have been identified and described within the PETUS Project have come from two main sources:

1. Tools that have been used within case studies, for these tools a comprehensive set of information has been collected including a summary of the tool, the characteristics of the tool, information on the application of the tool in practice, where the tool can be obtained from and opinion on the tool from the tool user within the case study.

2. Tools that were identified from a literature review, for these tools an extensive literature review has been undertaken by the PETUS team to identify tools that could be used to include sustainability into urban infrastructure projects. As no evidence has been found of these tools being used in practice a brief description of each tool is provided but comment on the application is not available.

Each tool is presented in respect to the sector of use and scale of application (Fig. 5) as well as with further information about accessibility, status of maintenance and costs of the tool.

![Sector/s of use](image)

**Sector/s of use**

<table>
<thead>
<tr>
<th>Waste</th>
<th>Energy</th>
<th>Water</th>
<th>Transport</th>
<th>Green/Blue</th>
<th>Building &amp; Land use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

*M - main sector, 1 - sub sector and 0 - n/a*

![Scale of applications](image)

**Scale of applications**

<table>
<thead>
<tr>
<th>Component</th>
<th>Building</th>
<th>Neighbourhood</th>
<th>City</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 5. Description of a tool for evaluation of urban infrastructure sustainability, as developed in PETUS project and available at the website.

4 CONCLUSION

COST C8 and PETUS project offer a comprehensive survey of tools and methods for evaluation of sustainability of urban infrastructure projects. The use of the tools is illustrated on a number of case studies and is aimed to provide a framework of practical evaluation tools that can be used to analyze and improve the sustainability of urban infrastructure projects. The described research is a useful source of information of stakeholders at a local level.
REFERENCES


http://www.petus.eu.com/
Chapter 2

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INTRODUCTION

“New materials, products and technologies are in the long term the necessary way to reduce environmental impacts. Construction products play a major role in improving the eco-efficiency of building. Radical innovations are needed for a real change towards sustainability.” Memorandum of Understanding. COST C25, Sustainability of Constructions: Integrated Approach to Life-time Structural Engineering.

Sustainable development, is development that is pursued in a manner that whilst meeting the present needs, does not compromise the ability of future generations to meet their own needs.

The papers presented in this chapter focus on two main areas:

- Identification & Evaluation of existing & new functional materials, construction products & processes, to comply with a reduction in the use of materials, a reduction of waste, reduction of emissions and energy saving goals.
- Improvement of the environmental performance of constructions, improvement of comfort in buildings, energy performance and the integration of innovative systems in buildings.

Sustainability in Construction, necessitates a better comprehension of construction materials, their performance, and the impact of construction techniques, with the objective of the Conservation of Resources.

Increased conservation of resources is one of the most significant principles of sustainability of buildings and constructions, which can also be achieved through the adoption of rational structural solutions, and the selection of construction materials of improved performance characteristics and increased strength.

Increase in the specific strength of structural elements, leads to a decrease in material consumption. Serdjuks D. et al discussed the possibility of the development of hybrid composite cables of increased specific strength, using carbon fiber reinforced plastics (CFRP), glass fiber reinforced plastics (GFRP) and Vectran, instead of steel cables. Hybrid composite cables with increased specific strength were considered for a prestressed saddle-shaped cable roof having dimensions 50m x 50m, leading to savings on materials and energy in the production process. (Serdjuks D., 2007, Composite Cable of increased specific strength, for large span structures.)

Silva N. et al, analysed the benefits of the incorporation of Phase Change Material (PCM) in gypsum plasters. This system presents environmental advantages leading not only to enhanced comfort but also economic benefits, with respect to conventional gypsum plaster. The assessment demonstrates that the PCM system is characterised by similar impacts in all categories; however it reveals a reduced impact in terms of Global Warming Potential due to energy conservation. (Silva N. et al, 2007, Environmental characterisation of gypsum-PCM plasters.)
The assessment of the performance of materials in practice is important in view of durability. Norvaisiene R. et al carried out a number of experiments intended to improve the test methods for the investigation of facade paint durability, by allowing for the impact of air pollution. The results for samples after 96 days of exposure in the climatic chamber, were compared with results obtained for unexposed and naturally weathered samples. The correlation between natural weathering and the accelerated artificial ageing was found to be sufficient. (Norvaisiene R. et al, 2007, The development of a new methodology for the estimation of durability of facade paints.)

The main concerns in wood construction, are associated with a relative reduced efficiency of the material, the low strength spectrum, anisotropy and preservation. Haller P. assessed the potential for innovation of wood, through the efficient use of the raw material, by improving its properties, cross-sections and production techniques. These developments lead to various improvements which include the reduced prices of materials; the densification of wood that surmounts the limits of the strength classes; the use of textile reinforcement as a technology that solves the problem of anisotropy at a favourable price and provides weather protection; and the shaping of efficient cross-sections. (Haller P., 2007, From tree trunk to tube or the quadrature of the circle.)

Welzbacher C.R. et al assessed the biological and mechanical properties of Norwegian spruce, which was densified in a common industrial scale process and afterwards thermally modified in an Oil-Heat treatment process. It was reported that the durability increased considerably as a result of Oil-Heat treatment. While the dynamic mechanical properties of densified and Oil-Heat treated spruce were reduced when compared to controls, the static bending strength was equal to untreated spruce. Densified and thermally modified samples demonstrated improved dimensional stability when compared to untreated densified material. (Welzbacher C.R., 2007, Biological and mechanical properties of densified and thermally modified Norway spruce.)

The concept of conservation of resources was discussed by Borg R.P., in the assessment of practical solutions with regards to the management of excavation, construction and demolition waste. The waste hierarchy provides an order of priorities for deciding on waste management practices, including the Reduction in Waste, and therefore minimizing on the use of resources and reducing the quantities of waste; Reuse of materials; Recycling and reprocessing of the waste material, for use in the manufacture of the same or different materials; Recovery of energy; and Disposal of waste, whereby waste is disposed without energy recovery only if there is no other appropriate solution.

Various proposals for waste reduction, reuse and recycling were assessed within the framework of the Waste Management Strategy. Potential measures need to be analysed in terms of environmental impact and economic feasibility. Solutions for waste management include the recycling of excavation, construction and demolition waste for use in Civil Engineering applications. The potential disposal of inert waste was also assessed with reference to disposal in quarries, and reclamation of land from the sea. (Borg R.P., 2007, A Sustainable Waste Management Strategy: Construction & Demolition Waste.)

The use of recycled materials was further analysed through experimental work conducted by Jevtic D. et al, on the properties and performance of cement composites based on recycled brick aggregate. In particular the density, compressive strength, flexural strength and shrinkage were assessed. The test results obtained for the mechanical properties of fiber reinforced recycled brick composites indicate that the addition of polypropylene fibers generally leads to improvements of these properties. The results indicate that there can be a wider scope for the application of concrete produced using crushed recycled brick aggregate. (Jevtic D et al, 2007, Properties and performance of cement composites based on recycled brick aggregate.)

The properties of concrete were also investigated by Malesev M., et al, in an experimental investigation on the use of recycled concrete as aggregate for structural concrete. A comparative analysis of the properties of fresh and hardened concrete with natural coarse aggregate, combination of natural and recycled coarse aggregate and with recycled coarse aggregate, was carried out. Concrete mixtures with recycled aggregate were noted to be very similar to concrete mixes with natural aggregate, and the performance of the Recycled Aggregate Concrete was satisfactory. (Malesev, M. et al, 2007, Recycled concrete as aggregate for producing structural concrete.)
In the selection of construction materials, the entire life cycle of the building must be considered, covering not only construction, use and maintenance, but also waste disposal. Factors that need to be assessed in planning an environmentally sustainable and cost effective building include minimal energy, minimal maintenance, minimal waste and suitability for local climate. Ermolli S.R. et al discussed the contribution of aluminium systems towards the sustainability of structures. New building systems and innovative design concepts incorporating aluminium alloys are adopted to provide more sustainable solutions. (Ermolli S. R. et al, 2007, Sustainable Aluminium Systems.)

Kozłowski A. et al, present inventory data collection for a light gauge steel frame structural system that can be used for residential and commercial buildings. The Life Cycle Inventory analysis of the system was performed for boundaries covering manufacturing processes. (Kozłowski A., 2007, Preliminary Life Cycle Inventory analysis of light gauge steel frame system.)

Numerous methods are utilised for the estimation of the energy consumption in buildings. A brief state of art of various methods is given by L. Berevoescu, et al. The methods used to assess the consumption of energy, are grouped into direct methods and reverse methods. (Berevoescu, L. et al, 2007, Energetic audit methods, part of sustainable development process.)

An analysis of the housing stock situation in Romania is presented by Dan D. et al. This is followed by an assessment of the requirements for the resistance to heat flow of elements of the building envelope, and a discussion on the latest trends in construction. The building envelope solutions adopted before 1984 were inadequate, while new improved solutions that were developed for exterior walls, were not used in practice due to initial higher investment costs. The Order issued by the Romanian Government in 2000, concerns the thermal rehabilitation of existing buildings and stimulates energy saving in buildings. A commercial center in Timisoara, Romania is used as an example of good practice, and illustrates this positive trend. (D. Dan, at al, 2007, Energy efficiency of old and new buildings in Romania.)

Dan D. et al discussed the efficacy of the thermal rehabilitation of a student hostel, and analysed the economical benefits of the solution adopted. The solution adopted includes improvements in the global thermal resistance of the building envelope, with the aim of reducing the loss of energy. The amortization period of the investment is reported to be about 6 years. The energy classification of the building stock, can be considered as an effective management tool. (D. Dan, at al, 2007, Thermal rehabilitation of a student hostel belonging to the Politehnica University of Timișoara.)

The thermal performance of houses built using different construction techniques in the Izmir region in Turkey, were compared by Altin M., et al. Houses built using traditional and conventional techniques are compared to light-weight houses. (Altin M. et al, 2007, Comparison of the improvement of comfort in Turkish houses which are built by using traditional, conventional and semi-industrialized construction methods.)

Werner G., reviewed a study conducted by the Swedish building and energy sectors, with the aim of identifying the most cost-effective and resource-efficient measures for the reduction of the environmental impact of buildings. The goal was to attain a system for energy supply, with the least possible environmental impact. (Werener, G, 2007, Low energy building design with sustainable energy end use.)

An integrated approach is necessary for an adequate assessment of construction materials, construction techniques and structural systems. The papers presented in this chapter address a variety of subjects, but have a unifying principle: Conservation of Resources. Innovation in construction and the potential development of emerging technologies and new materials, are essential towards achieving the goals of energy efficiency and resource management, within the context of sustainability in construction.

Improved performance requirements of buildings, necessitate an adequate analysis of energy efficiency of buildings. This enables the formulation of strategies based on adequate priorities for rehabilitation and construction, in the context of improved comfort and sustainability. The challenge is also to assess successful low energy building design solutions in different climate zones, and to gain sufficient knowledge towards effective solutions in different circumstances.

The contributions presented in this chapter, are yet another step, towards the objectives of COST C25, and for an integrated approach in the assessment of sustainability in construction.
Composite cable with the increased specific strength for large span structure

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ABSTRACT: Increase of specific strength of structural elements enables to decrease materials consumption and use more rationally natural resources. Possibility to develop hybrid composite cable with the increased specific strength in comparison with the steel cables was considered. Increase of specific strength was obtained by using of composite components, such as carbon fiber reinforced plastics (CFRP), glass fiber reinforced plastics (GFRP) and Vectran. Rational components for composite cable with the increased specific strength were evaluated. Hybrid composite cables with the increased specific strength were considered as materials of several cable groups for a prestressed saddle-shaped cable roof with dimensions 50x50m. The saddle-shaped cable roof was loaded by the design vertical load combination: dead weight and snow. Possibility to decrease consumption of cable net materials and to decrease pressure on the environment was stated.

1 INTRODUCTION

Reduce of resources consumption is one of the most significant principles of sustainability of buildings and constructions (Pinheiro 2007). Reduce of resources consumption for constructions could be obtained by the two following methods:
- use of rational type of structure;
- use of the materials with the increased specific strength.

The rational is a such type of structure, where materials with the increased specific strength can be used in the full scale. Large span cable structures, where nearly all main load-bearing elements work at tension are rational from the point of view of materials consumption (Serdjuks & Rocens 2003a).

High strength materials such as FRCC and FRP possess potential for their application as constructive materials in combination with the steel (Pakrastins et al. 2001). Carbon fiber reinforced plastic (CFRP), glass fiber reinforced plastic (GFRP) and Vectran are examples of such materials. As constructive materials they have following advantages:
- high specific strength;
- good durability in aggressive surrounding;
- CFRP is adaptable to be used in structures not allowed to be magnetic or electric conductive;
- low density.

However, CFRP, GFRP and Vectran have a number of disadvantages, which limit their application as constructive materials. Relatively small elongation at break (Serdjuks & Rocens 2003), probability of surface damages and increased cost (Serdjuks & Rocens 2004) are most significant disadvantages of CFRP, GFRP and Vectran in comparison with the steel cables.

Small elongation at break significantly decreases safety of construction due to probability of brittle failure during short time growing of the load. This disadvantage could be improved by
the adding of steel component, which enables to increase reliability of the cable. Addition of
distribution layer, which could be made of glass fiber reinforced plastic (GFRP), significantly
decreases the possibility of surface damages of CFRP in hybrid composite cable (Fig.1.).

![Figure 1. Hybrid composite cables on the base of steel and FRP: 1 – FRP core; 2 – FRP distributional layer; 3 – steel component.](image)

Yet the volume fractions of the components should be evaluated. So, the purpose of the study is
evaluation of rational volume fractions for hybrid composite cable components. Environmental
assessment of hybrid composite cable with the increased specific strength using for saddle-shaped cable roofs also should be done.

2 DESCRIPTION OF TECHNOLOGY

2.1 Material combinations for hybrid composite cable

The main directions of the considered hybrid composite cables application are prestressed nets of
saddle-shaped roofs. Here two types of hybrid composite cables with the increased specific
strength should be investigated. First of them is a hybrid composite cable with an increased, in
comparison with the CFRP ultimate elongation and decreased in comparison with that of steel
dead weight. These types of the cables could be used for the tension and suspension cables of the
prestressed net. Second is a hybrid composite cable with relatively high ultimate elongation for the
stressing cables of the prestressed nets. Combination of high strength and increased ultimate elongation is the main requirement for the first hybrid composite cable type. But the second type,
unlike the first, should possess first of all, an increased ultimate elongation.

Thus, the first cable type should obligatorily contain two types of materials: one material with
a large limit of strength and the other with an increased ultimate elongation. Third type of mate-
rials should be added to transfer perpendicular to the direction of axial force action pressure of
the external layer at the surface of the internal one.

Steel wire strands can be treated as a material with an increased up to 10% ultimate elonga-
tion for the first type of the cable. Properties of GFRP (E-glass and epoxy matrix at 60% fiber
content), CFRP (AS4/3501-6 graphite fibers and epoxy matrix at 60% fiber content), Vectran
HS 1500 and strands of steel wire are taken in accordanca with the sources (Beers 1990,
1997). Moduli of elasticity of steel wire strands, GFRP, CFRP and Vectran are equal to 2•10^5;
0.75•10^5; 1.37•10^5 and 0.65•10^5 MPa, respectively. Limits of strength are equal to 1900; 760;
2100 and 2850 MPa, respectively (Beers 1990, Bengtson 1994, Berger 2002, Blum 2000,
Costello 1997, Houtman 2003). Ultimate elongations are equal to 10, 2.64; 1.6 and 3.3 %, re-
spectively.

Basing on the above mentioned materials properties, two following materials combinations
can be considered for the first type of hybrid composite cable: steel, GFRP, CFRP and steel,
Vectran, CFRP. Second type of the cables should be based on the material with the increased ul-
timate elongation and limit of strength, which is enough to take up tension forces, acting in the
stressing cables of the net. Combination of steel, Vectran and GFRP, probably, enables to obtain
hybrid composite cables with such properties.
So, three three following variants of hybrid composite cable will be considered next. First variant is on the base of steel, GFRP and CFRP. Second and third are on the base of steel, Vectran, CFRP and steel, GFRP and Vectran, accordingly.

2.2 Evaluation of rational volume fractions of steel

Increase of volume fraction of steel causes the increase of load bearing capacity of the cable and the decrease of it specific strength from other side. Yet there is a minimum volume fraction of steel, which enables to prevent failure of single cable or cable net in the case of emergency, when all the components of hybrid composite cable, excluding the steel, are disrupted. The minimum volume fraction of steel was considered as a rational.

Diagonal suspension cable of saddle-shaped cable roof with dimension 50x50 m was considered as an object for evaluation of rational volume fraction of steel for three variants of hybrid composite cables. Design scheme of diagonal suspension cable was a prestressed simple cable with the supports at one level, which is loaded by the uniformly distributed load.

Initial deflection and span of the cable were equal to 20 and 70.71 m, accordingly. Intensity of uniformly distributed load was equal to 1.97 kN/m. The value of prestressing is assumed as a 20% from the tension force, which acts in the cable due to the vertical design load. Three above mentioned variants of hybrid composite cable were considered. Volume fraction of steel changes within the limits of 0.1 to 0.7 from the initial area of cross-section. The dependences of stresses, acting in the steel component of hybrid composite cables after other components disruption on the volume fraction of steel, are given in Fig.2.

The dependence illustrates, that the minimum volume fraction of steel, which prevents failure of the cable in the case, when other components are disrupted, is equal to 0.23, 0.28 and 0.29 for the first, second and third variants of hybrid composite cable, respectively. So, the hybrid composite cables with the rational volume fraction of steel possess following mechanical properties.

Moduli of elasticity are equal to $1.32 \times 10^5$; $1.35 \times 10^5$ and $1.36 \times 10^5$ MPa, for the first, second and third variant of the hybrid composite cable, respectively. Maximum axial forces, which can be taken up by the cables, are equal to 1242; 1313 and 1294 kN, for the first, second and third variant of the hybrid composite cable, respectively. Specific strengths are equal to $43.00 \times 10^3$; $41.00 \times 10^3$ and $40.50 \times 10^3$ m, for the first, second and third variant of the hybrid composite cable, respectively.

![Figure 2. Evaluation of rational volume fraction of steel (at constant vertical load): 1 – limit of strength of steel; 2 – dependence for variant of hybrid composite cable on the base of steel, GFRP and CFRP; 3 – dependence for variant of hybrid composite cable on the base of steel, Vectran and CFRP; 4 – dependence for variant of hybrid composite cable on the base of steel, GFRP and Vectran; $\sigma$ - stresses, acting in the steel component of hybrid composite cables after other components disruption; $V$ - volume fraction of steel.

However a single cable can not characterize behaviors of the cable roof in the full scale. So,
hybrid composite cable on the base of steel, GFRP and CFRP was considered as a material of tension and diagonal suspension cables of saddle-shaped cable roof with dimensions 50x50 m. The behaviors of the cable roof were evaluated for the diagonal suspension and tension cables in the cases, when all the components of hybrid composite cables, excluding the steel, were disrupted. Parameters of cable roof and methodology of numerical experiment are explained in chapter 3.

It was stated, that the maximum vertical displacements of the cable roof grows by 3 mm in the case of GFRP and CFRP components disruption of diagonal suspension cable. Maximum growing of the stresses from 899 to 1110 MPa took place in the suspension cables, which are neighboring to the diagonal suspension cables. The maximum vertical displacements of the cable roof grows by 1.37 m in the case of GFRP and CFRP components disruption of tension cables. Maximum growing of stresses from 897 to 1050 MPa took place in the diagonal suspension cable. Still the growing of stresses and maximum vertical displacements did not cause failure of any more cables.

3 USING OF COMPOSITE CABLE FOR INCREASING OF SADDLE-SHAPED CABLE ROOF RIGIDITY

Let us to consider how the using of hybrid composite cable in combination with the cable truss application enables to increase the rigidity of saddle-shaped cable roof.

A saddle-shaped cable roof 50x50 m in the plan was investigated. The existence of two symmetry planes allows us to regard, as a design scheme, a quarter of the cable net of a saddle-shaped cable roof with a main stressing cable as the shape of the cable truss, which is subjected to the prestressing and vertical design load (Fig.3).

Figure 3. Design scheme of cable roof: 1 – cable truss; 2 – cable net; $f_{st}$ – initial deflection of top chord of cable truss; $f_i$ – initial deflection of main stressing cable; $a_t$ – distance between the support points of tee-bars.

Three quarters of the cable roof are replaced by the bonds imposed on its one-quarter part. Hybrid composite cables on the base of steel, GFRP and CFRP with an elastic modulus of $1.32 \times 10^5$ MPa were assumed as a material of cable truss elements. Steel cables with an elastic modulus of $1.3 \times 10^5$ MPa were assumed as a material for the suspension, stressing (excluding main diagonal) and tension cables.

From the viewpoint of material consumption, the saddle-shaped cable roof has rational geometrical characteristics: the initial deflection of the contour cables was 8.6 m, the initial deflection of suspension and stressing cables 20 m, and the step in plan of the latter ones was 1.414 m (Serdjuks et al. 2000, Sedjuks & Rocens 2003b).
The structure was calculated for the basic combination of loads – the dead weight of the structure (0.27 kPa) and the weight of snow (1.12 kPa) – evenly distributed on the horizontal projection of the roof. The design load in the form of pointwise forces was applied to the nodes of the cable net. The roof had the following layers: a glass net coated with polymer resin (2 mm), foam plastic, reinforced with a glass net (120 mm), and saddle-shaped plywood sheets (6 mm) (Rocens et al. 1999).

The cable net was prestressed by applying tension forces to the suspension and stressing cables, such that the residual tension forces in the stressing cables were equal to 20% from their initial values under the vertical design load.

Two variants of support points of the main diagonal suspension cables fixation were considered:
− the displacements of the cable net at the support points were restricted by the deformation of the guys;
− the relations excluding any displacements were imposed on the support points of the cable net.

The cross-sectional areas of the cables occurring in the symmetry plane (the main diagonal cables), as well as the pointwise forces applied to the nodes of these cables, were divided by two. The pointwise force applied to the intersection node of the main diagonal cables was divided by four.

Maximum vertical displacements of the cable roof for all combinations of the main geometrical characteristics of the cable truss were determined as a maximum difference in the vertical coordinate of the cable net nodes before and after application of design vertical load. The dependence of the maximum vertical displacements of cable net on the initial deflection of top chord of the cable truss and distance between the support points of tie-bars is shown in Fig. 4.

Figure 4. Maximum vertical displacements $\delta$ vs. the initial deflection $f_{ij}$ of top chord of cable truss and distance $a_{ij}$ between the support points of tie-bars: 1 – displacements of the cable net at the support points are restricted by the deformations of the guys; 2 – the support points of the cable net are fixed.

The dependence shows, that the minimum values of vertical displacements of cable net were obtained, when the initial deflection of top chord of cable truss was equal to 16 m and distance between the nodes of the cable truss was equal to 2.8 m for both variants of support points fixation.

The dependence of the effectiveness of cable net materials using for maximum vertical displacements decrease on the initial deflection of the top chord of cable truss and distance between the cable truss nodes is shown in Fig. 5.
The effectiveness of cable net materials used for maximum vertical displacements decrease was determined from the formula:

$$\mathcal{E} = \frac{\Delta \delta}{V/A}$$

(1)

where $\Delta \delta$ is maximum vertical displacements decrease, $V/A$ is the volume of the material of the cable net per unit of the covered area (relative volume).

The cross-sectional areas of the cables were found according to the recommendations given in (Serdjuks & Rocens 2003b), from the formula:

$$F \geq \frac{1.6N}{kR}$$

(2)

where $F$ is the cross-sectional area of the cable, $N$ is the design force in the cable, $k$ is a coefficient, taking into account the drop in the breaking force of the cable caused by the inhomogeneity of stress distribution, $R$ is the ultimate strength of the cable material, and 1.6 is the reliability index of the material.

The area, covered by the roof was found with regard to the initial deflections of tension cables.

The dependence shows, that decrease by 31% of maximum vertical displacements values is joined with the growing by 24% of relative volume of cable net materials expenditure for the variant, when the displacements of the cable net at the support points are fixed. Maximum vertical displacements decrease by 38% in the case, when displacements of cable net were restricted by the deformations of the guys. Relative volume of the cable net materials consumption grows by 27% in the case.

The maximum value of the cable net materials consumption was obtained, when the initial deflection of top chord of cable truss was equal to 16 m and distance between the nodes of the cable truss was equal to 2.8 m.
4 EVALUATION OF RESOURCES ECONOMY DUE TO THE USING OF COMPOSITE CABLE WITH THE INCREASED SPECIFIC STRENGTH

The environmental effect of hybrid composite cable with the increased specific strength using was evaluated as the decrease of the materials and energy consumption.

The decrease of materials consumption was obtained due to the increased specific strength of CFRP, GFRP and Vectran components of hybrid composite cable. The using of hybrid composite cable on the base of steel, CFRP, GFRP and Vectran enables to decrease dead weight of the cable from 2.4 to 2.6 times in comparison with the steel ones. The decrease of relative consumption of cable net materials for saddle-shaped cable roofs with dimensions from 10x10 to 50x50 m is illustrated by the Fig. 6.

Figure 6. Dependence of cable net materials relative consumption on the dimensions of structure: 1 – cable net is made of steel cables; 2,3 – cable net is made of the hybrid composite cable on the base of steel, GFRP, Vectran and steel, Vectran and CFRP; 4 – cable net is made of hybrid composite cable on the base of steel, GFRP and CFRP; P - cable net materials relative consumption; a – dimension of saddle-shaped cable roofs.

The decrease of energy consumption due to the using of hybrid composite cable on the base of steel, CFRP, GFRP and Vectran also was evaluated for saddle-shaped cable roofs with dimensions from 10x10 to 50x50 m. Two types of energy were taken into account:
– energy for the producing of structural materials;
– energy for structural materials transportation.

It was shown, that the using of hybrid composite cables instead of steel ones enables to decrease energy for the producing of structural materials consumption up to 4 times. Energy for structural materials transportation decrease up to 2.6 times.

5 CONCLUSIONS

Rational components for hybrid composite cable with the increased specific strength were chosen. It was shown, that the minimum volume fraction of steel component is within the limits of 0.23 to 0.29 for the cables on the base of steel, CFRP, GFRP and Vectran.

Opportunity to decrease the displacements of composite saddle-shaped cable roof by the using of cable trusses as the main stressing diagonal cable structure was investigated.

It was shown, that the using of cable truss as a structure of main stressing diagonal cable enables to decrease by 31–38% the maximum vertical displacements of the cable net and to increase by 24–27% the relative volume of the cable net materials consumption in the case, when the main stressing diagonal cable is strengthened by the truss, which is made of hybrid composite cable but suspension and tension cables are made of steel.
It was shown, that the using of hybrid composite cables instead of steel ones enables to decrease energy for the producing of structural materials consumption up to 4 times. Energy for structural materials transportation decrease up to 2.6 times.

REFERENCES


Environmental characterization of gypsum-PCM plasters

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1 ABSTRACT:

Improvement in materials and building technologies can contribute to energy efficiency towards more sustainable construction. In this paper it is presented new gypsum based interior plastering system, incorporating phase change materials (PCM). Although for PCM no data is yet available, environmental assessment of gypsum plaster impact from extraction to construction phase is presented. Difference between systems operational energy and related Global Warming Potential was also considered, for a life time horizon of 30 years. Comparison with conventional gypsum plaster is made as reference. Results from experiments carried out in Passy’s test cells show the potential for energy savings of these materials.

2 DESCRIPTION OF MATERIAL

2.1 Field and range of applications

The building sector accounts for about 40% of the energy and greenhouse gases emissions. About one-third of energy’s end-use is consumed directly in buildings, mainly for regulating thermal comfort parameters and general services. In 2000, heating was responsible for nearly 80% of the total energy consumption in an EU average household (Ardente et al., 2007). The most effective ways to improve buildings energy performance are by thermal insulation of the building elements and by energy storage. This way is possible to reduce heat losses, save energy and operational costs with heating and cooling.

Phase change materials (PCM) have been used for improvement of thermal comfort inside buildings by thermal energy storage. PCM have the ability to change its physical state by absorbing or releasing latent heat at constant temperature, with much greater energy than the energy stored by sensible heat. PCM can be either organic, such as paraffin waxes or fatty acids, or inorganic, usually salt hydrates. Organic PCM have lower thermal storage capacities when compared to salt hydrates but have the advantage of lower thermal conductivity, leading to uniform transitions and stability of properties in time, under thermal cycling. Paraffin’s are cheap and present a wide range of melting temperatures, allowing the suitable choice to the end-use, result of the widespread refining process facilities and processes. Nevertheless their price tends to increase, with fossil fuels prices rising.

Gypsum wallboard incorporating PCM has been studied as passive solar system in lightweight construction has a mean to reduce overheating problems in summer and to decrease heating needs during winter. In buildings with high thermal mass, this problem is not so effective.
The incorporation of PCM seems therefore also a logical way to shift peak demands from network to night period.

Gypsum plasters exhibit good insulating properties due to low conductivity and high thermal inertia, very good hygrometric behaviour acting as a moisture regulator, high composition stability, good tensile and bending strength absorbing background movement, very good fire resistance and acoustic properties.

In order to avoid leakage during melting and freezing cycles and ensure density through materials lifetime, containment of the PCM inside the gypsum plaster matrix must be ensured. One way to do it is by microencapsulation in a thermosetting resin, supporting volume variation of the PCM during transition and increasing surface transfer area. The microencapsulated PCM exhibits good latent heat (thermal storage), low thermal conductivity and good fire properties. In the form of a powder it is easy to incorporate in plasters during production or mixing stage.

By incorporating PCM, the construction elements’ thermal mass is significantly increased. When compared to conventional plaster, the system contributes to a more effective interior temperature regulation, reducing maximum and increasing minimum temperatures, by absorbing and releasing latent heat. It is expected that mainly in autumn and spring, energy costs be reduced by shifting energy consumption to night period, when the cost is lower. Besides that, this advantage is archived with just a small increment in the initial cost, when compared to conventional solutions. As little maintenance is required, life-cycle period is not affected when compared to conventional solutions.

2.2 Components

The presented product is a finishing plaster that incorporates PCM and gypsum and is based in a conventional plaster, containing over 50% gypsum binder, fillers, water retainers and setting retarders mixed with a dispersion of commercial hexadecane paraffin wax, micro-encapsulated in a melamine-formaldehyde resin (low formaldehyde content), with an average particle size distribution of 20-30 µm, melting temperature around 20 ºC and a latent heat of fusion of 140 kJ/kg.

The final mixture, containing 20% weight PCM (70-80% weight paraffin), is mixed with a water/plaster ratio of 65%. Bending, compressive and adhesion strengths were determined according to European Standard EN 13279-2:2004 (CEN 2004) and are presented in Table 1. In-situ specific consumption around 0,75 kg/m² is expected, assuming support regular levelling.

<table>
<thead>
<tr>
<th>Bending Strength (MPa)</th>
<th>Compressive Strength (MPa)</th>
<th>Adhesion Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,77</td>
<td>2,70</td>
<td>0,48</td>
</tr>
</tbody>
</table>

2.3 Installation Techniques

It is possible to apply the presented system using conventional tools and techniques. This system is suitable for every conventional wall support material and is built with a plaster layer of 15 mm thick and three thin hands of gypsum-PCM finishing plaster, which can also be applied over cement render.

The first layer is applied directly to the support and covered with a very thin gypsum finishing plaster layer, manually applied. After at least 12 hours it is applied the first hand of the gypsum-PCM plaster layer, assuming dry weather, temperature bounded between 5 to 40 ºC and good ventilation conditions. There should be an interval of at least 1 hour between the last two hands of gypsum-PCM plaster.

A remark should be made, referring to the mixture procedure of the plaster with water. In order to guarantee the integrity of the microcapsules and the effectiveness of the system in time (i.e. avoid the leakage of the PCM by degradation of the container), it is important to keep the mixer speed low and under control. Additionally, sharp metal paddle edges should be avoided.
2.4 Maintenance

Gypsum plasters require little or no maintenance. Most of the degradation problems are related to moisture and support surface conditions. Maintenance is usually limited to surface treatment consisting in painting within undefined periods. Procedures, equipment and tools are the same as for conventional gypsum plasters.

As mentioned above, gypsum presents very good thermal and hygrometric properties, making it more suitable for interior plastering, due to moisture and comfort regulation effect, when compared to cement mortars. The main disadvantage of gypsum-PCM plasters when compared to conventional gypsum plasters and cement mortar is lower mechanical properties.

When in situ, mainly walls, plaster is sometimes exposed to accidental mechanical actions caused by different object shapes. Analysing the bending, compressive and adhesion strengths, a significant fall in the impact strength is expected. Nevertheless, it is not expected to have big differences in the mechanical behaviour in the final system, when compared to the conventional gypsum rendering, since the gypsum-PCM layer is very thin, and the support layer is assumed to be the same as in the conventional system.

2.5 Demolition

Gypsum recycling is a simple process, consisting mainly in crushing and dehydrating the material at temperatures around 160 °C. Melamine-formaldehyde resins are thermosetting plastics with good temperature resistance. Thermal gravimetric analysis performed (Su et al, 2005), reported degradation of the microcapsules with mass (mainly water) loss up to 20%, at this temperature, therefore further thermal studies should be carried in order to accurate define the recycling procedures for this type of product. Nevertheless selective demolition, dehydration of the product at the mentioned temperature and the incorporation of recycled mixture in new product would be a solution for the life-cycle end of the presented solution.

3 ENVIRONMENTAL ASSESSEMENT

3.1 System boundaries

For this scope, system boundaries are defined from raw materials extraction to final application of the system, in construction site. Difference between systems operational energy and related Global Warming Potential was also considered, for a life time horizon of 30 years. The selected functional unit for this assessment is the quantity of material and related environmental impacts necessary to cover 1 m² of wall.

3.2 Data of considered example

This assessment is based on experimental work that is being carried out in Passy’s type test cell in the University of Minho. The cell, oriented North to South in length, is 4,10 m length x 2,60 m width x 2,50 m high (internal dimensions). Interior floor, ceiling and walls are thermal insulated with a double layer of expanded polystyrene 5 cm thick plates, except for the south façade, consisting in a hollow polycarbonate sheet mounted in a wood frame.

Figure 1. Experimental wall (gypsum-PCM).
An 11 cm hollow brick wall with 4,05 m x 2,50 m was built, dividing the cell in two rooms each with 4,10 m x 1,20 m and leaving an aperture of 65 cm x 60 cm, to allow plastering, instrumentation and maintenance of the East room (this opening was then closed with a double layer of expanded polystyrene 5 cm thick plates and polyurethane foam). Each surface of the wall was covered with a 1,5 cm thick and 14 kg/m² density levelling layer of conventional gypsum plaster. After 24 hours, three very thin layers of finishing plaster were manually applied in both surfaces. In the West surface, gypsum-PCM mixture was used as finishing (Figure 1), while in the East surface was used only conventional gypsum plaster (conventional solution). Table 2 presents the characteristics of the finishing used on both wall surfaces.

Table 2. Material unit data for both solutions in study.

<table>
<thead>
<tr>
<th>Property</th>
<th>Reference Solution</th>
<th>Studied Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastered area (m²)</td>
<td>9,74</td>
<td>9,74</td>
</tr>
<tr>
<td>Gypsum plaster used (kg)</td>
<td>10</td>
<td>7,5</td>
</tr>
<tr>
<td>PCM used (kg)</td>
<td>---</td>
<td>1,9</td>
</tr>
<tr>
<td>Gypsum specific consumption (kg/m²)</td>
<td>1,03</td>
<td>0,77</td>
</tr>
<tr>
<td>PCM specific consumption (kg/m²)</td>
<td>---</td>
<td>0,20</td>
</tr>
<tr>
<td>Storage capacity (Wh/m²)</td>
<td>---</td>
<td>7,6</td>
</tr>
</tbody>
</table>

3.3 Environmental impact categories

Table 3 presents data for the environmental impact of the three different systems: reference and studied solutions and a third, considering different transportation impacts for the studied solution. The probable solution represents the possibility of premixing the components of the gypsum-PCM plaster in the gypsum plant. This possibility was assessed because is the most plausible from the commercialization point of view. Impacts shown are based on inventory results presented below, in paragraph 3, considering all materials of both systems, life-cycle from extraction of raw materials to the end of construction.

Table 3. Environmental impacts of the considered solutions.

<table>
<thead>
<tr>
<th>Impact categories</th>
<th>Unit</th>
<th>Reference Solution</th>
<th>Studied Solution*</th>
<th>Probable Solution*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water use</td>
<td>l/m²</td>
<td>247,3</td>
<td>232,4</td>
<td>232,4</td>
</tr>
<tr>
<td>Energy use</td>
<td>MJ/m²</td>
<td>33,6</td>
<td>33,1</td>
<td>33,2</td>
</tr>
<tr>
<td>Global Warming Potential (GWP)</td>
<td>gCO₂/m²</td>
<td>1075</td>
<td>1046</td>
<td>1055</td>
</tr>
<tr>
<td>Eutrophication Potential (EP)</td>
<td>gNO₂/m²</td>
<td>0,04(1)</td>
<td>0,03(1)</td>
<td>0,03(1)</td>
</tr>
<tr>
<td>Acidification Potential (AP)</td>
<td>gSO₂/m²</td>
<td>38,6</td>
<td>30,4</td>
<td>36,3</td>
</tr>
<tr>
<td>Photochemical Oxidant Creation Potential (POCP)</td>
<td>gNO₂/m³</td>
<td>2,9(2)</td>
<td>2,6(2)</td>
<td>2,8(2)</td>
</tr>
</tbody>
</table>

*PCM impacts were not considered, since life-cycle inventory data is not yet available
1 Considering only the transportation impact
2 Not considering the materials transportation impact

Considering 30 years of operational energy for both solutions, according to the experimental and inventory results, the Global Warming Potential of the studied solution is lower than the reference solution in about 92x10⁶ g of CO₂ per net square meter of the test cell.
4 INVENTORY RESULTS

4.1 Components
The results for inventory of the environmental impacts of system components were collected by Berge (2000) for Central Europe. Gypsum data is based in plasterboard while for PCM no data was found. Table 4 presents data collected.

<table>
<thead>
<tr>
<th>Impact categories</th>
<th>Unit</th>
<th>Gypsum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water use</td>
<td>l/kg</td>
<td>240</td>
</tr>
<tr>
<td>Energy use</td>
<td>MJ/kg</td>
<td>5</td>
</tr>
<tr>
<td>Global Warming Potential (GWP)</td>
<td>g CO₂/kg</td>
<td>265</td>
</tr>
<tr>
<td>Acidification Potential (AP)</td>
<td>g SO₂/kg</td>
<td>3</td>
</tr>
<tr>
<td>Photochemical Oxidant Creation Potential (POCP)</td>
<td>g NOₓ/kg</td>
<td>2</td>
</tr>
</tbody>
</table>

4.2 Package & Transport
For this study, it is considered that system components produced in different plants were mixed at construction site. Gypsum plaster was packed in recyclable Kraft paper bags of 30 kg, stacked in wood pallets and wrapped in PE film, while PCM was packed in reusable plastic bags.

Both gypsum plaster and PCM were transported by road in diesel truck, although from different locations. The distance from gypsum plant to construction site is about 240 km and from PCM plant to construction site is about 30 km.

In case the gypsum-PCM is pre-mixed in the gypsum plant, what for commercial reasons is a possibility that must be taken into account, the total transportation distance for this product would be around 480 km for PCM and 240 km for gypsum.

Table 5 presents the energy consumption and air pollutant emissions, considering both solutions studied and the third possibility presented.

Table 6 presents the transportation’s environmental impacts of the materials to construction site, for the two analyzed systems, as well in the case of the pre-mixed solution.

Table 5. Air pollutant emissions and primary energy consumption during materials transportation (Energy Research Group 1999).

<table>
<thead>
<tr>
<th>Emissions</th>
<th>Reference Solution</th>
<th>Studied Solution</th>
<th>Probable Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (kWh/t.km)</td>
<td>Emissions (g/m²)</td>
<td>Emissions (g/m²)</td>
<td>Emissions (g/m²)</td>
</tr>
<tr>
<td>CO₂</td>
<td>207</td>
<td>51,0</td>
<td>39,5</td>
</tr>
<tr>
<td>CH₄</td>
<td>0,3</td>
<td>0,07</td>
<td>0,06</td>
</tr>
<tr>
<td>NOₓ</td>
<td>3,6</td>
<td>0,89</td>
<td>0,69</td>
</tr>
<tr>
<td>CO</td>
<td>2,4</td>
<td>0,59</td>
<td>0,46</td>
</tr>
<tr>
<td>VOC’s</td>
<td>1,1</td>
<td>0,27</td>
<td>0,21</td>
</tr>
<tr>
<td>Energy</td>
<td>0,8</td>
<td>0,20</td>
<td>0,15</td>
</tr>
</tbody>
</table>
Table 6. Environmental impacts related with materials transportation.

<table>
<thead>
<tr>
<th>Impact categories</th>
<th>Unit</th>
<th>Reference Solution</th>
<th>Studied Solution</th>
<th>Probable Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy use</td>
<td>MJ/m²</td>
<td>0,71</td>
<td>0,55</td>
<td>0,67</td>
</tr>
<tr>
<td>Global Warming Potential (GWP)</td>
<td>gCO₂/m²</td>
<td>52,7</td>
<td>40,8</td>
<td>49,6</td>
</tr>
<tr>
<td>Eutrophication Potential (EP)</td>
<td>gNOx/m²</td>
<td>0,04</td>
<td>0,03</td>
<td>0,03</td>
</tr>
<tr>
<td>Acidification Potential (AP)</td>
<td>gSO₂/m²</td>
<td>35,5</td>
<td>27,5</td>
<td>33,4</td>
</tr>
<tr>
<td>Photochemical Oxidant Creation Potential (POCP)</td>
<td>gNOx/m²</td>
<td>0,89</td>
<td>0,69</td>
<td>0,83</td>
</tr>
</tbody>
</table>

4.3 Installing

For installation no difference between reference and studied solution is verified. Except for the mixture of the plaster, all the work is manually done and no additional energy consumption is required. Table 7 presents data for the installation environmental impacts. According to the Portuguese energy mix, 500 g of CO₂ equivalents are produced per each kW of delivered energy. The mixture was performed with a 1500 W plaster mixer, during 1 minute per hand.

Table 7. Environmental impacts of installation procedures.

<table>
<thead>
<tr>
<th>Impact categories</th>
<th>Unit</th>
<th>Reference Solution</th>
<th>Studied Solution</th>
<th>Probable Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water use</td>
<td>l/m²</td>
<td>0,72</td>
<td>0,63</td>
<td>0,63</td>
</tr>
<tr>
<td>Energy use</td>
<td>MJ/m²</td>
<td>27,7</td>
<td>27,7</td>
<td>27,7</td>
</tr>
<tr>
<td>Global Warming Potential (GWP)</td>
<td>gCO₂/m²</td>
<td>750</td>
<td>750</td>
<td>750</td>
</tr>
</tbody>
</table>

4.4 Operation – Thermal monitoring

In order to evaluate systems performance and assess environmental impacts during operation, temperatures and relative humidity of both rooms and wall surface temperatures were monitored. Figure 3 presents temperature data collected during the first 3 monitored days of approximately 26 days of experiment (640 hours).

Figure 3. Measured air and wall temperature profiles for the two test rooms.
From the results obtained was possible to verify that PCM has a benefit effect in room environment, decreasing maximum and increasing minimum temperatures up to 3°C and 1°C respectively. Higher minimum temperatures in PCM room were expected, however, the high outside temperatures during the period in which this experiment ran, inhibited in large extent the material from freezing, releasing the stored fusion heat (hexadecane paraffin has a melting temperature around 20°C but the freezing temperature is around 18°C).

The amplitude between wall and room temperatures is higher for the reference side as expected. For the reference room, 3°C in maximum and 1°C in minimum temperatures were observed, while in the PCM room, these values were both about 1°C. Additionally, the delay between maximum wall temperatures shows the heat absorbing during melting and heat transfer from the room to the wall.

In rooms with low thermal mass such as test cells used, the incorporation of PCM effectively contributes to the increase of this characteristic. This can be seen in Fig. 3 with the delay in maximum temperature of the PCM wall, in particular occurring for temperatures over 22°C, after PCM fusion.

From temperatures measured, the different heat fluxes between the wall and the air were calculated for both solutions, in order to isolate the PCM effect. Table 8 presents the results achieved. Here are represented the thermal resistance between wall surface and air (R), wall and room areas (A墙 and A房), the difference of heat fluxes between wall surface and air for both solutions during the total period analysed and hourly (∆QT和 ∆QH) and these heat fluxes per functional unit considered (∆Qw, ∆Qannual, ∆Qf and ∆QWF).

Table 8. Difference between heat fluxes for the considered solutions.

<table>
<thead>
<tr>
<th>R (m².ºC/W)</th>
<th>A墙 (m²)</th>
<th>A房 (m²)</th>
<th>∆QT640 (W)</th>
<th>∆QH (W)</th>
<th>∆Qw (W/m²_wall)</th>
<th>∆Qannual (MW/m²)</th>
<th>∆Qf (W/m²_floor)</th>
<th>∆QWF (W/m²_wall.m²_floor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,13</td>
<td>9,74</td>
<td>4,92</td>
<td>12164</td>
<td>19,0</td>
<td>2,0</td>
<td>61,6</td>
<td>3,9</td>
<td>0,4</td>
</tr>
</tbody>
</table>

4.5 Maintenance

Assuming regular use of the habitation and its elements, maintenance is almost irrelevant, as stated in paragraph 1.3. Should there is any accidental impact by a sharp object, it could be necessary to repair the affected area. In this case, procedures which are similar to reference solution, involve the application of new plaster in the affected area. Repairing procedures, equipment and tools of these plasters are the same as for conventional plasters, with the remark of paragraph 1.3.

4.6 Demolition

The presented system shows no difference to reference system when selective demolition is carried. Both solutions require the transport of construction waste to gypsum plant for recycling.

5 COMPARISON BETWEEN SOLUTIONS

Comparison between presented solutions should be done in terms of physical, mechanical and thermal properties. An interesting extra comparison can be made with other possible solutions, namely cement renders.

In terms of mechanical properties, as referred in paragraph 1.2, the gypsum-PCM system presents lower performance due lower binder content of the final plaster with the PCM not presenting binding nor filling characteristics. Obviously when compared to cement mortars, both reference and studied system have lower performance however, considering appropriate use, durability of the studied system is very good.
Hygrometric behaviour is at some extent improved with the incorporation of PCM. From the experiment that was carried out it was observed that relative humidity (HR) in the PCM room is lower (average around 55% versus 62%) and with narrow amplitude (around 20% versus 40%). Both systems present better moisture regulation effect when compared to cement render.

Thermally the studied system presents the advantage of latent heat storage, which occurs at approximately constant temperature and can contribute both to delay in time and reduce maximum temperature and increase minimum temperature. In the study presented, the effect on minimum temperature was not verified due to outdoor high temperatures, disabling the PCM to discharge, however an increase in thermal mass was observed. In terms of thermal conductivity, both systems should present similar values, since PCM is approximately the same as gypsum (0,25 W/m.ºC). Both solutions present better thermal performance when compared to cement mortar, which has higher thermal conductivity (0,70 W/m.ºC).

The lack of LCI data available for PCM and the outdoor weather conditions (high temperatures) for the period during which the experiment ran are difficulties to overcome for the accurate assessment. It is expected that mainly during autumn and spring when during daytime temperatures can rise up to 20-25ºC but in the night fall to 5-10ºC, PCM used can more efficient, loading and discharging energy, instead of mainly acting as inertia thermal mass, as in the case of this experiment.

In spite of not considering the environmental impacts of the PCM, it is expected that the studied solution presents higher impacts until the end of the construction phase, since PCM is petroleum derived.

Although, in a life-cycle assessment that involves operation phase, the lower operational impacts dilute the materials’ embodied impacts. Considering a time horizon of 30 years, data collected and the Portuguese energy mix, reference system would need to be provided with 61,6 MW/m², for the same energetic performance of the studied system, corresponding to more 92x10⁶ gCO₂/m² GWP.

6 CONCLUSION

From the performed assessment it is possible to see that the benefits of the incorporation of PCM in gypsum plasters. This system presents environmental advantages that produce both indoor comfort and economic benefits. The calculated environmental assessment shows that the PCM system presents similar impacts in all categories but a much smaller impact in terms of GWP due to energy conservation during operation phase.

Comparison between the studied solution and the probable solution presented shows no significant difference in all considered impacts, which from the commercial point of view is very positive, revealing that is possible to develop a new sustainable product, based in some materials whose sustainability has been very discussed, like PCM petroleum derived.

REFERENCES


The development of a new methodology for the estimation of durability of facade paints

R.Norvaišienė, E.Smetonaitė, V.Dikavičius
Institute of Architecture and Construction of Kaunas University of Technology, Kaunas, Lithuania

ABSTRACT: The Laboratory of Building Thermal Physics at the Institute of Architecture and Construction in Kaunas has carried out a number of experiments to improve the test methods of facade paint durability investigation by including the impact of air pollution. A painted rendering with the roughened surface was the principal test material. The paper offers a detailed description of the improved accelerated weathering test. The test results obtained after 96 days of exposure to the UV radiation, temperature and acidic rain in the climatic chamber have been compared with the ones obtained with the unexposed and naturally weathered samples. The performance assessment is based on the intermittent measurements of water permeability properties of the paint coatings expressed by 2h surface water absorption rate of the painted samples during the weathering process. The correlation between natural weathering and the accelerated artificial ageing has been established to be sufficient.

Facade paints decorate the building facades and protect them against the deteriorating atmospheric effects. Since rendering is an expensive procedure requiring high skill on the part of the workers the choice of a proper and durable paint coating is of extreme importance.

With the increase of the paint coating’s water permeability during exploitation, the rendering under the coating is affected by the climatic factors more intensively – it gets aged sooner. One of the least investigated factors that play an important role in the acceleration of the facade finishes deterioration is air pollution causing the phenomenon of acidic rains. Due to acidic precipitation caused by air pollution, additional acidic effects occur. Together with other climatic factors such as the ultraviolet radiation, temperature and moisture, air pollution is considered a deteriorating agent badly affecting the building materials (Yates 2002, Haneef et al. 1988, Haynie et al. 1984, Norvaisiene et al. 2003).

It is important to define the laboratory parameters of the cyclic accelerated artificial ageing of the facing materials in order to find out the relation between climatic ageing and natural weathering thus affording the opportunity to prognosticate the real durability of the facade paints under natural ageing conditions.

The results of accelerated laboratory ageing of the painted rendering in the climatic chamber are compared with the ones obtained during natural weathering.

The paper discusses the development of the climatic ageing cycle for the painted building facades modelled on the basis of the obtained results and Lithuanian statistical climatic data.

1 ANALYSIS AND MODELING OF CLIMATIC FACTORS

During the last decades, the ageing of facing materials of the building enclosures has grown more intensively which determined the demand for a more accurate prognosis of the state of the building finish with regard to the main climatic destructive agents. The growing requirements
for the quality of building construction and increasing atmospheric pollution urge to investigate the reasons that determine the ageing of the exterior finish under the impact of outdoor climate.

1.1 Modelling of solar impact in a climatic chamber.

In Lithuania, the ultraviolet (further UV) radiation makes only 6% of the whole solar radiation, however, in the spectrum of all solar radiation waves its impact on the ageing of the finish material is the most extensive. That is why, during the analysis of the impact of solar radiation on the ageing of the building materials, only the impact of the ultraviolet waves has been modelled.

The intensiveness of ultraviolet radiation in a climatic test chamber has been calculated on the basis of the highest hourly intensiveness of solar radiation onto a vertical south-western surface. In the 290-450 mm ultraviolet radiation wave range, under the conditions of the climatic chamber the radiation intensiveness was 40 W/m². The calculated radiation period embraced 456 h/yr.

1.2 Modelling of temperature impact.

Temperature fluctuation causes the deformations in the painted rendering’s external layer, which by frequent recurrence exhaust the material. Actually, the intensity of drying as well as the moisturous state of the tested materials depends on temperature conditions. Thus, in the climatic chamber, the drying of tested materials was modelled with respect to:

1) high outdoor temperature;
2) incandescence of the surface due to direct solar radiation.

Heating. The following temperature regimes have been worked out:
- ambience temperature 29 °C, relative humidity (45-50)% – 180 h/yr,
- ambience temperature 39 °C, relative humidity (25-30)% – 100 h/yr,
- ambience temperature 49 °C, relative humidity (15-18)% – 75 h/yr.

Unilateral freezing. The greatest deteriorating effect has been suffered by the external surface layer of the moistened wall in which water gets frozen up and thawed. On the basis of the climatic data it has been found out that the impact of the annual natural frost cycles on the painted rendering should be imitated by 10 freezing cycles per year each lasting for 5 hours at the ambient air temperature of −0.5 °C.

1.3 Modelling of rain impact.

Acidic rains are formed due to the entering of sulphur and nitrogen combinations into atmospheric air (Sopauskiene 2001). Under solar radiation and due to the chemical admixtures found in the air as well as humidity these harmful materials turn into sulphuric and nitric acids. Naturally, unpolluted precipitation is subacidic – the average pH value makes 5.6 because atmospheric water reacts with CO2 thus forming carbonic acid. The pH values of acidic rains formed by air pollution are 4-4.5 or sometimes lower. Fog water comes out to be the most acidic one (pH = 2.5).

Acidic rain and clean rain duration periods and their amounts affecting the southwest building wall in its most moistened places (where the intensity of the rain is about 2.5 times higher than the average value) were calculated with the use of the specially composed computer calculation program “Moisture”. The results of calculations are presented in Table 1. This program has been written for the purposes of this research in the Laboratory of Building Thermal Physics at the Institute of Architecture and Construction.

Table 1. Average amounts and duration periods of acidic and clean rains per year (1988-1998) on a vertical southwest oriented surface, calculated with the computer calculation program “Moisture”
<table>
<thead>
<tr>
<th>Data collection of acidic rain (pH=4.5)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total rain duration 183 h/yr (49 times)</td>
</tr>
<tr>
<td>Rains during which water absorption is $\Delta \omega \leq 1.5%$ were neglected</td>
</tr>
<tr>
<td>Average rain duration 5 h</td>
</tr>
<tr>
<td>Rain duration 3-4 h, water absorption $\Delta \omega \equiv 2%$ - 15 times;</td>
</tr>
<tr>
<td>Rain duration 5-6 h, water absorption $\Delta \omega \equiv 3%$ - 11 times;</td>
</tr>
<tr>
<td>Rain duration 7-8 h, water absorption $\Delta \omega \equiv 4%$ - 7 times.</td>
</tr>
<tr>
<td>In average water absorption during acidic rain $\Delta \omega \equiv 2.8%$, repetition – 33 times/yr</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data collection of clean rain (pH=5.6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total rain duration 347 h/yr (36 times)</td>
</tr>
<tr>
<td>Rains during which water absorption is $\Delta \omega \leq 1.5%$ were neglected</td>
</tr>
<tr>
<td>Average rain duration 9.6 h</td>
</tr>
<tr>
<td>Rain duration 4-5 h, water absorption $\Delta \omega \equiv 2.5%$ - 8 times;</td>
</tr>
<tr>
<td>Rain duration 6-7 h, water absorption $\Delta \omega \equiv 3.5%$ - 8 times;</td>
</tr>
<tr>
<td>Rain duration 8-9 h, water absorption $\Delta \omega \equiv 4.5%$ - 4 times;</td>
</tr>
<tr>
<td>Rain duration 10-12 h, water absorption $\Delta \omega \equiv 5.0%$ - 7 times;</td>
</tr>
<tr>
<td>Rain duration 13-18 h, water absorption $\Delta \omega \equiv 6.5%$ - 8 times;</td>
</tr>
<tr>
<td>Rain duration $\geq 19$ h, water absorption $\Delta \omega \equiv 7.0%$ - once.</td>
</tr>
<tr>
<td>In average water absorption during clean rain $\Delta \omega \equiv 4.4%$, repetition - 36 times/yr</td>
</tr>
<tr>
<td>Both acidic and clean rain average duration is 7.35 h, average water absorption during rain $\Delta \omega \equiv 3.6%$, clean rains – 36 times/yr and acidic rains – 33 times/yr.</td>
</tr>
</tbody>
</table>

*Note: it was based on assumption that an acidic rain is to be if the amount of rain is not more than 2 mm.

On the basis of ten-year statistical climatic data (rain, its intensity, amount and duration; wind speed and direction; average monthly temperatures and monthly round day temperature fluctuation amplitudes) the moistening of the painted rendering during rain has been calculated as well as the duration periods of acidic and clean rains. To work out the calculation program, laboratory tests were carried out and the surface water absorption and drying curves for the samples of the painted rendering were determined at different temperatures, wind speed and relative air humidity.

The laboratory experiments led to the determination of the fact that the winds of average velocities and relative air humidity do not have a significant drying effect on the painted surfaces (Paukstys 2002, Norvaisiene 2004) as temperature does. Therefore the computer program was employed exclusively for the estimation of the impact of temperature to the drying rate to the outside painted rendering layer.

Materials used for tests. For the working out of the painted rendered facade durability tests related with the climatic destructive factors, the tests were performed with the standard factory prefabricated plastic cement-lime rendering mixture (mark SIIa, S5, 0/2). The CO$_2$ analysis showed that the amount of chalk in the mixture was higher than 30 %; the ratio of water and dry materials in the rendering mixture made 20 %. Out of it the 100 mm in diameter and 25 mm thick circle samples were made, some used for the laboratory tests and others exposed to natural weathering (Fig. 2). The samples were formed in plastic rings until they set. After samples begin to set, the excess of material was whisked out and surface blotted – to get a naturally rough surface as it does on building site. The size and shape of samples was chosen in order to measure the water vapour resistance of them during ageing tests.

The following facade rendering paints of four different sorts were chosen: water vinyl co-polymeric (V); acrylic, modified by silicon water dispersive (A); water polyurethanes (P) and the PVA latex paints (E). These are the typical examples of the rendering finish paints most often used in Lithuania. The sides of the samples were covered with several layers of the epoxy paint coating. For the research purposes 70 peaces of samples have been prepared.

The acidity of precipitation in 1981 – 1990 at an average was pH = 4.5, the acidity of fog water, in its turn, at an average made pH = 2.5. The acidic water solution composed of H$_2$SO$_4$ and HNO$_3$ acids with pH = 2.5 was used to imitate the impact of natural precipitation and fog during the artificial accelerated ageing process of samples in the climatic chamber. Acidic water solutions affect the render material by penetrating through the paint cover (the more water-permeable the paint cover, the greater absorption is caused) and encourage chemical reactions in it, during which new calcium compositions are formed. The authors relied on the research results, obtained during the earlier laboratory tests (Norvaisiene 2004), during which the
relationship between the impacts the painted samples after moistening them in different water solutions (whose acidities pH = 2.5, pH = 4.5 and pH = 7.0) was determined. On this basis, the total weathering time in a climatic chamber to imitate one natural year with use of acidic water solution pH = 2.5 was enabled to shorten to 24 round days.

Types of the employed ageing tests. The two types of durability tests have been carried out – under natural weathering and artificial accelerated weathering in a climatic chamber. For natural weathering the sample panel was constructed and attached to the external southwest wall of the building in a height of 3.5 m from the ground. The surface and air temperatures, relative humidity of air were monitored and recorded every 15 min. In order to create the conditions close to natural ones, the joints at the perimeter between the panels and the wall were insulated and sealed.

Artificial accelerated weathering has been carried out in a climatic chamber. The results of both types of tests have been compared with each other.

Evaluation of ageing. The physical ageing of paint coating has been considered in the research. It is considered that the paint coating has lost its protective quality as the 2h water absorption value reaches the value of unpainted render (Norvaisiene 2006).

2 DURABILITY TESTS OF THE PAINTED RENDERING SAMPLES

2.1. The Cycle of Climatic Tests

The climatic chamber used for the experiment was made in the Laboratory of Building Thermal Physics at the Institute of Architecture and Construction in Kaunas.

The aim of the complex accelerated climatic tests was to verify the suitability of the worked out methodology for ageing of the painted rendering by investigation of the impact of the temperature-moisture caused deformations on the ageing of the painted rendering.

The climatic cycle by which the samples were treated was worked out to imitate the natural climatic factors on the most unfavourable places of facade. In the climatic cycle, the imitation of the UV solar radiation, temperature alterations and precipitation as based on the calculations of annual statistical data (Table 2).

<table>
<thead>
<tr>
<th>Process No.</th>
<th>Process</th>
<th>Temperature, °C</th>
<th>Temperature change rate, °C/h</th>
<th>Relative humidity, %</th>
<th>UV radiation</th>
<th>Spraying</th>
<th>pH</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Spraying</td>
<td>+7</td>
<td>-</td>
<td>-</td>
<td>UV</td>
<td>yes</td>
<td>2,5</td>
<td>1 minute</td>
</tr>
<tr>
<td>2</td>
<td>Freezing/</td>
<td>+7</td>
<td>-</td>
<td>-</td>
<td>UV</td>
<td>–</td>
<td>–</td>
<td>29 minutes</td>
</tr>
<tr>
<td></td>
<td>Heating</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Spraying</td>
<td>+6</td>
<td>-</td>
<td>-</td>
<td>UV</td>
<td>–</td>
<td>2,5</td>
<td>7 h</td>
</tr>
<tr>
<td>4</td>
<td>Freezing</td>
<td>-10,5</td>
<td>-</td>
<td>-</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>5 h</td>
</tr>
<tr>
<td>5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>UV</td>
<td>–</td>
<td>–</td>
<td>0,5 h</td>
</tr>
<tr>
<td>6</td>
<td>Heating</td>
<td>+29</td>
<td>60</td>
<td>–</td>
<td>UV</td>
<td>–</td>
<td>–</td>
<td>18 h</td>
</tr>
<tr>
<td>7</td>
<td>Heating</td>
<td>+39</td>
<td>60</td>
<td>40</td>
<td>UV</td>
<td>–</td>
<td>–</td>
<td>2 h</td>
</tr>
<tr>
<td>8</td>
<td>Heating</td>
<td>+39</td>
<td>–</td>
<td>–</td>
<td>UV</td>
<td>–</td>
<td>–</td>
<td>8 h</td>
</tr>
<tr>
<td>9</td>
<td>Heating</td>
<td>+49</td>
<td>–</td>
<td>–</td>
<td>UV</td>
<td>–</td>
<td>–</td>
<td>7,5 h</td>
</tr>
</tbody>
</table>

The natural climatic impacts of a round year suffered at the most unfavourable places of the building’s facade were imitated in the climatic test chamber (Table 3).
Table 3. Cycling in the climatic chamber

<table>
<thead>
<tr>
<th>Duration</th>
<th>Sequence of processes in cycling</th>
<th>Repetition</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 days</td>
<td>Alternation of 1 and 2 processes</td>
<td>once</td>
</tr>
<tr>
<td>2 days</td>
<td>In course 3,4,5,6,7,8,9 processes</td>
<td>5 times</td>
</tr>
<tr>
<td>2 days</td>
<td>Alternation of 1 and 2 processes</td>
<td>once</td>
</tr>
<tr>
<td>2 days</td>
<td>In course 3,4,5,6,7,8,9 processes</td>
<td>5 times</td>
</tr>
</tbody>
</table>

During 24 round days the natural one-year ageing effect was imitated in the climatic chamber:
- For 48 h the impact of fog and dew at 9 ºC (alternation of 1 minute spray with water solution whose pH = 2.5 with break for 29 minutes);
- For 456 h the impact of the UV radiation: intensity 35 - 40 W/m² @ 290 – 400nm;
- Freezing 10 times for 5h at -10.5 ºC;
- 10 times for 7 h rain imitation with the help of the water solution whose pH = 2.5;
- High temperature impact: drying at 29 ºC for 180 h; 39 ºC for 100 h; 49 ºC for 75h.

2.2. WATER ABSORPTION OF THE SAMPLES AGED IN THE CLIMATIC CHAMBER AND THE COMPARATIVE ANALYSIS OF THE CHAMBER AND THE NATURAL TEST RESULTS

Water permeability of the wall’s external surface coating depends on the water absorption rate and the potential of penetration depth into the wall’s construction during rain. The surface water absorption rate of the building materials shows what amount of water has been absorbed by the surface due to the material’s capillary sucking potential. The transfer of the liquid moisture in a material was caused by the capillary attraction, osmotic and gravitational forces. The earlier investigation (Norvaisiene 2004, Norvaisiene 2006) revealed, that the 2h (initial) water absorption rate of the painted rendering should be considered a reliable and simple indicator of the ageing of the protective properties of the paint coating. However, the 24h water absorption coefficient of the painted renderings is not so sensitive and reliable. The same samples every 4 months (natural weathering) and 24 days (artificial ageing) were taken out and capillary water absorption, drying rates curves as well as initial intensities of water absorption rate were determined: after drying in the oven at 50ºC, the samples were immersed, exposed faces down into 1-3mm of distilled water and then were weighted at various time intervals.

After the 4 years imitation in climatic chamber, an obvious increase of the samples’ initial surface water absorption rate was discovered (Fig 1).

![Figure 1](image-url)

Figure 1. The 2h surface water absorption rates of the samples (V) painted with water based vinyl copolymeric paint during the weathering in the climatic chamber
Table 4 presents the results of the 2h surface water absorption rate alterations observed under natural weathering and during the climatic tests in the chamber.

Table 4. The 2h initial surface water absorption rate of samples during the climatic tests and under natural weathering, % of mass by mass moisture content

<table>
<thead>
<tr>
<th>Sample</th>
<th>Untreated</th>
<th>Imitation of the natural year in the climatic chamber ('strong' cycling test)</th>
<th>Natural weathering</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 year</td>
<td>2 years</td>
</tr>
<tr>
<td>V</td>
<td>0.58</td>
<td>4.24</td>
<td>8.44</td>
</tr>
<tr>
<td>E</td>
<td>1.65</td>
<td>8.52</td>
<td>10.69</td>
</tr>
<tr>
<td>P</td>
<td>0.49</td>
<td>5.29</td>
<td>9.18</td>
</tr>
<tr>
<td>A</td>
<td>0.22</td>
<td>0.20</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Note: the 2 h water absorption rate of unpainted rendering — in average (11-12)%.

In the case of the imitation of a natural year in the climatic chamber, the water absorption rate of the painted rendering samples (E) approaches the water absorption rate of the unpainted render already within two years. When in the climatic chamber, well rendering protective acrylic paint coating (A) undergoes ageing very slowly yet considerably. After four years of ageing their protective properties still remain a bit better than those of the vinyl co-polymeric (V) paint coating after a year of ageing.

Having compared the ageing of the samples (E) in the chamber with that under natural weathering in the panel, it has been observed that both cases demonstrated a similar degree of ageing. The degree of the water absorption rate got diminished after a few years of weathering due to the new combinations composed in the rendering material, in other words, due to salt crystallization.

Due to the impact of the seasonal changes on the properties of the naturally aged samples’ water absorption (Norvaisiene 2006) all the results of the water absorption rate during each calendar year of natural weathering were averaged. The increase of the averaged water absorption rate after one year of weathering reached 0.57 % (Fig 2). Fig 1 demonstrates that, after one year of imitation, the growth of the surface water absorption rate of the samples (V) aged by the climatic cycles in the climatic chamber made 3.66 %.

![Figure 2](image_url)

Figure 2. The 2h surface water absorption rate of the samples (V) painted with the water based vinyl co-polymeric paints during natural weathering
The ageing of the painted coating during natural weathering was slower than in the climatic chamber. Natural weathering lasted for 2 years and the climate of the period was mild in comparison with an average statistical year. The complex climatic cycle was worked out on the basis of the 10-year climatic data. The test panels used for natural weathering were located in the middle of the southwest wall, i.e. the place that was inconsiderably moistened by the driving rain (about 0.41 times in comparison with an undisturbed vertical plane (Lvov 1982). The rain intensities onto most unfavourable places of a vertical wall surface affected by the driving rain are being 2-3 times greater than the intensity onto undisturbed vertical plane (Lvov 1982).

During the complex climatic weathering tests in the climatic chamber the water spraying intensity was increased 2.5 times thus imitating the most unfavourable rain-washed and moistened places on the vertical southwest wall. Hence by having estimated the discussed coefficients, during natural weathering the annual increase of the water absorption rate in the samples (V) coated with the water-based vinyl co-polymeric paints could make up to $0.57\times2.5/0.41 = 3.45\%$. Therefore, it is possible to claim that, practically, the accelerated ageing in the climatic chamber corresponds to the ageing of the samples under natural conditions.

After four years of weathering in the climatic chamber, the decision was made to stop the tests due to the physical and aesthetic deformity of the samples. The paint coating lost its physical protective properties; blisters appeared and the paints got deteriorated (i.e. the samples were worn out aesthetically).

3 CONCLUSIONS

The carried out experiments demonstrated that the improvement of the methods for determining the facade paint durability is a relevant field of scientific enquiry and practical achievement. Therefore the method determining the durability of the exterior wall finish with regard to the impact of air pollution might be widely applied for the more accurate prognosis of the exterior wall finish durability dependant on the climatic specificity of a particular locality.

One of the most significant factors for the facade paint durability is the impact of the moisture deformations caused by the moistening-drying cycling which is strengthened by acidic precipitation. Therefore, the accelerated climatic tests should also contain the precise and exhaustive modelling of the effect of the moistening-drying cycling and acidic precipitation.

The physical ageing of the paint coating usually appears before the visual defects. This physical degradation of the paint coating put on the rendering is faithfully defined by the increment of the sample’s $2h$ (initial) surface water absorption rate.

In order to increase the durability of rendered facades, the paint coatings demonstrating low water permeability yet preserving good vapour permeability should be used.

The composed artificial ageing methodology is adapted for Lithuanian climate conditions, but the principals are common to use it in other localities with similar climate too. The offered methodology for the investigation of the painted rendering’s durability may be employed both for the determination of the physical ageing of the paint coating and for the estimation of the alteration of its aesthetic appearance.

REFERENCES


Yates, T. 2002. Mechanisms of Air Pollution Damage to Brick, Concrete and Mortar. In:


INTRODUCTION

The importance of wood as a building material and its role to be played in a sustainable development will decisively depend on the amount to which it will guarantee an economic and high-quality solution of our tasks. Therefore it is not enough to possess a renewable raw material it also has to come up to today’s and future expectations.

Engineers decide on the use of certain materials according to technical and economic points of view. In the course of their academic education they deal with a great variety of building and engineering materials that still will increase in the future. In contrast to craftsmen engineers are not bound to use a special material, nevertheless wood is excluded from use in many fields of engineering right from the beginning. Only in civil engineering there is the application of wood still seriously taken into account. Despite ecological advantages a decision in favour of wood always requires technological and economical arguments. For that reason science and technology should create the preconditions for an efficient and more frequent use of this resource.

The forest is not only one of the greatest but also one of the cheapest producers of material in the world. It is difficult to believe that a material produced on one third of the area of our country with the help of solar energy is inferior with regard to its price to materials that are produced using large amounts of fossil energy and capital. One significant reason for this can be seen in the fact that the forest is not considered as producer of material but as producer of cross sections. We will have a closer look at this later.

Moreover, we have to ask what further disadvantages prevent the use of wood for technical applications and whether they can be removed or not. In particular these are
1. the low strength spectrum as compared to structural materials
2. the directional dependence of the mechanical properties, the so-called anisotropy, and
3. the low weather resistance.

DENSE, DENSER, DENSEST

Wood has a well-balanced profile of properties, but nearly always specialised materials surpass certain properties of wood. It is without question that wood is ecologically beneficial as long as

ABSTRACT: Generally spoken, difficulties in wood construction arise from four sources: the bad material efficiency compared to technical materials, the low strength spectrum, anisotropy as well as preservation. This paper deals with several technologies coping with these drawbacks. A new technology that transforms raw wood into profiles which considers the material as a cellular solid is being presented. Technical textiles turn out as a versatile technique that improves structural performance and serviceability.
Figure 1. Spruce squared timber cross section before and after densification.

this is not ruined by additional treatment. Also the price per unit mass, that even allows a thermal use, is cheaper than of most other materials of our time.

The mechanical parameters play a central role for load bearing structures and mostly depend on density and growth structure. The differences among different kinds of wood amount to approximately one order of magnitude. The comparison between structural building timber and timber with parallel fibres and without knots and irregularities in growth presents additional differences so that the unused strength potential increases to a total of a good order of magnitude.

The densification of wood (see fig. 1), especially hard wood, using heat and pressure is a technique in wood production known since long. Also nowadays resin-bonded veneer panels, e.g. for electric installations, are produced in this way. The precondition for the densification is the cell construction of the wood that allows densification by means of a press after the softening temperature of the lignin was reached. Thanks to this thermo-mechanical treatment strength and stiffness can be increased proportionally to densification. Further heating above 200 °C leads to an increase in biological resistance, so that the heat influences two important properties, i.e. strength and durability.

Figure 2 presents strength classes of different building materials and their compounds. In this regard wood shows low increments that can be significantly increased by the use of timber with parallel fibres and densification (see fig. 3).

![Strength Classes](image)

Figure 2. Strength values and classes of today’s building material and newly developed building materials.
3 FROM A TRUNK TO A CROSS SECTION

The growth of a tree and its cutting in the saw mill on the one hand lead to a lot of waste and on the other hand to full cross sections that as compared to technical profiles reach low area moments. The forest as producer of material belongs to the most low-priced sellers, but its competitiveness gets lost while the raw material is transformed into cross sections. Therefore it is absolutely necessary to check all possibilities of material economy in the production of cross sections.

The techniques in the saw mill present the first and most important step in the production of cross sections. The relation between output and waste significantly determines the processing and thus the price margin of other partly competing wooden products. This technique considers only one dimension and favours “one-dimensional” kinds of trees. So that in case of reforestation coniferous soft wood, especially spruce, is preferred to hard wood typical for the region as e. g. oak-trees or beeches with their widespread tree-tops.

Wood is said to be worked easily, but the opposite is true. Wood is transformed into cross sections by cutting and joining with synthetic bonding agents afterwards. This does not demand any knowledge of the microstructure. But just this presents a great potential for the development of new techniques and products that has not been paid sufficient attention to in science and technology until now.

![Figure 4. Output of wood with reference to round timber and flexural rigidity EI for different techniques of cross section production.](image)
The saw mill delivers a squared rectangular cross section that - as compared to technical profiles made of metal or plastic - has a low efficiency of material. If one adds the bad output of wood by sawing one receives a quite dramatic result. Starting from round timber figure 4 demonstrates the output of material and the area moment reached in the production of different kinds of cross sections.

At first sight we are tempted to assume especially good qualities for bearing structures there where we find high strength. But this has to be looked at more closely. What do engineers do when they are planning bearing structures? They transfer forces and moments with the help of the product of a material factor, i.e. the strength, and a geometrical factor, i.e. the cross-sectional area or the moment of area. In simple words: if a material is only half as strong its cross-sectional area will be doubled. But it cannot be more than doubled because with area moments the distance between cross section and neutral fibre is raised to a power. Therefore structural components are easier to be dimensioned by varying the dimensions of the cross section but by changing the strength class.

The way of choosing round or square solid cross sections in timber engineering hides the fact that the resource productivity is low. In this respect a comparison between squared timber and technical profiles shows a relation of approximately 1:15, what on the one hand results from the losses in the saw mill and on the other hand from the low moment of area of the solid cross section (see fig. 5).

Since timber does not directly depend on the cross section it has to be optimally placed there according to mechanical considerations and has to fulfill the following three conditions:
1. the cross section must not be limited by transverse or longitudinal dimensions of the tree
2. it has to be efficient, i.e. it has to have a great area moment for a given area
3. a cheap production of large quantities must be guaranteed

Squared timber does not meet condition 1 and 2; glued timber does not meet condition 2 and 3. Only the shaped timber profile shown in figures 6 and 7, based on a new understanding of the material, has the potential to meet all tree conditions.

4 TIMBER IN TOP FORM

As far as production techniques are concerned timber construction relies on two basic processes: dividing, i.e. sawing, planing, shredding etc., and then joining by synthetic or metallic fasteners. Already nowadays there is a great variety of possible constructions based on each of these basic processes and their combinations. Imagine this variety could still enlarged by one or two additional ones.

Domestic soft wood has a porosity of about 60 %. Its polymeric structure allows slight plastic deformation transversally to grain at a temperature of 140 °C and a pressure of 5 MPa. Thus the dimension of the cross section can be approximately halved (see fig. 1), whereby the microstructure of the wood folds up. This possibility to improve mechanical properties was already mentioned in the preceding paragraph.

It is also important to know that it is possible to nearly completely reverse and fix the compression without causing any damage to the microstructure if a suitable process is applied.
Its great porosity allows to consider the wood in a completely new manner as a foam-like, cellular material that now indeed becomes a material easily to be processed. Thus fracture elongation transversally to grain increases from one to 100 per cent, i.e. by two orders of magnitude. Soft and hard wood are both suited for this.

Starting from these thoughts at the Institute for Steel and Timber Structures there were made glued laminated timber boards and densified in the direction of the plane. Afterwards under certain heat and humidity conditions there were produced prismatic cross sections reversing the compression by completely folding up the cells.

The bending radius of the deformation depends on the preliminary densification. Depending on the production technique the minimum bend corresponds to about twice the thickness of the
board. This way basically all open and closed prismatic cross sections of any length can be produced.

According to this method, which meanwhile was patented, tubes of structural dimensions have been successfully produced. Figure 6 shows an example that begins with the densification of round timber. The division in the direction of maximum density and subsequent gluing lead to a solid panel that can be transformed into a tube by means of thermo-mechanical treatment. As compared with the round timber material economy amounts to about 80 per cent. 50 per cent of it can be saved by avoidance of waste in the saw mill and the rest by an efficient placement in the profile.

5 TREAD MEETS FIBRE

When timber is used for bearing structures not only mechanical and biotical behaviour are of great importance but also its anisotropy. The first-mentioned can be improved by sorting and thermal and/or thermo-mechanical procedures whereas the directionality of strength is met by different measures in design.

Strength and rigidity can very efficiently be compensated in the course of dimensioning the cross section in longitudinal direction. But even experienced structural engineers face problems dealing with shear and transverse stresses. Meanwhile a lot of different solutions and design methods are available that led to complex special knowledge. Therefore it is desired that the problems connected with anisotropy shall be met by a universal technology.

A look at nature could teach a lot of things because many natural constructions meet mechanical stresses by optimally directed fibres: as e.g. crotches of a tree, blades of straw or muscles. Fibre reinforced plastics present a technical application according to this example. The connection of threads to flat or three-dimensional structures is a subject of textile technology. The Collaborative Research Centre (SFB, Sonderforschungsbereich) 528 “Textile Reinforcement for Structural Strengthening and Retrofiting” at the Faculty of Civil Engineering examines their application in civil engineering.

This Collaborative Research Centre also elaborates the fundamentals of textile reinforcement of timber structures. The cooperation with the Institute of Textile and Clothing Technology enables the timber engineers in Dresden to apply fully fashioned stress related textile reinforcements made of glass, carbon, aramide or natural fibres that are glued on by synthetic resins afterwards.
Technical textiles help to build a bridge between timber engineering and light weight construction what is thought to lead to a completely new quality in the use of this renewable resource.

Besides the mechanical behaviour of the construction the low durability of organic building materials proves to be a decisive disadvantage for exterior application that nowadays is answered by modified wood properties and structural design. But in both cases will arise additional costs.

The complete reinforcement of whole building components in connection with surface treatment as in light weight construction will not only provide structural reinforcement but also an effective protection against weathering. This is an important advantage not only what concerns humidity but also with regard to a corrosive environment.

6 CONCLUSION

The presented developments deal with all shortcomings of present technical applications of wood and in the author’s opinion fundamental solutions are offered. This concerns the efficient use of the raw material that leads to low material prices; the densification of wood that surmounts the limits of the strength classes; textile reinforcement as technology that completely solves the problem of anisotropy at a favourable price and also provides weather protection; and the shaping of efficient cross section profiles as probably the most far-reaching innovation.

These new developments can be applied everywhere where cross sections are needed. These may be bearing elements in civil engineering as columns and girders, in light-weight and equipment construction, but also non-bearing parts for furniture or interior work. Moreover a lot of things with an open or closed prismatic cross section can be produced this way, e.g. cable drums, poles, barrels, tanks, rotor blades or hulls.

Wood will become of greater technical importance if its properties, cross sections and production techniques can come up to the expectations of engineers more properly. Old constructions always are bound to meet old reservations. So it is easier to apply new methods as astonishingly as this may sound. Wood has the potential for innovations based on material and techniques. That there are few innovations is not to be explained by the wood itself but by structures impeding its development.

REFERENCES

Biological and mechanical properties of densified and thermally modified Norway spruce

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*Institute for Steel and Timber Structures, Dresden University of Technology, Germany*

ABSTRACT: For the first time, untreated Norway spruce (*Picea abies* Karst.) was densified in a common industrial scale process and afterwards thermally modified in an Oil-Heat treatment process. Biological and mechanical properties were investigated on axially matched samples. Wetting and drying cycles were performed to determine the change in dimensional stability of densified and heat treated samples compared to references. Biological tests of resistance to basidiomycetes on malt agar according to EN 113 (1996) and soil block tests according to prEN 807 (2001) showed substantially reduced mass losses with densified heat treated material, compared to untreated controls. According to the classification of natural durability (EN 350-1, 1994) the densified and Oil-Heat treated material was classified as ‘very durable’ (durability class 1). The bending strength of densified and Oil-Heat treated material was only slightly reduced compared to untreated Norway spruce. The MOE of densified and Oil-Heat treated material was increased by 42 %, whereas the impact bending strength was decreased by 44 % compared to untreated Norway spruce controls. Densified and thermally modified samples showed improved dimensional stability compared to untreated densified material.

1 INTRODUCTION

The natural durability of most European wood species restricts the use of wood without wood preservation in outdoor application. As an alternative to chemical preservation systems, thermal modification processes as non-biocidal techniques of wood protection were developed and promoted in recent years (Leithoff and Peek 1998). Thermal treatments improve some wood properties, e.g. dimensional stabilization and decay resistance (Militz and Tjeerdsma 2001, Rapp and Sailer 2001), but also reduce the strength properties of wood (Bengtsson et al. 2002, Brischke and Rapp 2004). To overcome this disadvantage of decreased strength, thermo-mechanically densified material with increased initial strength properties compared to non-densified wood was applied to an Oil-Heat treatment process.

Densification of solid wood is an established process to improve selected mechanical and physical properties e.g. MOE, MOR, surface hardness, transversal shear strength and dimensional stability (Morsing 1997, Navi and Girardet 2000). The combination of mechanical load in radial direction and elevated temperature during the densification process is conversant since the beginning of the 20th century (Kollmann 1936, Seborg et al. 1945). Nevertheless the transformed compression-set during densification is unstable and leads to set-recovery under the influence of liquid water or even elevated moisture.

Prior examinations on densified wood predominately deal with the problem of dimensional stabilisation, fixation of set-recovery and increased mechanical properties. In contrast, this study aims on the examination of biological properties of densified wood, in particular the change in natural durability due to a densification process with elevated temperatures and an subsequent Oil-Heat treatment to stabilise the compression set.
2 EXPERIMENTAL

2.1 Material

Untreated Norway spruce (*Picea abies* Karst.) with an average density of 0.52 g/cm$^3$ at an initial moisture content of 12 % was applied to the thermo-mechanical densification process. Untreated non-densified and untreated densified spruce was furthermore thermally modified by an Oil-Heat treatment (OHT) process. Besides the densified and thermally modified material, untreated pine sapwood controls (*Pinus sylvestris* L.), untreated Norway spruce, Douglas fir heartwood (*Pseudotsuga menziesii* Franco), oak heartwood (*Quercus petraea* Liebl.) and pine sapwood specimens vacuum-impregnated in treating solution containing 0.7 % and 2.8 % CCB were taken in biological tests as references. All samples were cut into the respective test specimens and tested at the Federal Research Centre for Forestry and Forest Products (BFH), Hamburg, Germany.

2.2 Thermo-mechanical densification and Oil-Heat treatment

Solid spruce samples of 1000 by 150 by 40 mm$^3$ were densified in radial direction by ‘Deutsche Holzveredelung Alfons & Ewald Schmeing oHG’, Kirchhundem, Germany, using a conventional industrial hot press. The intermittent thermo-mechanical densification process was divided into three steps: heating up, compression, and cooling/conditioning, wherein the heat transmission was achieved by contact of the samples and the heated upper and lower press plates. A diagram of the densification process is given Figure 1.

Untreated non-densified and densified spruce specimens of 500 by 140 by 20 mm$^3$ were thermally modified by an Oil-Heat treatment at 220 °C for four hours at BFH. The treatment temperature was measured inside the specimens by means of thermocouples.

2.3 Resistance to basidiomycetes

The resistance to basidiomycetes was tested according to EN 113 (1996) with the following alterations: n = 10 specimens of 40 by 10 by 10 mm$^3$ were incubated in large Petri dishes (120 mm diameter) for 12 weeks. In preliminary tests with brown and white rot causing fungi (Welzbacher and Rapp 2002), Poria placenta caused the highest mass losses on heat treated wood compared to all other tested fungi including Coniophora puteana and Coriolus versicolor. Therefore the following strain was used for the study: Oligoporus placenta var. Monticula = (Fr.) Gilbertson et Ryv. FPRL 280 BAM, 8/1997.

To assess the grade of durability, the relative durability was calculated as the quotient of mass loss of the tested material and untreated Scots pine sapwood controls (X-Value, EN 350-1 1994), as is normally done for the classification of naturally durable timber.

Figure 1. Scheme of a distance controlled densification process for compression of solid wood form 40 to 20 mm
2.4 Resistance to soft-rotting micro-fungi and other soil inhabiting micro organisms

The resistance to soft-rotting micro-fungi was tested according to prEN 807 (2001). Therefore n = 20 specimens of 100 by 10 by 5 mm³ were incubated for 32 weeks in natural top soil substrate (compost and test fields) from two different areas at BFH in Hamburg, Germany.

2.5 Mechanical testing

The bending strength (MOR) and the MOE was determined in a three point bending test according to DIN 52 186 (1978) with n = 40 specimens of 200 by 10 by 10 mm³.

Impact bending strength was tested according to DIN 52 189 (1981) applied on n = 40 specimens of 200 by 10 by 10 mm³ using a Louis Schopper pendulum impact machine.

2.6 Dimensional stability

Specimens of 10 by 20 by 20 mm³ (n = 20) were cut from non-densified Norway spruce and densified Norway spruce both heat-treated and untreated. Eight cycles of oven drying at 103 °C for 24 h followed by a soaking phase by means of water pressure impregnation at 8 bar/20 min with subsequent water storage of 24 h at 60 °C were performed to determine the change of dimensional stability due to densification and heat treatment. Swelling and shrinking was measured after each wetting and drying phase in radial direction by determining the radial length.

3 RESULTS AND DISCUSSION

3.1 Resistance to basidiomycetes

Both processes, the thermo-mechanical densification and the Oil-Heat treatment, applied to spruce specimens, resulted in significantly increased resistance against fungal decay compared to the mass loss found in untreated spruce (figure 2). Untreated spruce showed mass loss of 30.7 %, significantly lower mass loss of 7.5 % was observed in densified spruce wood. An average weight loss of 8.9 % was found for Oil-Heat treated spruce (spruce OHT), whereas densified and Oil-Heat treated spruce (densified spruce OHT) exhibited a mass loss of 0.8 % only.

The effect of increased resistance against fungal decay of densified wood compared to controls was also observed by Welzbacher et al. (2004) and Schwarze and Spycher (2005). In both studies Norway spruce specimens, subjected to the two-stage THM procedure of Navi and Girardet (2000), were tested. In tests with *Poria placenta* Schwarze and Spycher (2005) found an average mass loss of about 13 % in densified spruce (21 % in controls), whereas Welzbacher et al. (2004) observed 27 % mass loss in densified specimens (36 % in controls). Nevertheless, a post-treatment of the densified specimens at 180 °C for 30 min in saturated steam conditions only reduced the mass loss slightly to 10 % (Schwarze and Spycher 2005), and 17 % respectively (Welzbacher et al. 2004). The influence of a steam post-treatment on durability seems to be negligible compared to the impact of an Oil-Heat treatment.

3.2 Resistance to soft-rotting micro-fungi

The compost substrate was taken to determine the resistance against soft-rotting microorganisms, since it generated higher mass loss to the specimens than the field substrate. The mass loss of densified and non-densified spruce specimens was reduced significantly by an Oil-Heat treatment (figure 3).

A mass loss of 30 % was found in untreated spruce and about 18 % in densified spruce specimens. Oil-Heat treated specimens showed significantly lower values: 5 % mass loss was observed in spruce OHT whereas 3 % mass loss occurred in densified spruce OHT. The Oil-Heat treatment increased the resistance against decay to a higher extent than the densification. The highest increase in durability was found as a result of both processes combined. This can be seen from the classes of natural durability according to EN 350-1 (1994) based on the tests according to prEN 807 (2001) and based on the tests according to EN 113 (1996), as listed in table 1.
Spruce was classified as not durable (class 5) in tests with *Poria placenta* as well as in tests in compost soil against soft-rotting micro-organisms. As a result of the thermo-mechanical densification, durability class 3 (moderately durable) was achieved by densified spruce. An Oil-Heat treatment increased the natural durability to a higher extent: spruce OHT was durable to moderately durable (class 2-3) in tests according to EN 113 (1996), and very durable (class 1) in tests according to prEN 807 (2001) respectively. In addition, the combination of densification and subsequent Oil-Heat treatment resulted in durability class 1 (very durable) in both applied biological tests.
Table 1. Density of the different materials tested and assigned classes of natural durability according to EN 350-1 (1994) based on absolute (g-basis) and proportional (%-basis) mass loss after biological tests according to EN 113 (1996) and prEN 807 (2001)

<table>
<thead>
<tr>
<th>material</th>
<th>Oven dry density [g/cm³]</th>
<th>Durability classification based on tests according to EN 113 on g-basis</th>
<th>Duration classification based on tests according to prEN 807 on %-%basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>spruce</td>
<td>0.48</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>spruce OHT</td>
<td>0.43</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>densified spruce</td>
<td>1.08</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>densified spruce OHT</td>
<td>0.86</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2. Average values of density, MOR, MOE and Impact bending strength; untreated spruce is taken as basis for proportional examination of mechanical properties

<table>
<thead>
<tr>
<th>material</th>
<th>density [g/cm³]</th>
<th>MOR [N/mm²]</th>
<th>MOE [%]</th>
<th>Impact bending strength [kJ/m²]</th>
</tr>
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<tbody>
<tr>
<td>spruce</td>
<td>0.50</td>
<td>108.0</td>
<td>100</td>
<td>31.8</td>
</tr>
<tr>
<td>spruce OHT</td>
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<td>84.7</td>
<td>78</td>
<td>16.5</td>
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<td>densified spruce</td>
<td>1.09</td>
<td>209.3</td>
<td>194</td>
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<tr>
<td>densified spruce OHT</td>
<td>0.86</td>
<td>105.0</td>
<td>97</td>
<td>17.7</td>
</tr>
</tbody>
</table>

3.3 Mechanical testing

Densification of solid Norway spruce improved MOR, MOE and Impact bending strength significantly (table). This is causally connected to increased density (Morsing 1997, Navi and Girardet 2000, Heger et al. 2004).

The Oil-Heat treatment reduced the MOR of densified spruce significantly by 50 %, but densified spruce OHT still had an average MOR equal to untreated spruce. The influence of the Oil-Heat treatment on the dynamic strength was more critical: Impact bending strength of densified spruce OHT was reduced by 44 % compared to spruce (Table 2). The influence of the heat treatment on MOE was rather negligible since MOE of densified spruce OHT was still increased about 50 % compared to untreated spruce.

![Figure 4](image_url)

Figure 4. Radial swelling and shrinking after eight cycles of oven drying at 103 °C for 24 h (A) followed by water pressure-impregnation at 8 bar/20 min and subsequent water storage for 24 h (B)
3.4 Dimensional stability

After eight cycles of wetting and drying, densified spruce specimens showed maximum swelling in radial direction of about 88 %, whereby a set-recovery of approximately 60 % was observed (Figure 4). Thermal modification resulted in significantly decreased maximum swelling (19 %) and in addition, permanent fixation of compression-set was achieved (set-recovery 3.5 %). This is exactly what Heger et al. (2004) observed on THM-densified wood, since the set-recovery was below 3 % and maximum swelling in a range from 15 to 20 % after post-treating the THM-densified specimens at 180 °C for 30 min.

4 CONCLUSIONS

Both, the post-treatment according to Heger et al. (2004) as well as the Oil-Heat treatment achieved permanent fixation of compression-set of densified spruce. In contrast to the steam-post-treatment, significantly increased durability was a result of an Oil-Heat treatment. As a drawback, the dynamic mechanical properties of densified and Oil-Heat treated spruce were reduced by 40 % compared to controls, though static bending strength was equal to untreated spruce.

REFERENCES


1 INTRODUCTION

The impact of the construction industry on the environment is significant at all stages. Large demands on mineral resources and the environment result due to the extraction of raw materials, to service the construction industry. The waste generated from construction-related activities is also considerable and need to be assessed within the framework of a comprehensive strategy.

In a small densely populated Island State like Malta, the management of solid waste through environmentally sound and sustainable systems offers major challenges to develop and maintain, because of the economies of scale. There is a growing concern on the depletion of resources and the generation of waste material.

The sustainable management of waste refers to the more efficient use of resources, reduction in waste produced and where generated, dealing with it in a way that will help achieve the goals of sustainable development; that is development pursued in a manner that whilst meeting the present needs, does not compromise the ability of future generations to meet their own needs.

The aim of this paper is to assess the objectives of The Solid Waste Management Strategy for the Maltese Islands (Ministry for the Environment, 2001) as an integrated approach to waste management, and to analyse potential practical solutions, for the conservation of resources, and the effective reduction, reuse and recycling of excavation, construction and demolition waste.
2 WASTE MANAGEMENT STRATEGY

The Waste Management Strategy for the Maltese Island is intended to provide a policy and decision-making framework for the management of wastes, and for the preparation of detailed implementation plans. (Ministry for the Environment, 2001) In this process waste management is implemented in accordance with national legislation and policies, international conventions of which Malta is signatory, whilst putting into practice the requirements of European Directives. The key principles taken into account in the implementation of the waste management strategy are;

- Sustainable development
- Proximity principle and self sufficiency
- Precautionary principle
- Polluter pays principle
- Waste hierarchy
- Best Practicable Environmental Option
- Producer Responsibility.

The Proximity Principle is based on the premise that the waste should be treated or disposed of as near as possible to the point where it is generated. The Precautionary Principle involves taking precautions now, to avoid potential environmental damage or harm to human health in the future, even though scientific basis for taking the precautions may be inconclusive. The Polluter Pays Principle means that the polluters should bear the full cost of the consequences of their actions. The Waste Hierarchy provides an order of priorities for deciding on waste management practices.

- Reduction in Waste: minimization of the use of resources and reducing the quantities of waste.
- Reuse: Using products once again for the same or different application.
- Recycling: reprocessing of the waste material, for use in the manufacture of the same or different materials.
- Recovery: Obtaining value from waste by energy recovery or other technology.
- Disposal: Waste is disposed of through land-filling or incineration without energy recovery only if there is no other appropriate solution.

The Best Practicable Environmental Option is the outcome of a systematic decision making process emphasizing the protection of the environment. For a given set of objectives and circumstances the process establishes the option or combination of options that provides the greatest benefits or least damage to the environment as a whole, at acceptable costs in the short and long term. The Producer Responsibility Principle means that the producer of products that lead to the generation of waste should take collective responsibility for the waste rather than expecting the community to beat the burden of arranging and paying for waste collection, treatment and disposal. The manufacturer of a product is considered to take the key decisions concerning the design and composition of the product, that lead to its waste generation potential and management characteristics. Therefore the producers shall take responsibility of the following;

- Minimise the waste arising
- Design and develop goods that are inherently recyclable and do not contain materials that pose unnecessary risk or burden for the environment.
- Develop markets for the reuse and recycling of the goods produced.

Further to these principles, it is also necessary to achieve and maintain an effective balance between economic development and protection of the environment. Within the constraints of a Small Island State, the markets for waste management service shall be encouraged. Where possible economic instruments shall be preferred to legal instruments, to induce and encourage changes towards the objectives of the strategy.
The strategy for an integrated and sustainable waste management system is based on different actions. The Strategy addresses the changes necessary to improve the practices and systems in the management of waste, including the need of new systems for the handling, processing and disposal of waste, and on closing and rehabilitating existing and former disposal sites. Furthermore, it addresses the importance of legal and policy measures to provide necessary incentives towards the goals of the plan. (Ministry for the Environment, 2001)

3 EXCAVATION, CONSTRUCTION AND DEMOLITION WASTE.

3.1 General.

The strategic management of solid waste is of highest priority towards sustainable development. In general the waste generated in Malta has been on the increase, with the largest source of waste production being the Construction Industry, exceeding 1 million tonnes of waste generated annually. (Ministry for the Environment, 2001).

Much of the waste generated from excavation, demolition and construction activity comprises soft stone, and is essentially inert. In excess of 80% by weight of the solid waste generated originates from excavation, construction and demolition activities. The Solid Waste Management Strategy for the Maltese Islands (Ministry for the Environment, 2001), reported that while some of the materials are reused and recycled as part of reclamation or landscaping schemes, the bulk of the waste is deposited in disused quarries, disposed at the Maghtab and Qortin Landfill sites in Malta and Gozo respectively, deposited at a designated site at sea, or illegally dumped. Soil from excavation works is deposited on agricultural land.

Quarrying activities, in particular soft stone quarrying, results in considerable material wastage and in the generation of limestone residues in the form of waste gravel and crushed rocks, and dusty and powdery wastes.

3.2 Objectives for Construction & Demolition Waste

The aim of the Solid Waste Strategy of the Maltese Islands is also to reduce the construction and demolition (C&D) waste generation, and recover C&D waste and excavation material. The targets set in the strategy included the banning of the landfilling of C&D waste co-mingled with other waste, the reduction of 20% of total waste, the recovery of 60% of rock/stone, and the recovery of 50% of mixed inert wastes by 2005. (Ministry for the Environment, 2001)

3.3 Solid Waste Management: Constraints

The main strategic issues and constraints include;

Legislation & Enforcement: Successful implementation of the strategy depends on legislation, and effective monitoring and enforcement.

Land use Availability: Land is a scarce resource in Malta, and the use of land for waste management purposes, and the selection of suitable sites is a major constraint. Therefore the landfilling of large volumes of waste is unsustainable.

Operational Reliability and Flexibility: The limited size of Malta leads to difficulties in making rapid adaptations for the handling of large volumes of waste.

Economic Factors: The capital investments and unit costs are important considerations. The economies of scale are particularly important leading to some processes not being effective on a small scale. The market for recyclable materials is limited in Malta

Public Perceptions: The development and implementation of a comprehensive programme for ongoing communication and consultation with the public and all stakeholders is important throughout the process.

3.4 Strategic Objectives

Strategic objectives and targets for the future management of waste are necessary in the following areas and activities;
3.5 Implementation Measures

The strategic objectives lead to the development and implementation of interrelated measures which can be summarised in the following groups: policy and legislative; institutional and organizational; economic and financial; technical and operational; and other measures which include stakeholder awareness and communication. Specific measures that are outlined in The Solid Waste Management Strategy for the Maltese Islands (Ministry for the Environment, 2001), and which are specifically relevant to Excavation, Construction & Demolition waste, are discussed.

3.5.1 Policy & Legislative Measures.

Policy and Legislative measures include the adoption of the Waste Management Strategy (Ministry for the Environment, 2001) and the enactment of relevant regulations. Other measures include Assessment, Monitoring and Enforcement; Technical Standards; Land Use Planning Policy; and Producer Responsibility / Compliance Schemes.

Monitoring and Enforcement: Monitoring, inspecting and enforcement are necessary to ensure compliance, and need to be based on sufficient human and technical resources.

Technical Standards & Codes of Practice: The aim of the standards is to establish minimum technical requirements for specific materials, resources and operation & performance of specific activities. National standards need to compliment relevant EU standards.

Land Use Planning Policy: In the assessment of new waste management facilities, preference is given to waste recovery / recycling plants.

Producer Responsibility: Those responsible for processes which give rise to excavation, construction and demolition wastes should bear some or all of the responsibility for arranging and paying for their management in accordance with relevant legislation and standards.

3.5.2 Economic & Financial Measures

Charges for the Use of Publicly owned / Operated Waste management Facilities / Services: On the basis of the Polluter Pays Principle, the charges for the use of public waste management facilities were planned to increase progressively over a period of three years, reaching levels that recover the full cost of their provision and operation in accordance with national and European legislation and standards.

Development Planning: In order to achieve the targets for reducing and recovering excavation, construction and demolition waste, a developer is requested to prepare a waste management plan, to be assessed by the Planning Authority, prior to the granting of development permits. Such a plan includes assessments and estimates of the waste generated, clear proposals for the reduction, reuse and recovery as much as possible of the waste materials generated from the development, together with proposed methods for safe disposal of any remaining amounts.
Restricted use of Landfills: The strategy recommends the restricted use of landfills for the disposal of some types of excavation, construction and demolition wastes by imposing progressive restrictions on the quantities that may be accepted, and requesting the adoption of a differential pricing structure in which the prices for accepting such wastes are substantially higher than for other types of wastes. The above can be implemented after sufficient capacity for the treatment / processing and recovery of the waste streams has been developed and in operation.

Preferential Public Service procurement: Preferential Public Service Procurement Policies are referred to in the strategy. The Government will give preference to recycled and recyclable products and materials when purchasing some types of products, as long as such products and materials are of adequate quality for the intended use, and the prices of the products and materials does not exceed the prices of the equivalent by an unreasonable or unacceptable amount.

Financial Incentives for Locally Manufactured Recycled Products / Recycling Processes: Financial incentives are planned in order to encourage the development of locally manufactured recycled products and recycling processes.

3.5.3 Technical & Operational Measures

Interim Storage, processing and Recovery of Excavation and other recyclable Excavation, Construction and Demolition Waste: The aim of the strategy is also to establish facilities for the interim storage, processing and recovery of excavation waste, and also recyclable construction, demolition and excavation wastes.

New Landfill facilities for Disposal of inert Waste: The strategy refers to the land-filling of inert waste in Malta. The engineering, operational and after-care requirements for inert waste landfill sites are considerably less demanding and expensive than for landfill sites receiving non-inert wastes. The capacity requirements depend on the possible reduction in quantities through waste avoidance, recovery and recycling. Even if the disposal of inert material is reduced, there will be the need to dispose of substantial volumes of inert material. The strategy refers to the potential for restoring the existing voids in the Maltese landscape, created by the extraction of stone and other minerals. The strategy gives preference to the restoration and reclamation of quarries, as against schemes involving the reclamation of land from the sea. However it refers to the latter as a likely option in the long term. The strategy also refers to the inert waste at the Maghtab landfill, and if economically beneficial it should be reclaimed and utilized profitably.

Rehabilitation and Restoration of Existing and Former Waste Dump Sites: Once the waste treatment facilities have been constructed and brought in operation, the strategy outlines the closure, restoration and reutilization of the waste disposal sites at Maghtab and Qortin.

4 ASSESSMENT OF POTENTIAL ACTION.

4.1 General

The implementation of The Solid Waste Management Strategy for the Maltese Islands (Ministry for the Environment, 2001) is an ongoing process, with action taken in line with recommendations, and detailed implementation plans. The strategy is dynamic, and requires constant review to ensure that the objectives are achievable. It is also necessary to allow for adjustments as new information and experiences suggest.

The following section outlines relevant proposals that are considered for implementation, or discussed by stakeholders in various instances. The proposals are not to be seen in isolation, but within the framework of the strategy and relevant regulations. The potential benefits and drawbacks of all proposals need to be assessed through an integrated approach.

4.2 Construction and Demolition Waste.

Organised stripping of the buildings and separation at source requires adequate recycling facilities and a market for the secondary products. Furthermore the products must be at competitive prices, and of sufficient quality for reuse. Construction and Demolition (C&D) waste
should be kept separate from clean excavation material, and should be separated and stored until recycling facilities are available. Waste separation facilities are required in order to tackle the reuse and recycling of demolition waste. Alternative ways of safe and effective demolition of buildings should be considered. The potential dismantling of typical load-bearing masonry buildings, with stone and concrete block walls and reinforced concrete roof slabs, can lead to the effective separation of construction materials, but is normally not cost effective. Such separation has environmental and economic implications.

4.3 Reuse of stone blocks.

The re-use of stone blocks necessitates careful separation and dismantling, to reduce damage to the stones, resulting in extra costs. There is a market for the reuse of old stone, in the refurbishment of old buildings. Blocks resulting from dismantling might not be suitable for reuse due to various defects, including those arising during the dismantling operation, and their reuse may be limited to selected applications. Therefore classification and certification of the blocks according to specific criteria might be necessary. The feasibility of the dismantling of stone should be assessed from an economic and environmental point of view. The extra costs and energy in dismantling, stacking and transporting, modifying and re-working the stone blocks should be assessed. However the reuse of stone leads to a direct reduction in waste generated, and also to reduced demands and potential savings on new stone blocks, resulting in reduced quarrying and conservation of resources. The Sustainable Development Strategy for the Maltese Islands refers to potential incentives for the recycling of stone and disincentives associated with the use of new stone. (NCSD, 2006)

4.4 Reduction of Excavation Waste

Due to the limited land available for development and planning criteria, building development normally entails the excavation of the site, to maximize on the space available. This results in considerable amounts of excavation material. If the material originating from excavation is of good quality, it may be used for the production of aggregate for use in specific civil engineering applications. This is usually the case of hard stone material normally used as aggregate for the production of concrete and for road construction. If the material excavated is of inferior quality, it is normally not considered useful for most civil engineering works. This is typically the case of excavated globigerina limestone.

In such circumstances a potential measure can be the extraction of large blocks of stone from the excavation site, rather than the normal practice of breaking the material. The large blocks can then be transported and further processed in designated plants. This measure will lead to a reduction of waste material, and potential savings of a finite resource. The proposal should be assessed through feasibility studies, based on different methods of excavation, quality of the material extracted, cost implications, and the time and energy necessary for extraction and processing.

4.5 The Use of Waste material in Civil Engineering Applications

The Waste Management Subject Plan encourages the recycling of natural spoil and construction wastes for reuse as secondary aggregate or as a material for landscaping or restoration. (Planning Authority, 2001). In general the excavation and demolition waste can be classified and assessed for potential use in specific civil engineering applications. These can include the processing of the material for the potential use as aggregate for different applications including concrete production, and road construction, if specific requirements of the material properties are satisfied.

Other potential initiatives can include the infilling of concrete caissons with inert waste, which are eventually sealed and used in civil engineering applications. Various other potential reuse and recovery options have been considered or adopted including the reuse as cover-up material for landfills, and the use as a soil substitute. Limestone waste can potentially also be used for the production of cement.
The use of excavation, construction and demolition waste for the production of concrete products, including concrete block-work has been considered. In this case, strength and durability characteristics need to be assessed, together with other properties like for example thermal properties and sound insulation. The production of reconstituted stone with waste limestone material is another potential alternative that requires further research.

A market for the secondary products is required. Feasibility studies are necessary, in order to assess the actual quality and quantity of material that can be utilised effectively for specific applications.

4.6 The Use of Waste Material in Concrete

4.6.1 General.

Concrete can be produced using alternative materials as substitutes for the conventional materials. The alternative materials can include waste material. Important factors to be considered are costs and economic viability of the use of waste material. Costs are generally associated with handling, processing and transportation. Important consideration should be given to energy requirements for processing and production of the concrete, and pollution, before a concrete product using waste material can be assumed to be a better alternative. The stability and durability characteristics of the concrete produced with the waste material, over its life cycle, is important when considering its intended use in structural applications. This necessitates clear guidelines and specifications, and appropriate quality criteria in the use of specific wastes in concrete.

In general waste materials can be used in making concrete. Materials can be used as a replacement of the cement, or also as aggregates in the concrete. Reference is to be made to current standards and codes of practice on the quality and quantity of waste material used in concrete.

The use of waste materials leads also to a reduction in the use of new material, and to conservation of resources. Research on the use of these materials in concrete is necessary in order to assess the life cycle performance, and life cycle costs.

4.6.2 Use of Globigerina Limestone in Concrete

The potential use of crushed globigerina limestone as a substitute for part of the cement leads to a limited percentage use of the waste material. The processing of the materials should also be taken in consideration. In general crushed globigerina limestone used as aggregate in concrete results in a concrete of reduced strength. Good quality aggregate is normally extracted for important structural elements. However the materials of low quality can be suitable for specific applications, while respecting the requirements of standards and specifications.

The material is used in the production of crushed soft stone for specific applications, including lean concrete and specific concrete products.

4.6.3 The Use of Recycled Concrete Aggregate

Crushed hardened concrete can be used as aggregate in concrete. It is necessary to eliminate other demolition waste, namely stone blocks, from the concrete. The separation of reinforcement from the concrete is also necessary. The concrete manufactured with recycled concrete aggregate can be potentially used in selected applications, with reference to standards and specifications.

4.7 Disposal of Waste

4.7.1 Disposal of Waste in Quarries

The Waste management Subject Plan (Planning Authority, 2001) refers to the development of additional capacity of inert wastes in former mineral workings (generally disused quarries) or derelict sites that cannot be satisfactorily reclaimed in any other way. It also refers to the disposal of waste by land-raising, with due regard to specific criteria including assessment of envi-
ronmental impacts. The utilization of disused quarries for disposal of the inert waste has the advantage of providing a solution for both the disposal of the material, and also for the regeneration of the quarries. Waste is best separated at source rather than at the quarry, where it is difficult to separate. Important screening of the waste is necessary before deposition at the point of disposal. Furthermore the potential contamination of the aquifer has to be assessed. Waste material can be considered as a resource, and the dumping of selected and controlled material will allow for its potential future extraction and reuse. (Borg R.P., 2006) The landfill capacity required in the future is influenced by the extent of waste reduction, reuse and recycling.

4.7.2 Disposal at Sea

The disposal of inert waste at sea has attracted continuous debate. It can be seen as a practical solution to the disposal of the large volumes of inert waste. However the dumping of inert waste at sea is also considered as the wastage of a potential resource. Furthermore according to the Waste Management Subject Plan (Planning Authority, 2001), the dumping of material at sea should be avoided as much as practically possible, and the dumping at sea should be considered as an option of last resort. The disposal of inert waste will only be permitted at an official dump site if the proposal meets specific criteria;

- Land based alternatives have been discounted.
- Only uncontaminated inert waste shall be acceptable.
- The disposal will only be allowed in dump sites that have an environmental monitoring programme in place.

Proposals for new dumpsites need to demonstrate that marine ecosystems and features of acknowledged importance will not be affected. Such an option has direct implications on the ecosystem and on the sensitive coastal environment of Malta. As against the dumping of the inert material in quarries, where it can be re-extracted in the future, the deposition of inert waste at sea can be considered as the dumping and wastage of a potential resource.

A distinction is usually made between the deposition of inert waste at sea for purposes of land reclamation, and the deposition of this waste for purposes of disposal. Controlled land reclamation can potentially be one of the main solutions.

The proposals for land reclamation should be assessed in view of detailed assessments of the inert waste material that is available for disposal, and the volumes of material required for specific projects. Land reclamation needs to be considered through a comprehensive assessment of various factors including the impact of the project on the marine environment, intended use, and viability of such projects. Such projects will necessitate further infrastructural works, which will inevitably take up more resources. Potentially recommended uses for land reclamation include projects associated with renewable and alternative energy.

4.8 Conservation of Mineral Resources

Limestone is extensively used in construction in Malta. It is broadly grouped into Globigerina Limestone, and Upper and Lower Coralline Limestone. Globigerina Limestone blocks are extracted and used as a building product. The Coralline Limestone is quarried for the production of crushed aggregate, which is used in various civil engineering applications. In general, the extraction of limestone blocks for construction, and aggregate for concrete and other civil engineering applications, results in large open pits, leaving scars in the landscape, and with negative impacts on the environment.

In order to reduce the demand of globigerina limestone, which is a non-renewable resource, alternative construction materials can be considered. The characteristics and performance of the globigerina limestone and alternative products needs to be assessed. Further potential action intended to reduce the demand of the globigerina limestone, is to limit the use of limestone to cladding panels in specific applications. Potential reduction in the waste generated during the extraction and production of globigerina limestone blocks for construction, should be considered.
A potential alternative to the extraction of hard stone aggregate from quarries, includes the importation of aggregate of consistent and improved properties, for specific applications. In assessing the costs and feasibility of such a proposal, it is necessary to consider the extensive environmental impact of quarries in Malta, and the reduced reserves of quality material, available for extraction. The characteristics and properties of the material, and the suitability for its intended use in specific civil engineering applications should also be assessed.

4.9 General Considerations

The conservation of resources is an important objective, which can be achieved through the adoption of rational structural solutions, and selection of construction materials of improved performance characteristics, and increased strength.

In the appraisal of construction materials, construction techniques and structural systems, the entire life cycle of the building needs to be considered, covering the building construction, maintenance, alterations and demolition. Alternative structural systems and construction techniques can be assessed in view of the potential reduction in waste generation, reuse and recycling of construction products. Specific construction systems can lead to a reduced demand on resources, and more effective waste management practices.

When one considers the broader spectrum of the building industry in Malta, a relevant concern is the surplus of property on the market, and the percentage of vacant houses (23%). (MEPA, 2005) Therefore incentives for the reuse of existing buildings, need to be considered. Furthermore, the potential for alterations and adaptations of existing building stock, rather than demolition and reconstruction can be assessed.

5 CONCLUSIONS

The potential measures recommended within the framework of The Solid Waste Management Strategy for the Maltese islands (Ministry for the Environment, 2001), are based upon practical attempts at addressing the issue of excavation, construction and demolition waste, and the current debate on waste in Malta.

Practical short and long term solutions need to be assessed in terms of environmental impact and economic feasibility. Ongoing research is necessary to support various options. Such research can also lead to the formulation of technical standards and recommendations, within the legal framework. Incentives are recommended for the reduction of construction and demolition waste (NCSD, 2006). Assistance and guidance from the responsible entities, together with the proper incentives are necessary in order to facilitate the implementation of potential measures through a practical approach.

The fundamental goal is to promote the conservation of resources, and to exploit Construction and Demolition Waste as a potential resource, through the objectives of sustainable waste management.

6 REFERENCES

INTRODUCTION

The idea to use crushed brick as the aggregate for mortar and concrete is not a new one. The first known attempts to make this type of composite material go back to the age of ancient Greeks and Romans, and it was a mixture of lime, sand and water with addition of crushed bricks.

Generally, concrete based on crushed building ceramics is made using following types of aggregates:

- Old bricks collected from the destroyed walls (so called recycled bricks);
- Shattered ceramics – waste left after the production of building ceramics;
- Naturally baked clay, which is often present at coal excavation sites.

In the western, technologically highly developed countries, recycling represents the usual way of production of crushed brick aggregate. This is the case, because of the frequent and thorough reconstructions of central city areas in these countries. In that process, the old and ruined buildings (or even whole blocks of buildings) are being partially or completely destroyed and the waste material has to be removed from these locations. Also, there are a lot of buildings that should be replaced with newer, technologically and economically superior solutions, because of their long-term degradation and expired exploitation period. Regrettfully, in recent years we are witnessing numerous natural catastrophes (like earthquakes, floods, tsunamis or fire) and unnatural disasters (such as wars or terrorist attacks). All these events are unavoidably being followed by cleaning operations in order to remove the waste building material. Therefore, storing of such material becomes a growing problem, especially in the densely populated urban areas. The solution of this problem represents a special challenge in technical, technological, eco-

ABSTRACT: The results of experimental testing conducted on mortar specimens made with crushed brick aggregate are presented in this paper. Certain specimen series were made with addition of monofilament polypropylene fibers. Six different mortar mixtures were tested. The experimental part of the investigation consisted of monitoring of the following time-dependant properties of recycled-brick based mortar: density (both in fresh and in hardened state), compressive strength, flexural strength and shrinkage. The testing results of mechanical properties of fiber reinforced recycled brick composites showed that the addition of polypropylene fibers generally leads to improvement of these properties. For example, the increase of compressive strength varies between 5 and 16% and the increase of flexural strength between 4 and 25%, in comparison to the non-reinforced mortar. These improvements can also vary with the change of the applied type of aggregate, i.e. depending on the adopted solution: making mortar with just recycled bricks or combining recycled bricks with regular river sand.

1 INTRODUCTION

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Properties and performance of cement composites based on recycled brick aggregate

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onomic, but also in ecological sense. The number of recycling plants for crushed brick material is growing very fast: for example there are more than 60 plants working today just in Holland – which is a fact that places this country among world leaders in this field.

In Serbia, the recycling of used bricks has not yet become a regular procedure, which practically means that this type of aggregate could be obtained only from the waste material left after the production of building ceramics. However, as the quantities of these byproducts are not large (in the case of modern technology application they amount to 3-5% of the whole production) there is a question whether it is economical or not to use this waste material as concrete aggregate. Namely, the producers of building ceramics often find it more profitable to return this waste material into the production process (as a new raw material) or to grind it into powder and sell it as a "dirt" surface for tennis courts. On the other hand, if we take into account that more than 80% of all buildings in our country are completely or partially built using brick material, it is obvious that the future lies in recycling of old, degraded bricks.

During the recycling process, special attention should be paid to the presence and removal of undesirable and/or harmful ingredients (such as lime, clay, gypsum, humus, etc.) which makes this process even more complicated and expensive. However, if we put all advantages and disadvantages together and especially if we bear in mind the growing popularity of so called ecologically suitable materials (and ceramic materials certainly fall into that category), the conclusion could be drawn that mortar and concrete based on recycled bricks shall become more extensively applied in the near future.

2 COMPONENT MATERIALS

During the concrete mix design, special attention should be paid to the selection and quality control of component materials. This is mainly related to the aggregate because the application of other components (cement, water, admixtures) does not particularly differ from the classical concrete. The quantities of cement vary between 250-400 kg/m³, while the water content required for plastic consistency amounts to 400-450 kg/m³ – which is considerably more than the usual values. The quality of aggregate largely depends on the quality of basic material – ceramics which is crushed in several phases, separated into standard fractions and eventually dusted using air-stream. The most important properties of recycled-brick aggregates, which must be tested in the lab, are water absorption (in relation to the significant porosity of the basic material) and compressive strength (triaxial compression test). Beside its physical-mechanical properties, the granulometric composition of the aggregate largely affects the quality of mortar, i.e. concrete. Also, there is the so called pozzolanic activity effect (considering the smallest ceramic particles) that should be taken into account. Namely, the research has shown that if the aggregate contains between 15-20% of particles which are smaller than 0.063 mm, this contributes not only to the larger final strength of the composite, but also affects the fresh mixture acting as a plasticizing – water retaining agent. On the other hand, because of the presence of such pozzolanic admixture it is possible (if necessary) also to reduce the amount of cement.

For the experimental mortar mix the waste from the ceramics (left after the production of building ceramics), which was separated into three fractions (I:0/2mm, II:2/4mm and III:4/8mm), in combination with river sand (fraction IV: grain size 0/4mm), were used as aggregates. The grading properties of these aggregate types are given in Table 1. The mortars were made using two different mixtures of aggregates. Aggregate mixture 1 was made using 35% of fraction I, 30% of fraction II and 35% of fraction III. On the other hand, aggregate mixture 2 was made using 20% of fraction I, 25% of fraction II, 35% of fraction III and 20% of fraction IV. Physical properties of aggregates (such as bulk density, organic matter and clay content) are given in Table 2. The mean value of density of crushed brick aggregate was determined to be 2540 kg/m³. The measured water absorption of crushed brick aggregates was in average 41%. Fraction III (4/8 mm) was also submitted to triaxial compression test, which showed the mean compressive strength value of 1.44 MPa.

Among other component materials, there are different types of fibers (acting as a special micro-reinforcement) whose application is constantly increasing. These fibers generally improve certain physical-mechanical and deformational properties of otherwise brittle composite materials like mortar or concrete. Steel and synthetic fibers (polypropylene, polyethylene, nylon, etc.)
are most frequently used. The fibers may be single (monofilament) or connected (fibrillated). The polypropylene fibers are usually added in relatively small quantities (app. 0,1%-Vol) and their greatest contribution is in the field of shrinkage reduction and crack propagation control. During the mixing process it is important to pay attention to the order of addition of component materials, but also to the mixing time which should be at least doubled in relation to the classical mortar and concrete mixes. Some of the experimental mortar mixtures were made using monofilament polypropylene fibers "Fibrin23", which technical data is given in the Table 3. A photo showing (Fig. 1) different types of polypropylene fibers is given next to the Table 3.

Table 1. Grading properties of different aggregate types

<table>
<thead>
<tr>
<th>Fraction / Sieve (mm)</th>
<th>Passage through sieve opening ( in mass%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0,125</td>
</tr>
<tr>
<td>I(0/2mm) crushed brick</td>
<td>32,5</td>
</tr>
<tr>
<td>II(2/4mm) crushed brick</td>
<td>0,5</td>
</tr>
<tr>
<td>III(4/8mm) crushed brick</td>
<td>-</td>
</tr>
<tr>
<td>IV(0/4mm) river sand</td>
<td>3,9</td>
</tr>
<tr>
<td>Aggregate mixture 1</td>
<td>11,5</td>
</tr>
<tr>
<td>Aggregate mixture 2</td>
<td>7,4</td>
</tr>
</tbody>
</table>

Table 2. Physical properties of different aggregate types

<table>
<thead>
<tr>
<th>Fraction</th>
<th>I (0/2 mm)</th>
<th>II (2/4 mm)</th>
<th>III (4/8 mm)</th>
<th>IV (0/4 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density (kg/m³)</td>
<td>1072</td>
<td>840</td>
<td>871</td>
<td>1724</td>
</tr>
<tr>
<td>Bulk density compacted (kg/m³)</td>
<td>1177</td>
<td>930</td>
<td>965</td>
<td>1862</td>
</tr>
<tr>
<td>Organic matter content</td>
<td>acceptable</td>
<td>acceptable</td>
<td>acceptable</td>
<td>acceptable</td>
</tr>
<tr>
<td>Clay content (%)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3. Properties of fibers "Fibrin23"

<table>
<thead>
<tr>
<th>Synthetic fibers</th>
<th>Fibrin 23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic material</td>
<td>100% Polypropylene</td>
</tr>
<tr>
<td>Production method</td>
<td>Stretching by pulling</td>
</tr>
<tr>
<td>Fiber type</td>
<td>Monofilament fibers</td>
</tr>
<tr>
<td>Cross section</td>
<td>Rounded</td>
</tr>
<tr>
<td>Diameter</td>
<td>0,018 mm</td>
</tr>
<tr>
<td>Length</td>
<td>12 mm</td>
</tr>
<tr>
<td>Aspect ratio (L/d)</td>
<td>667</td>
</tr>
<tr>
<td>Number of fibers/kg</td>
<td>~ 300 million</td>
</tr>
<tr>
<td>Specific surface</td>
<td>~ 230 m²/kg</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>560 MPa</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>4200 MPa</td>
</tr>
<tr>
<td>Melting point</td>
<td>160 °C</td>
</tr>
<tr>
<td>Usual dosage</td>
<td>0,6 – 0,9 kg/m³</td>
</tr>
</tbody>
</table>

Figure 1. Different types of polypropylene fibers

3 EXPERIMENTAL TEST RESULTS

Prior to the adoption of the final mix design of the mortar (or concrete) it is essential to make trial mixes in order to confirm the quality of the composite, both in the fresh and in the hardened state. At the end, between several different mixtures the optimal one can be chosen, considering the desired properties and performance of the composite.

Having this in mind, six different mortar mixtures (marked with capital letters A, B, C, D, E and F) were made and tested. All mixtures were made using 400 kg/m³ of Portland cement blended with 15% of pozzolana. Other properties of these mixtures are following:

1. Mixture A – mortar based on crushed-brick aggregate fractions 0/2, 0/4 and 4/8 mm.
2. Mixture B – mortar based on crushed-brick aggregate fractions 0/2, 0/4 and 4/8 mm with addition of 900 g/m³ monofilament polypropylene fibers - type "Fibrin" (Adfil, Great Britain).
3. Mixture C - mortar based on crushed-brick aggregate fractions 0/2, 0/4 and 4/8 mm and river sand with grain diameter between 0/4 mm.

4. Mixture D - mortar based on crushed-brick aggregate fractions 0/2, 0/4 and 4/8 mm and river sand with grain diameter between 0/4 mm with addition of 900 g/m^3 monofilament polypropylene fibers - type "Fibrin" (Producer: Adfil, Great Britain).

5. Mixture E - mortar based on crushed-brick aggregate fractions 0/2, 0/4 and 4/8 mm with addition of 2% of "Iriplast" superplasticizer (Producer: Iris, Skoplje, R. of Macedonia).

6. Mixture F - mortar based on crushed-brick aggregate fractions 0/2, 0/4 and 4/8 mm with addition of fibers (same as mixture B) and superplasticizer (same as mixture E).

The adopted mix designs for all of the six tested mortars are presented in the Table 4. The quantities of water shown in the table represent the total doses, which means that one part of the used water was absorbed by the aggregate, and another part provided the desired consistency of the fresh mixture.

<table>
<thead>
<tr>
<th>Mortar type</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (kg/m^3)</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Aggregate (kg/m^3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(I) 0/2 mm</td>
<td>574</td>
<td>574</td>
<td>328</td>
<td>328</td>
<td>574</td>
<td>574</td>
</tr>
<tr>
<td>(II) 0/4 mm</td>
<td>492</td>
<td>492</td>
<td>410</td>
<td>410</td>
<td>492</td>
<td>492</td>
</tr>
<tr>
<td>(III) 4/8 mm</td>
<td>574</td>
<td>574</td>
<td>574</td>
<td>574</td>
<td>574</td>
<td>574</td>
</tr>
<tr>
<td>(IV) 0/4 mm</td>
<td>-</td>
<td>-</td>
<td>328</td>
<td>328</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>1640</td>
<td>1640</td>
<td>1640</td>
<td>1640</td>
<td>1640</td>
<td>1640</td>
</tr>
<tr>
<td>Water (kg/m^3)</td>
<td>490</td>
<td>490</td>
<td>416</td>
<td>416</td>
<td>430</td>
<td>430</td>
</tr>
<tr>
<td>Polypropylene fibers (kg/m^3)</td>
<td>-</td>
<td>0.9</td>
<td>-</td>
<td>0.9</td>
<td>-</td>
<td>0.9</td>
</tr>
<tr>
<td>Superplasticizer (kg/m^3)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>8</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

The experimental part of the investigation consisted of monitoring of the following time-dependant properties of recycled-brick based mortar: density (both in fresh and in hardened state), water absorption, compressive strength, flexural strength and shrinkage.

The results of measuring of density in the fresh state are given in the Table 5, whereas the change of density in the hardened state during time could be analyzed according to the data presented in the Table 6. All final results are calculated as the mean values based on three testing results.

<table>
<thead>
<tr>
<th>Type of mortar</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m^3)</td>
<td>1922</td>
<td>1984</td>
<td>2017</td>
<td>2051</td>
<td>2000</td>
<td>2002</td>
</tr>
</tbody>
</table>

According to their properties, these composites are somewhere in between mortar and concrete. If we place them into the group of fine-aggregate based concretes, the final conclusion could be drawn (also regarding the achieved values of fresh-state and hardened-state densities) that they belong to the class of light-weight concretes.
Analyzing the measured values of water absorption, which are given in the Table 7, the conclusion can be drawn that crushed brick aggregate mortars show considerable increment of this physical property (up to two times higher values when compared to “normal” mortar).

<table>
<thead>
<tr>
<th>Type of mortar</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water absorption (%)</td>
<td>18,7</td>
<td>18,6</td>
<td>16,1</td>
<td>16,0</td>
<td>17,1</td>
<td>17,0</td>
</tr>
</tbody>
</table>

As it was already said, the testing of mechanical properties consisted of compressive strength and flexural strength tests. These properties were tested at the age of 7, 28 and 180 days, and each test was carried out on three specimens (with dimensions 4x4x16 cm) from each of the six series. Table 8 contains the compressive strength testing results of mortar specimens of series A, B, C, D, E and F.

<table>
<thead>
<tr>
<th>Type of mortar</th>
<th>Age of specimens (days)</th>
<th>7</th>
<th>28</th>
<th>180</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>20,10</td>
<td>30,50</td>
<td>31,80</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>20,97</td>
<td>32,08</td>
<td>32,85</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>20,02</td>
<td>31,69</td>
<td>32,60</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>21,30</td>
<td>36,82</td>
<td>37,23</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>22,60</td>
<td>32,40</td>
<td>33,80</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>22,60</td>
<td>34,65</td>
<td>35,68</td>
<td></td>
</tr>
</tbody>
</table>

Although the valid Serbian and European standards do not regard flexural strength test as an obligatory experiment for quality control of mortar, it still represents an important mechanical property of such composite materials. Especially in the case of polypropylene fiber reinforced mortar, the flexural strength test represents one of the best ways to compare different mixtures as well as to evaluate the efficiency of the applied micro-reinforcement.

Table 9 contains the flexural strength testing results of mortar specimens of series A, B, C, D, E and F.

<table>
<thead>
<tr>
<th>Type of mortar</th>
<th>Age of specimens (days)</th>
<th>7</th>
<th>28</th>
<th>180</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4,04</td>
<td>5,82</td>
<td>6,00</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>4,29</td>
<td>6,14</td>
<td>6,20</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>4,02</td>
<td>4,83</td>
<td>5,10</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>4,28</td>
<td>6,04</td>
<td>6,30</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>4,42</td>
<td>5,96</td>
<td>6,10</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>4,75</td>
<td>6,20</td>
<td>6,42</td>
<td></td>
</tr>
</tbody>
</table>

As the rheological properties are concerned, the experiment consisted of shrinkage measurement which was performed on mortar prisms with dimensions 4x4x16 cm. This part of the test was especially important because of the fact that the shrinkage values for crushed-brick mortars and concretes are usually 20-60% higher than the same values for normal composites. Because of the limited space, only the most interesting results will be highlighted here instead of the more detailed or complete presentation. So for instance, at the age of 28 days the specimens of series B had 8% smaller average shrinkage than the specimens of series A, whereas the mortar marked as series D showed a 17% decrement in shrinkage deformation in relation to the mortar C. These relative rheological improvements in mortar quality can be contributed mostly to the presence of monofilament polypropylene fibers at series B and D.
As a part of the final discussion, current situation and possibilities as well as future perspectives for application of recycled brick aggregate should be mentioned. Investigation of the current state-of-the-art in Serbia’s civil engineering showed that the scope of usage of recycled brick aggregate is still very limited. Namely, this material is mostly used for road embankments (factories “Opeka” from Smederevska Palanka and “Podunavlje” from Čelarevo), for tennis courts surfaces (production of “Tenisi” factory and “Kubršnica” from Arandelovac), as well as for production of three-layered prefabricated “YU chimneys” based on “Schiedel” system (GIP “Gradevinar”, “YU chimney” from Bačka Palanka).

If we apply a corresponding technological procedure in order to produce a porous (cavernous) concrete, such material will primarily possess good thermo-insulation properties and thus it should be used for production of various full or hollow bricks. Mortars based on recycled bricks made with addition of polypropylene fibers may be successfully used as facade mortars, but also as thermo-insulation or soundproofing composite materials (the fiber reinforcement can improve to some extent thermal and acoustical properties of these materials, but the basic effect of its application is not direct - it consists of simultaneous increment of ductility, resistance to different actions and durability in general). Also, because of their appropriate characteristics, such fiber reinforced composite materials could be successfully applied as fireproofing mortars.

The testing results of mechanical properties of fiber reinforced recycled brick composites showed that the addition of polypropylene fibers generally leads to improvement of these properties. For example, the increment of compressive strength varies between 5 and 16% and the increment of flexural strength between 4 and 25%, in comparison to the non-reinforced mortar with the same consistency in the fresh state. These improvements can also vary with the change of the applied type of aggregate, i.e. depending on the adopted solution: to make the mortar using just recycled bricks or to combine recycled bricks with regular river sand. As the time-dependent shrinkage deformations are concerned, they usually tend to have higher values if the composite is based on recycled brick aggregates, but such negative effects can be diminished to some extent with addition of fiber reinforcement. This hypothesis was confirmed during laboratory testing, which showed maximal decrement of shrinkage in amount of approximately 17%.

Although the application of “ceramic concrete” which is based on ‘pure’ crushed brick waste material has not yet became accepted worldwide, it certainly has a good future. The main reasons for such estimation could be found both in ecological and economic aspects of its application, but also within the fact that this composite material possesses quite a few of the advantageous physical-mechanical properties - a fact that was supported also by the experimental research that is described in this paper. Future directions for research in this field could be pointed towards testing of thermo-technical properties of the given composite material. An example that could confirm the relevance of such opinion may be the fact that a 10 cm thick wall made of recycled brick concrete is equivalent (in the sense of thermo-insulation) to a 30 cm thick wall made of normal concrete with the same compressive strength.

Having in mind everything that has been said before, the authors of this paper strongly believe that in the near future mortar and concrete based on recycled brick aggregate (with or without fiber reinforcement) will find much wider scope of application in our civil engineering practice.

References

Muravljov M., Pakvor A., Kovačević T. Explorations of Concrete and Structural Concrete Elements made of Reused Masonry; 3rd International RILEM Symposium on Demolition and Reuse of Concrete and Masonry, Odense, Denmark, 1993.
Akhtaruzzaman A., Hasnat A. Properties of Concrete using Crushed Bricks as Aggregate; Concrete International, 2/83, 1983.
Recycled concrete as aggregate for producing structural concrete

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ABSTRACT: A comparative analysis of experimental investigation of properties of fresh and hardened concrete with natural coarse aggregate, combination of natural and recycled coarse aggregate and with recycled coarse aggregate, is presented in the paper. Three types of concrete mixtures were encircled by this experimental research. Kind and quantity of coarse aggregate were varied in the following way: the first concrete mix has 100% natural river coarse aggregate (R0), the second concrete mix has 50% natural river coarse aggregate and 50% recycled coarse aggregate (R50) and the third concrete mix has 100% recycled coarse aggregate (R100). Ninety nine samples were formed for the testing of basic properties of hardened concrete. On the basis of obtained test results and their analysis it was concluded that concrete mixtures with recycled aggregate are very similar to concrete mixes with natural aggregate if rules for design and production of this new concrete type are taking into account. Obtained test results of hardened concrete samples showed that recycled aggregate concrete had satisfactory performance that did not differ from properties of ordinary concrete significantly, if quality recycled concrete coarse aggregate was used. For example, mechanical properties of all three kinds of concrete (concrete compressive strength, splitting and flexural strength) had almost the same values.

1 INTRODUCTION

Demolishing of old and deteriorated buildings and their substitution with new buildings is frequent phenomenon in urban areas and in the scope of traffic infrastructure. Main reasons for demolishing of existing buildings is change of their purpose, ageing of structures, rearrangement of a city parts, expanding of traffic directions and increasing of traffic load, natural disasters (earthquake, fire, flood) etc. For example, in countries of EEC, forty years ago 50 million tons of concrete was demolished per year and the prediction was that in the beginning of this millennium that quantity will increase three times (Rilem Report No.6, 1992). In USA the construction waste produced from building demolition alone is estimated to be 123 million tons per year (FHWA National Review, 2004). The most common method of managing this material has been through disposal in landfills. In that way huge deposits of construction waste are created and consequently agriculture land is decreasing and that becomes real ecological problem, because construction waste is a potential polluter of human environment. For that reason in developed countries, restricted laws in a form of prohibitions or special taxes for creating of waste areas are bring into practice.

From the other hand, production and application of concrete is rapidly increasing which results in increasing of consumption of natural aggregate as a largest concrete component. This can be proved by example that two billion tons of aggregate are produced each year in the United States. Production is expected to increase to more than 2.5 billion tons per year by the year 2020 (FHWA National Review, 2004). This situation led to question about the availability of natural aggregates and where will we find new aggregate sources. Many European countries have placed a tax on the use of virgin aggregates.

The solution of these problems state agencies and the aggregate industry find in recycling concrete debris as an alternative aggregate.
2 RECOMMENDATIONS FOR PRODUCTION AND BASIC PROPERTIES OF CONCRETE WITH RECYCLED AGGREGATE

In this chapter recommendations for production and the most important properties of fresh and hardened concrete with recycled aggregate are briefly presented. Presented data are results of comparative testing of properties of ordinary concrete and concrete with recycled aggregate of other researchers.

Recycled aggregate compared to natural aggregate has following properties:
- increased water absorption,
- decreased bulk density,
- decreased specific gravity,
- increased abrasion,
- increased crushability,
- increased quantity of dust particles,
- increased quantity of organic impurities (if concrete is mixed with earth during building demolition) and
- possible content of chemically harmful substances (depends on service conditions in building from which by demolition and crushing recycled aggregate is obtained).

It is recommended to use aggregate from recycled concrete only as a course aggregate if quality concrete have to be produced. In USA it is allowed partial substitution of natural fine aggregate with recycled fine aggregate up to 20%.

Technology of production of concrete with recycled aggregate is different from the production procedure for ordinary concrete. One possibility to provide design consistency of fresh concrete is to previously saturate recycled aggregate to the condition “water saturated surface dry”.

Available testing results of concrete with recycled aggregate vary in wide limits, sometimes are even opposite, but general conclusions about properties of concrete with recycled coarse aggregate compared to concrete with natural aggregate (Rilem Report No.6, 1992), are:
- Increased drying shrinkage (up to 40%),
- Increased creep (up to 50%),
- Water absorption depends on differences between water-cement ratio of new and old concrete which was used for recycling (there are no differences if new concrete has bigger water-cement ratio from recycled concrete),
- Decreased compressive strength (5-30%),
- Decreased splitting tensile strength (0-10%),
- Decreased flexural strength (0-10%),
- Decreased modulus of elasticity (10-30%),
- Same or increased frost resistance.

3 OWN EXPERIMENTAL INVESTIGATION

The aim of this investigation was comparison of basic properties of referent concrete (concrete with natural aggregate) and concrete with recycled aggregate.

Research program encircled three concrete types (Malešev et al. 2006). Compositions of the tested concrete types were determined in accordance to the following conditions:
- same cement quantity,
- same consistency after 30 min,
- same max. grain size (32mm),
- same granulometric curve of aggregate fractions,
- same kind and quantity of fine aggregate,
- variable kind and quantity of coarse aggregate.
Kind and quantity of coarse aggregate were varied in the following way:
- the first concrete mix has 100% natural river coarse aggregate (R0), referent mixture
- the second concrete mix has 50% natural river coarse aggregate and 50% recycled coarse aggregate (R50)
- the third concrete mix has 100% recycled coarse aggregate (R100)

Mentioned conditions for determination of mixture compositions enable to find out the influence of used quantity of coarse recycled aggregate (0%, 50% and 100%) on tested concrete properties. The following properties of concrete were selected for testing:

- $\Delta h$ - consistency (slump test) immediately after mixing and 30 min after mixing,
- $\gamma_{b,sv}$ - bulk density of fresh concrete,
- $\Delta p$ - air entrained quantity,
- $\gamma_{b,oc}$ - bulk density of hardened concrete,
- $u_v$ - water absorption (age 28 days),
- $h$ - waterproofness according to DIN 1048, (age 28 days),
- wear resistance (age 28 days),
- $f_p$ - compressive strength (age 2, 7 and 28 days),
- $f_{sc}$ - splitting strength (age 28 days),
- $f_c$ - flexural strength (age 28 days),
- $E$ - modulus of elasticity (age 28 days),
- $\varepsilon_s$ - drying shrinkage (age 3, 4, 7, 14, 21 and 28 days),
- $f_{st}$ - bond between reinforcement and concrete (ribbed and mild reinforcement),

For the testing of listed properties of hardened concrete 99 samples were formed.

Component materials for concrete mixtures were:
- Portland-composite cement CEM II/A-M(S-L) 42.5R, (Lafarge - BFC)
- Fine aggregate (river aggregate, separation Luka Leget, fraction 0/4mm)
- Two kinds of coarse aggregate:
  - river aggregate, separation Luka Leget, fractions 4/8, 8/16 and 16/31.5mm,
  - aggregate form recycled concrete (fractions 4/8, 8/16 and 16/31.5mm)
- Potable water.

Aggregate from recycled concrete was produced by crushing of "old" concrete with class C30/37 and C40/50. Raw materials for crushing were concrete cubes used for compressive strength testing (Fig. 1) and one precast reinforced concrete column, which had inappropriate dimensions (Fig. 2). The primary crushing was done with pneumatic hammer (Fig. 2) and the secondary crushing was performed in rotating crusher. Obtained material after primary crushing is shown in Fig. 3, and after secondary crushing in Fig. 4.

Crushed concrete particles were separated in standard fractions of course aggregate (4-8mm, 8-16mm and 16-31.5mm) (Fig. 5).
All component materials were tested before mix design. Regarding test results it was concluded that tested cement and river aggregate satisfy prescribed requirements of quality. The results of testing of recycled concrete aggregate are shown in Table 1:

<table>
<thead>
<tr>
<th>Tested property</th>
<th>Measured value</th>
<th>Fraction</th>
<th>Quality requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushing resistance (in cylinder) mass loss (%)</td>
<td>18.3 26.7 30.7</td>
<td>4/8 8/16 16/32</td>
<td>&lt; 30</td>
</tr>
<tr>
<td>Freezing resistance test mass loss (%)</td>
<td>2 1.4 1.0</td>
<td>4/8 8/16 16/32</td>
<td>&lt; 12</td>
</tr>
<tr>
<td>Chemical testing mortar part of recycled aggregate chloride content</td>
<td>0 0 0</td>
<td>4/8 8/16 16/32</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td></td>
<td>sulfate content in traces in traces in traces</td>
<td>&lt; 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>pH</td>
<td>9.85 9.85 9.85</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Content of weak grains (%)</td>
<td>0 3.7 7.1</td>
<td>4/8 8/16 16/32</td>
<td>&lt; 3 (4)</td>
</tr>
<tr>
<td>Crushing resistance (machine &quot;Los Angeles&quot;) mass loss (%)</td>
<td>29.6 33.7 34.0</td>
<td>4/8 8/16 16/32</td>
<td>&lt; 30</td>
</tr>
<tr>
<td>Water absorption after 30 minutes (%)</td>
<td>4.59 2.87 2.44</td>
<td>4/8 8/16 16/32</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Fines content (%)</td>
<td>0.45 0.23 0.36</td>
<td>4/8 8/16 16/32</td>
<td>&lt; 1</td>
</tr>
</tbody>
</table>

3.1 Mix design

Compositions of concrete mixtures were chosen on the basis of following conditions:

- cement content 350kg/m³,
- water content according to required consistency (slump test, \(\Delta h=10\pm2\)cm after 30 minutes from mixing of concrete),
- aggregate content from the amount of absolute volume of component materials in 1m³ of concrete, \(\gamma_{s,a}=2670\) kg/m³, \(\gamma_{s,ar}=2500\) kg/m³ and \(\gamma_{s,c}=3060\) kg/m³
- granulometric content of aggregate mixture according to the Fuler grading curve,
- air content \(\Delta p=1\)%.

Designed compositions of all tested concrete mixtures are shown in Table 2 and quantity of each aggregate fraction in Table 3:

<table>
<thead>
<tr>
<th>Concrete mixture</th>
<th>Cement (kg/m³)</th>
<th>Water (kg/m³)</th>
<th>Aggregate (kg/m³)</th>
<th>Additional water * (kg/m³)</th>
<th>Bulk density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R0</td>
<td>350</td>
<td>180</td>
<td>1857</td>
<td>0</td>
<td>2387</td>
</tr>
<tr>
<td>R50</td>
<td>350</td>
<td>180</td>
<td>1816</td>
<td>19</td>
<td>2365</td>
</tr>
<tr>
<td>R100</td>
<td>350</td>
<td>180</td>
<td>1776</td>
<td>37</td>
<td>2343</td>
</tr>
</tbody>
</table>
- dry recycled aggregate, basic water content and additional water quantity were used to achieve required concrete consistency. Additional water quantity was calculated using results of water absorption of recycled aggregate after 30 minutes.

**Tab. 3 - Design quantities of aggregate fractions**

<table>
<thead>
<tr>
<th>Concrete mixture</th>
<th>Content of natural river aggregate (kg/m³)</th>
<th>Content of recycled aggregate (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0/4</td>
<td>4/8</td>
</tr>
<tr>
<td>R0</td>
<td>612</td>
<td>298</td>
</tr>
<tr>
<td>R50</td>
<td>600</td>
<td>145</td>
</tr>
<tr>
<td>R100</td>
<td>586</td>
<td>0</td>
</tr>
</tbody>
</table>

### 3.2 Results of testing of fresh concrete

Results of testing of consistency (Fig. 6), air content and bulk density are presented in Table 4. In the same table calculated real quantities of component materials, are shown also.

**Tab. 4 - Testing results of fresh concrete**

<table>
<thead>
<tr>
<th>Concrete mixture</th>
<th>$m_{c,av}$ (kg/m³)</th>
<th>$m_{w,av}$ (kg/m³)</th>
<th>$m_{a,av}$ (kg/m³)</th>
<th>$m_a/m_c$</th>
<th>$\Delta h_1$ (cm)</th>
<th>$\Delta h_2$ (cm)</th>
<th>$\Delta p$ (%)</th>
<th>$\gamma_{b,av}$ (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R0</td>
<td>352</td>
<td>181</td>
<td>1866</td>
<td>0.514</td>
<td>16</td>
<td>10</td>
<td>1.5</td>
<td>2399</td>
</tr>
<tr>
<td>R50</td>
<td>352</td>
<td>200</td>
<td>1826</td>
<td>0.5683</td>
<td>14.5</td>
<td>8.5</td>
<td>1.4</td>
<td>2378</td>
</tr>
<tr>
<td>R100</td>
<td>348</td>
<td>216</td>
<td>1765</td>
<td>0.62</td>
<td>11</td>
<td>9</td>
<td>1.3</td>
<td>2329</td>
</tr>
</tbody>
</table>

$\Delta h_1$ - measured slump immediately after mixing, $\Delta h_2$ - measured slump after 30 minutes

Fig. 6 – Consistency (slump test)

Differences in water content which are necessary to achieve the same consistency after 30 minutes are shown in table 5.

**Tab. 5 - Differences in water content between concrete mixtures R0, R50 and R100**

<table>
<thead>
<tr>
<th>$m_{w,R0}$ (kg/m³)</th>
<th>$m_{w,R50}$ (kg/m³)</th>
<th>$m_{w,R100}$ (kg/m³)</th>
<th>$(m_{w,R50}-m_{w,R0})/m_{w,R0}$ (%)</th>
<th>$m_{w,R100}-m_{w,R0}$ (kg/m³)</th>
<th>$(m_{w,R100}-m_{w,R0})/m_{w,R0}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>181</td>
<td>200</td>
<td>216</td>
<td>19</td>
<td>10.55</td>
<td>19.33</td>
</tr>
</tbody>
</table>

Comparison of air content ($\Delta p$) in concrete mixtures R0, R50 and R100 (Tab. 4) showed that differences are insignificant. By analysis of bulk density values, it was concluded that bulk density of concrete with natural aggregate was maximum 3% bigger than bulk density of concrete with recycled aggregate.
3.3 Results of testing of hardened concrete

Results of testing of compressive strength of concretes R0, R50 and R100 at age of 2, 7 and 28 days (Radonjanin et al. 1989), are presented in Table 6. For testing 15cm cubes were used.

<table>
<thead>
<tr>
<th>Vrsta betona</th>
<th>$\gamma_{o,tv}$ (kg/m$^3$)</th>
<th>$f_{p,2}$ (MPa)</th>
<th>$f_{p,7}$ (MPa)</th>
<th>$f_{p,28}$ (MPa)</th>
<th>$s$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R0</td>
<td>2424</td>
<td>27.55</td>
<td>35.23</td>
<td>43.44</td>
<td>1.57691</td>
</tr>
<tr>
<td>R50</td>
<td>2379</td>
<td>25.74</td>
<td>37.14</td>
<td>45.22</td>
<td>1.2089</td>
</tr>
<tr>
<td>R100</td>
<td>2332</td>
<td>25.48</td>
<td>37.05</td>
<td>45.66</td>
<td>3.50163</td>
</tr>
</tbody>
</table>

Measured values of drying shrinkage of concretes R0, R50 and R100 are shown in Table 7. The samples were prisms 10x10x40cm and for measuring of dilatation changes extensometer with base of 25cm was used.

<table>
<thead>
<tr>
<th>Concrete type</th>
<th>$\varepsilon_{s,4}$ (mm/m)</th>
<th>$\varepsilon_{s,7}$ (mm/m)</th>
<th>$\varepsilon_{s,14}$ (mm/m)</th>
<th>$\varepsilon_{s,21}$ (mm/m)</th>
<th>$\varepsilon_{s,28}$ (mm/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R0</td>
<td>0.0173</td>
<td>0.124</td>
<td>0.2027</td>
<td>0.2773</td>
<td>0.3387</td>
</tr>
<tr>
<td>R50</td>
<td>0.0360</td>
<td>0.086</td>
<td>0.1760</td>
<td>0.2540</td>
<td>0.3060</td>
</tr>
<tr>
<td>R100</td>
<td>0.0907</td>
<td>0.204</td>
<td>0.2507</td>
<td>0.3347</td>
<td>0.4067</td>
</tr>
</tbody>
</table>

Results of testing of other properties of hardened concrete are presented at Table 8.

<table>
<thead>
<tr>
<th>Concrete type</th>
<th>Water absorption, (%)</th>
<th>Waterproofness, (mm)</th>
<th>Splitting strength, (MPa)</th>
<th>Flexural strength, (MPa)</th>
<th>Wear resistance, (cm$^2$/50 cm)</th>
<th>Bond between mild reinforcement and concrete, MPa</th>
<th>Bond between ribbed reinforcement and concrete, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>R0</td>
<td>5.61</td>
<td>26</td>
<td>2.66</td>
<td>5.4</td>
<td>13.40</td>
<td>6.48</td>
<td>8.22</td>
</tr>
<tr>
<td>R50</td>
<td>6.87</td>
<td>18</td>
<td>3.20</td>
<td>5.7</td>
<td>15.58</td>
<td>5.87</td>
<td>7.50</td>
</tr>
<tr>
<td>R100</td>
<td>8.05</td>
<td>35</td>
<td>2.78</td>
<td>4.2</td>
<td>17.18</td>
<td>6.76</td>
<td>7.75</td>
</tr>
</tbody>
</table>

Waterproofness of concrete R0, R50 and R100 was tested on cubes 20cm. Splitting strength of concrete was tested on cubes 15cm and flexural strength on prisms 10x10x40cm.

Cylindrical samples with diameter 10cm and height 15cm and with embedded ribbed and mild reinforcement (R$\varnothing$12mm and $\varnothing$12mm) were used for testing of bond between reinforcement and concretes R0, R50 and R100. Length of embedded part of reinforcement was 15cm. For testing of bond, axial tension procedure and tearing device were used (Fig. 7).

![Testing of bond between concrete and reinforcement](image)

According to the analysis of the concrete compressive strength values, it was concluded:
- all three concretes have bigger 28-day compressive strength than 40MPa.
– differences between compressive strengths of concrete R0, R50 and R100 are negligible for the same concrete age.

Fig. 8 – Concrete compressive strength gain through time

To find out if differences between obtained compressive strengths of concrete R0, R50 and R100 at age of 28 days are accidental or not, difference between their mean values was statistically tested. For that purpose pairs of corresponding 28-day strength were formed (R0-R50, R0-R100 and R50-R100). The statistical analysis showed that differences between tested compressive strengths are accidental (all results belong to the same set of results). This conclusion led to the fact that coarse aggregate kind didn't influence on concrete compressive strength value.

According to the analysis of 28-day drying shrinkage values (Table 7), it was concluded:
– The lowest shrinkage has concrete R50 (0.3mm/m), and the highest R100 (0.4mm/m).
– Drying shrinkage of concrete R100 is 20% higher than shrinkage of concrete R0.
– Difference between 28-day shrinkage of concrete R0 and R50 is less than 10%.

Testing results of wear resistance are shown in Fig. 9. It was concluded that the highest material loss has concrete R100 and the lowest concrete R0.

Analysis of water absorption values (shown in Fig. 10), pointed to the following:
– The lowest water absorption was registered in concrete R0 and the highest in R100.
– Concrete R50 has 22% higher absorption, while concrete R100 has 44% higher absorption than referent concrete R0.

Fig. 9 – Testing results of wear resistance

According to the analysis of water penetration depths (Table 8), it was concluded that almost there are no differences in waterproofness between tested concretes because they all satisfy prescribed condition of waterproofness according to standard DIN 1048.

Statistical analysis of presented values of splitting strengths (Table 8), showed that differences between tested splitting strengths were accidental (all results belong to the same set of results). The same conclusion was drawn after comparison of obtained flexural strengths results (Table 8).

Analysis of obtained values of bond between mild and ribbed reinforcement and concrete R0, R50 and R100 (Table 8) showed that:
– Difference between lowest and highest bond for both reinforcement types is about 10%.
– Bond between tested concretes and ribbed reinforcement is higher at least 15% than bond between tested concretes and mild reinforcement.
CONCLUSION

On the basis of comparative analysis of testing results of basic properties of concrete with natural coarse aggregate, concrete with combination of coarse aggregate (natural and recycled) and concrete with recycled coarse aggregate, it was concluded:

- Kind of course aggregate has no influence on air content;
- Bulk density of concrete is slightly decreased with increasing of quantity of recycled aggregate;
- The way of preparing of recycled aggregate for concrete mixtures has influence on concrete consistency. Consistency of concrete with natural and with recycled aggregate will be almost the same in the case of use of "water saturated - surface dry" recycled aggregate. If dry recycled aggregate and additional water quantity are used, the same consistency could be achieved after a prescribed time. Additional water quantity depends on time when same consistency has to be achieved and is determined with water quantity which recycled aggregate absorb for the same period of time.
- Concrete compressive strength mainly depends on the quality of recycled aggregate. If quality aggregate which is obtained by crushing of higher strength class concrete is used for production of new concrete, the recycled aggregate will have no influence on decrease of compressive strength. Quantity of replaced natural coarse aggregate with recycled aggregate has no influence on concrete compressive strength in this case. The same conclusion is valid for concrete tensile strength (splitting and flexural).
- Water absorption depends on quantity of recycled aggregate. The quantity of absorbed water is proportionally increased with increasing of recycled aggregate participation.
- Concrete with recycled aggregate could achieve satisfactory waterproofness. The concrete waterproofness depends on porosity of cement matrix in new concrete and porosity of cement matrix of recycled concrete. If recycled aggregate is produced from low porosity concrete, waterproofness of new concrete depends on aggregate grading and achieved structure of new cement matrix.
- Wear resistance of concrete depends on quantity of recycled aggregate. Concrete wear resistance decreases with increasing of recycled aggregate content, due to the increased quantity of hardened cement paste, which wears easier than grains of natural aggregate.
- Bond between recycled aggregate concrete and reinforcement is not significantly influenced by recycled concrete aggregate because bond is realized through new cement paste.
- According to these tests, performance of recycled aggregate concrete could be adopted as satisfactory ones, regarding not only the compressive strength of recycled concrete, but also all the other requirements related to mixture composition design and production of this concrete type.

References
Transportation Applications of Recycled Concrete Aggregate, FHWA State of the Practice National Review, September 2004, pp. 47.
Demolition and Reuse of Concrete and Masonry, Proceedings of the Third International RILEM Symposium, Denmark, 1993, pp. 316.
ACI Committee 555 Report, American Concrete Institute, Farmington Hills, Michigan, 2001, 26 pages.
Sustainable aluminium systems

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ABSTRACT: In the present paper, an analytical presentation of some popular aluminium systems that contribute to sustainability of structures is presented. Special emphasis has been shown to the properties of aluminium members, while the influence of these systems in the overall performance of the structure regarding environment and economy is described. In particular, characteristics of aluminium elements as high reflectivity and recyclability and their role into life cycle analysis (LCA) are analysed, while the connections between energy efficiency and conservation of buildings and aluminium applications is discussed. Building applications such as curtain walls, window frames and facades sheets are presented and thoroughly investigated regarding environmental and economic aspects. Furthermore, many innovative techniques, where aluminium elements collaborate with other systems in order to produce renewable energy c.f. eg solar panels and photovoltaics are being introduced. Finally, environmental innovations like optimised ventilation mechanisms and light and shade management systems based on aluminium members are presented.

1 INTRODUCTION

As the consequences of environmental impacts have day by day more negative influence to our daily life, the need for taking immediate measures for the protection of the environment is imperative. There is a global ecological concern being developed and the need for adopting environmentally friendly policies is deeply felt by more and more factors (society, industries, governments etc). The climate change, the greenhouse effect and the depletion of the ozone layer are some of the impacts of the uncontrolled industrial activities.

The building sector is the biggest consumer of raw materials and energy, while the role of environmental parameters regarding the design and construction of building applications is becoming more significant. In the construction field, buildings consume significant amounts of energy, namely energy consumption in buildings represents today about 40% of the total energy consumption in the member states of the European Union (EU) and contributes about 45% of the carbon dioxide emissions released in the atmosphere. In this framework, the need to reduce the consumption of fossil sources of energy, to deal with the problem of material flow and waste production and its treatment is imperative. In the last years, the green building perception has started to become a nowadays trend, whereas the necessity to adopt an approach in assessing the impact of building activities on the environment, economy and society is recognized by all factors in construction business.

The scope of the present research effort is to focus on environmental perception and to investigate the relationship of sustainability and aluminium building systems. Aluminium is a new constructional material comparable to steel or concrete and can contribute to sustainability of structures, where its physical and mechanical properties can provide buildings a green performance in terms of ecology and economy besides functionality and structural stability. This paper
aims at presenting some of the most commonly used aluminium systems and all their special features that contribute to sustainability.

2 ALUMINIUM IN THE CONSTRUCTION

2.1 Structural Aluminium: The material

Lightweight materials such as aluminium offer the construction industry an opportunity to design and manufacture high performance structures that are safe, energy-efficient and environmentally friendly and much lighter than traditional designs. The introduction of these materials and their wide applications challenge can fully realize the potentials that can be gained in the interaction between these materials, structural design and the manufacturing process.

In civil engineering works, aluminium is concerned usually as a metal whose basic ingredient is either aluminium or aluminium alloys. Pure aluminium is a metal with a strength varied from 90 N/mm² to 140 N/mm², thus its use in construction is reluctant. When it is added with other metals such as Mg, or Si though, aluminium alloys are formed whose strength is high and in some cases it can reach to 500 N/mm² (Kissel & Ferry 2002). Aluminium alloys are classified in various categories regarding their chemical composition and their further process they are subjected to, where every alloy is characterized by unique properties and exhibits different structural behaviour. They represent a wide family of constructional materials, whose mechanical properties make them extremely popular in civil engineering works and cover an extended range of application fields.

In addition, their physical properties, such as lightness give advantages as erection phases can be simplified, as the loads transmitted to foundations can be reduced and as the physical labour can be reduced. Another characteristic of aluminium alloys is their corrosion resistance which results in reducing the maintenance costs and adopting a good performance in highly corrosive environments (Efthymiou 2005). It is noteworthy that the functionality of aluminium alloys regarding geometrical shapes can make them really competitive as the geometrical properties can be improved through the design of sections, as stiffened shapes can be obtained without using built up systems and as simplifying connecting systems among different structural members, thus improving joint details (Baniotopoulos 2003). Aluminium applications can be both structural and non structural. Regarding structural applications, aluminium alloys are usually used in large span roof systems, where live loads are small compared to dead loads. In addition they are used in structures located in inaccessible places far from the fabrication shop, thus they can provide transport economy and ease of erection. In structures like swimming pool roofs, harbour elements, river bridges, which are characterized be humid environments, the aluminium alloys is preferable (Mazzolani 1995).

2.2 Sustainable features of aluminium alloys

The concept of "sustainable construction" has been developed which involves minimizing building costs, materials and waste, minimizing energy use and improving energy efficiency of the structure. Sustainability also includes low operating and maintenance costs, along with creating the conditions for healthy, safe and comfortable living. Furthermore, it includes also the choice of recyclable construction materials and products, as saving energy is a major objective and the removal or not of materials at the end of their life cycle is dependent on this choice. In addition, sustainable design means considering the whole lifetime of a structure, investigating ways of reducing the environmental impacts of building activities, importing the assessment of life-cycle costs of buildings in the primary process. In this framework techniques and methods of minimizing the release of emission and the consumption of resources in the construction of building products in transport, installation and maintenance during their service life, are also included in sustainable design. Generally, sustainable building is the building where the principles of sustainable development in the construction industry are applied. These are to optimize struc-
tures depending on their requirement at 3 levels simultaneously, namely ecological, economic and socio-cultural (Maydl 2006).

Sustainability in architecture means buildings which combine comfort for the user with respect for the environment and minimum energy usage. Energy performance, user comfort, building functionality and cost over the lifetime of the building are the main objectives. Sustainable buildings emit less "greenhouse" gases and their materials can be infinitely recycled. Aluminium can justifiably be described as the "green metal": it is non-toxic and recyclable, easily formed yet strong, durable yet modern. Large savings in energy usage can be achieved using Aluminium façades, which act as solar reflector and thermal buffer. An aluminium facade can be integrated into the diversity of the architectural tradition.

From the sustainable point of view, aluminium alloy structures provide great credibility when a long term approach is being adopted. Despite the initial high cost and the great amounts of energy consumption during production, the special features of alloyed aluminium enable sustainable performance when the consideration refers to the whole service lifetime of the structure (Radlbeck et al. 2004).

To begin with, building aluminium material has a very long life cycle, ranging from 30 to 50 years and due to durability, the maintenance costs are very low over the lifetime of the structure. In addition, the majority of alloys used in construction are weather-proof and corrosion resistant, thus a long serviceable lifetime is assured. Another important characteristic of the material is its high reflectivity, which can be exploited in several building techniques and systems. An example of this is when aluminium solar collectors are installed to lower energy consumption regarding heating in winter and artificial lighting while there is the case of aluminium shading devices reducing the need for air-conditioning in the summer. Furthermore, aluminium alloys exhibit excellent recyclability. Used aluminium products and scrap can be recycled and at the same time the environmental impact related to recycle processes is reduced. As almost all aluminium material used in construction can be recycled, the considerable energy invested in the production of primary aluminium can be reinvested into other aluminium products. Scrap may not necessarily be recycled back into its original product or even reused in the country in which it was first manufactured, but the original energy investment will not be lost.

Concerning structural applications and aluminium alloys, their strength, weight and versatility make them ideal building and cladding materials. Since they are corrosion resistant, they are mostly used in maintenance-free applications such as siding, windows, skylights, doors, screens, gutters, down spouts, hardware, canopies and shingles, etc. Regarding aluminium siding, systems are also available with insulation and reflective foil backing, so walls can be made weatherproof and energy-efficient. A layer of insulated aluminium siding is four times more effective than uninsulated wood siding, four inches of brick or ten inches of stone masonry.

In addition, the relatively low melting point (660°C) of aluminium alloys means they will "vent" early during a severe fire, releasing heat and thereby saving lives and property. Regarding recycling, aluminium not only has important economic implications but also contributes to environmental production, whereas depositing or incineration does not have harmful side-effects even if inadvertently dispersed in the environment.

2.3 Life Cycle Analysis and Aluminium

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. The life cycle of aluminium alloys is divided into several stages. In the first phase which refers to design and calculation, various alloys with different characteristics and strength values are considered. According to the type of alloy, high strength values, even within the range of steel, are available. The low material density values of aluminium can reduce the total weight of structures significantly, with savings up to 50% of comparable steel sections. Static design and quality control are covered in various standards, currently being further developed and harmonized. The second phase includes the production, transport and assembly. Production of 1ton of aluminium requires 4 tons of bauxite. The subsequent chemical and electrolytic processes consume a rather
high amount of energy. For the production of one ton primary aluminium currently an average of 15.5 MWh sufficient for the production of 5 tons of steel are required. Depending on product, cross section form and respective energy price the initial cost is rather high, but may vary widely. Due to its light weight and its high grade of formability aluminium cuts costs, energy and time in transport and erection too. The next stage is the use- service phase. The natural corrosion resistance provides a high level of durability, together with minimum inspection and maintenance requirements. This leads to significant cost and energy savings, especially in comparison to other materials requiring regular painting. Aluminium in the building envelope requires well-planned thermal insulation because of its high heat conductivity value \( \lambda_{\text{RAI}}=200 \), \( \lambda_{\text{RAlloy}}=160 \) compared to other building materials \( \lambda_{\text{RGlass}}=0.80 \), \( \lambda_{\text{RSteel}}=60 \). The dismantling, transport and recycling procedures are the final phase in the life cycle, as the disposal of a relevant matter, being non-hazardous and of high scrap value.

Aluminium structures are easy to dismantle and transport, while the recycling process is carried out with only 5% of the input energy for primary aluminium and with no loss in quality. Currently, a recycling rate of 85% is achieved in the building industry. In total 6% of recycled aluminium is reused in building structures. The final phase of a building’s life needs to also be considered when making material choices. Ideally the material will be recycled in an economically and environmentally sustainable way. Usually the least desirable option is landfill, whereas a large amount of waste building materials goes to landfill sites at a cost to both the economy and the environment; others are recycled at a cost to the community. In contrast, aluminium is recycled in a way that pays for itself and is sustainable. Aluminium has a low melting temperature and is therefore able to be recycled with comparatively little energy. The energy required to produce secondary ingot from scrap is only about 5% of that required to produce primary aluminium. About 30% of the world's annual aluminium usage is supplied from processing post-consumer scrap.

3 SUSTAINABILITY AND ALUMINIUM SYSTEMS

Aluminium applications can be both structural and non structural. Regarding structural applications, aluminium alloys are usually used in large span roof systems, where live loads are small compared to dead loads. In addition they are used in structures located in inaccessible places far from the fabrication shop, thus they can provide transport economy and ease of erection. In structures like swimming pool roofs, harbour elements, river bridges, which are characterized be humid environments, the aluminium alloys is preferable (Mazzolani 1995).

In the building sector popularity of aluminium alloys in load carrying structures as well as in secondary or decorative elements has increased significantly over the past 50 years. Currently, a total of 26% of all aluminium products is used in building applications. All kinds of aluminium products are used in new home construction and in rehabilitation and renovation of existing structures. The range of building applications of aluminium is wide: it is commonly used in the building envelope for facades, glazed and roofing systems, curtain walling, window frames and doors. It is also applied for railings, balconies, staircases, heating/ air conditioning and solar elements.

The use of aluminium cladding on building facades is a promising construction alternative for building or the renovation of non-insulated buildings. Aluminium cladding is placed at a proper distance from the external wall, ranging from 5-10 cm for alignment purposes. The air gap that is created between the building’s wall surface and the aluminium cladding, acts as a thermal buffer zone. In particular, curtain walling or roofing can use aluminium with glazing or other transparent and semitransparent materials, creating uninterrupted large surfaces and atriums. Large curtain walling is usually recommended in climates with heating loads (Fig. 1).
There are also facade and roof systems where aluminium is used in window and glazing frames and glazing spacers. The function of these systems is to provide daylight, visual contact between the exterior and the interior, provide protection against the weather (rain and wind), provide passive solar heating gains, help keep interior thermal comfort and keep the energy use for operation at its minimum (Adresen et al 2001).

In addition, the ventilated facades are complex systems of construction which offer both aesthetic quality and effective insulation permitting energy savings (Andresen et al 2001). This kind of system consists of an outer cladding, an air space at least 40 mm deep, a sub-structure generally made of aluminium anchored to the building and an insulating layer secured to the outer wall of the building. The main functions of the outer cladding are aesthetic and protective and the air gap is essential for activating the natural ventilation that is necessary for the system to function as a whole. The aluminium sub-structure ensures stability of the cladding system, while the insulating layer, usually consisting of self-supporting water-repellent glass wool panels, takes care of adequate thermal stability. These claddings provide an ideal means to achieve the increased energy performance of buildings and to contribute to the improvement of the urban environment.

Regarding shading systems, there are venetian blinds, screens, overhangs, sidefins and others. Aluminium is used in lamellas, screens and fins. The function of these systems is to prevent glare and overheating and thereby minimise the energy use for space cooling. The literature survey did not identify any studies dealing with the environmental impacts of such systems that are relevant for this project (Fig 3). There are also Daylighting systems: this includes devices that enhance the daylight penetration and distribution into the room, e. g. light shelves, light-reflecting lamellas, etc. Better daylight availability and distribution in the space makes it possible to save electricity for artificial lighting, by turning the lights off when there is sufficient daylight. This may also, in turn, reduce the needs for cooling. Aluminium may be used as light directing devices. However, no studies were found that included environmental analysis of such systems.
Aluminium is used also in window frames where it provides flexible and popular window geometry and operation. Since aluminium is a good heat conductor, it is necessary to use proper thermal breaks for enhanced thermal performance. Regarding insulation, it offers high levels of heat and noise insulation and the flexible design of systems used in doors and windows enables you to choose from among traditional or modern structures. Aluminium is a material that does not wear out in time, thus ensuring the longevity of your frames. It is also appropriate for areas with high temperatures and intense sunlight. The maintenance and care of frames is quite easy, and they can be cleaned periodically. Aluminium is of natural origin, and there is plenty of it in nature. As it is environmental friendly and 100% recyclable, it does not have a negative effect on human health and the environment.

In places like Mediterranean where the ample sunlight and wind potential offer plenty of solar and wind power the exploitation of renewable energy sources is the main objective. The maximum energy from sunlight is produced at peak consumption times and solar energy is converted to a usable form of energy (electricity) through the photovoltaic effect (Fig 4). Photovoltaic Systems in developing countries and isolated areas (e.g. the Greek islands) can offer energy solutions and improve the standard of living. The functions of these thermal systems is to provide energy for domestic hot water heating and/or space heating in order to reduce the auxiliary energy use. The function of photovoltaic systems is to produce electricity that can be used directly for running lights and equipment in the building or fed into the electric utility grid. In this case, aluminium is used for absorbers, frames and casings for thermal collectors and for frames and support structures for photovoltaic modules.

4 CONCLUSIONS AND FUTURE SUGGESTIONS

The construction industry is faced with a number of environmental issues ranging from its direct impact on climate change to its choice of materials and its methods of waste disposal. The entire life cycle of a building must be considered when assessing these issues. At the same time environmental considerations need to be balanced against the realities of design, function and economy. When choosing the optimum material for each building an approach which takes account
of the full lifetime of the material should be adopted, covering construction, use, maintenance and disposal phases. When planning an environmentally sustainable and cost effective building, factors like minimal energy minimal maintenance, suitability for local climate and minimal waste should be considered.

Nowadays, new building systems and innovative design concepts regarding aluminium alloys cooperating with building elements are adopted in order to provide more sustainable solutions and to meet future ecological demands. In particular facades incorporating aluminium systems can decrease energy consumption in buildings up to 50% have just started to appear in european construction era. Shading systems, photovoltaic systems which are based on aluminium are characterized by constructive interaction with the exterior, markedly reducing heating, cooling, ventilation and lighting energy demands. New technologies mean solar power captors can be inserted in aluminium frames, thus saving considerable amounts of energy and protecting the environment. Numerous techniques are being adopted and processes need to be verified and tested in order to ensure long term sustainability and at the same time static stability and fitness.

5 REFERENCES

Etem Building Systems, www.etem.gr
Preliminary Life Cycle Inventory analysis of light-gauge steel frame system

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ABSTRACT: Paper presents the draft inventory data collection for light gauge steel frame structural SUNDAY system. This technology may be used for residential and commercial buildings. The LCI analysis of considered system was performed for boundaries covering manufacturing processes, in which light-gauge, galvanized steel (strip coil) is pre-formed (into C or U channel sections) and pre-cut (into studs or truck) using a SUNDAY roll-form machine. Still under the roof of the fabrication shop, these pieces are combined and fastened with a screw gun into building elements (wall panels, roof trusses, floor joists, and headers). Results of the LCI analysis could be used as input data for LCIA of buildings.

1 GENERAL DESCRIPTION OF THE TECHNOLOGY
1.1 Range of application

SUNDAY system may be used for residential and commercial buildings over ground structural systems basically in form of wall panels, ceiling girders and roof trusses. Ready made prefabricated units are delivered to site were they are assembling to designed form.

Figure 1. SUNDAY System under construction

The structure is fixed (screwed) on a previously prepared foundation or existing sub structure (in case of extending stories). The range of application results from bearing capacity and deformation limits of elements and units calculated according to standards requirements. Generally, it is limited up to four stories and 12 m span.
The technology is based on cold-bent and zinc-coated four basic steel profiles, which are combined and fastened with the use of self-drilling screws to form wall panels, ceiling girders, roof trusses and auxiliary elements.

1.2 Input materials: profiles and connectors

1.2.1 Zinc-coated steel sheets
The profiles and gusset plates are manufactured from zinc-coated steel strips or sheets by cold forming and cutting in special machines adapted for the support of the system. The steel is characterized by the following durability parameters:
- Yield stress point $R_e = 195$ MPa.
- Tensile strength $R_m = 315$ MPa.

The galvanic zinc layer offers protection for bend and surface scratches as well as for the cut edges of the elements. The minimal thickness of zinc coating measured on both sides should amount to 275 g/m².

1.2.2 Basic profiles
The main steel profiles used in the system are the following:
- the U 90 and U 140 U-shaped profiles
- the C 90 and C 140 C-shaped profiles

The height of these profiles is 9 cm and 14 cm respectively, whereas their thickness is 0.9, 1.25 and 1.5 mm.

1.2.3 Auxiliary profiles
Auxiliary profiles used in system are listed in Table 1

Table 1. Auxiliary profiles.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Dimensions mm * mm * mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>U38 * 0.90</td>
<td>38 * 16 * 0.90</td>
</tr>
<tr>
<td>U38 * 1.25</td>
<td>38 * 18 * 1.25</td>
</tr>
<tr>
<td>U38 * 1.50</td>
<td>38 * 18 * 1.50</td>
</tr>
<tr>
<td>½ * U90*0.90</td>
<td>45 * 38 * 0.90</td>
</tr>
<tr>
<td>½ * U140*1.50</td>
<td>70 * 50 * 1.50</td>
</tr>
<tr>
<td>BL 160</td>
<td>160 * 0.90</td>
</tr>
</tbody>
</table>

Gusset plates (joint sheets) in trusses are made from steel sheets 1.25 and 1.50 mm thick cut to appropriate shape.
1.2.4 Connectors
Connections between profiles in unit and units in structure are made by self-drilling screws. Types of used screws are presented on Figure 3.

<table>
<thead>
<tr>
<th>ITEM</th>
<th>SIZE</th>
<th>HEAD TYPE</th>
<th>MAXIMUM DRILLING THICKNESS</th>
<th>SCREW-DRIVER BIT</th>
<th>APPLICATION</th>
<th>APPEARANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.8</td>
<td>PAN</td>
<td>4.5 mm</td>
<td>Ph 2</td>
<td>For mounting the posts and lintels in the wall panels and for other connections where a smooth surface is required</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>4.8</td>
<td>HWH</td>
<td>4.5 mm</td>
<td>Hexagonal 8 mm</td>
<td>Any other connections not specified in Item 1</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>5.5</td>
<td>PAN</td>
<td>5.3 mm</td>
<td>Ph 2</td>
<td>As for Item 1</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>5.5</td>
<td>HWH</td>
<td>5.3 mm</td>
<td>Hexagonal 8 mm</td>
<td>As for Item 2</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Connectors used for units prefabricating

1.2.5 Hot-rolled steel profiles
In particular cases for stiffening the building structures, frames of welded hot-rolled I- and channel sections steel profiles are used. The steel is characterized by the following durability parameters:
- Yield stress point $R_e = 235$ MPa.
- Tensile strength $R_m = 360$ MPa.

1.3 Manufacturing processes
Manufacturing process on production plant covers two main operations: shaping the elements and prefabrication of the mounting or shipment units.

Shaping the elements consist in forming the profiles by cold bending of steel strips and cutting to desire length (also for gusset plates and hot-rolled profiles).

Prefabrication (of wall panels, roof trusses etc.) consist of geometrical arrangement of elements on mounting table and fixing them together by connectors (self-drilling screws). In particular cases additional undercutting and bending is done. Scale of prefabrication depends both on dimensions of ready to install units and means of transport to site. For local transport (mainly used for family houses in distance up to 50 km) generally size limits are 2.4 m height (wall panels) and 6 m length (roof girders and ceiling beams). For long distance transport by heavy trailer prefabrication is generally limited to linear parts. In this case, completing of mounting units is performed on site.

For some applications, additional elements made from hot-rolled steel profiles are prepared by cutting and welding with prefabrication limits as above.

For all manufacturing operations electric equipment is used.

1.4 Mounting (framing) units characteristics
The system distinguish three basic units:

1.4.1 External (bearing) wall panels
Wall panels are made of steel posts (the C 90 or C 140 C-shaped profiles), their spacing equal to 60 cm, placed in the U 90 or U 140 U-shaped profiles, which constitute the basis and the closure of a wall.

Transverse bracing and spandrel beams are made of steel strips or appropriately cut profiles. Wall panels, assembled in the factory, provide for window and doorway openings, and include lintels of a special design.
Post-to-longitudinal elements connection requires one screw on every flange of post and additional one screw for every second post. In case where two or more elements run together parallel (terminal or opening posts, lintels) two rows of connectors spaced 30 cm are applied.

1.4.2 Inter-story floors (ceilings)
For inter-story floors, the C 90 and C 140 C-shaped profiles, as well as the U 90 and U 140 U-shaped profiles are used, in different configurations. In the case of larger span lengths, floor girders are made of profiles of a greater height. The optimal span length is up to 4.5 m. The typical spacing of the beams is 60 cm.
In case where two profiles run together, two rows of connector spaced 30 cm are applied.

1.4.3 Roof trusses
The load bearing structure of the roofs is constituted of steel trusses made of the C 90 and C 140 C-shaped profiles. Truss joints are covered with metal sheets (gusset plates), on both sides for the span length > 6.0 m. Connections are executed with the use of sheet-metal screws. The constituent elements of the girders are joined directly. Buildings with a usable attic are provided with a special roof structure. Bracing of the roof structure is executed with the use of the C 140 or C 90 C-shaped profiles. The typical roof girder spacing equals 60 cm.
In every connections, minimum distance to element edge and distance between connectors should be 19 mm. In case of joints with gusset plates on both sides, on the web side of the profile design number of screws should be applied, and on opposite side at least 2 for every profile. Minimum distance of connectors must be not less than 100 mm. Direct connection of profiles webs or with gusset plate between should be done with two rows of screws.

2 RANGE OF LCI ANALYSIS
2.1 Function and functional unit
The basic function of considered system is to provide steel structure as a part of buildings framing. The assumed functional unit is 1 tone of prefabricated steel structure ready for shipment to construction site.

2.2 Analyzed impact categories
Following environmental impacts and their indicators were collected and calculated:
- Extraction of abiotic resources
- Chemical Oxygen Demand – COD
- Eutrophication Potential \( P_{\text{tot}} \)
- Nitrification Potential \( N_{\text{tot}} \)
- Global Warming Potential – \( \text{CO}_2, \text{CH}_4 \) and \( \text{N}_2\text{O} \) emissions
- Acidification Potential (eq. \( \text{SO}_2 \))
- Photochemical Ozone Creation Potential (\( \text{NO}_x \))
- Human toxicity (NMVOC)
- Process wastes

2.3 System boundary
The considered analysis is performed for system boundary shown on Figure 4 covering:
1. On-plant transport of materials (steel strips and sheets)
2. Profiles forming and cutting, gusset plates cutting
3. Prefabrication of shipment units
4. On-plant transport of shipment units
Figure 4. System boundary scheme

2.4 Data collecting procedures

For input materials (zinc-coated steel sheets, hot-rolled steel and connectors) data were collected from public sources – databases. The same way was for energy consumption.

Materials and energy flow per assumed functional unit (1 ton of shipment unit) was obtained based on direct information from producer for one year production.

2.5 Inputs and outputs

Zinc-coated steel and hot rolled steel profiles are the main input materials for analyzed technology. In assembling process connectors in form of self-drilling screws are added.

In all processes covered by system boundary only electric AC energy from public network is used.

The considered outputs are prefabricated shipment units and steel scraps.

3 INVENTORY RESULTS

3.1 Inputs and outputs

Inputs and outputs related to functional unit are presented in Table 2 below:

Table 2. Inputs and outputs factors (related to FU=1 ton)

<table>
<thead>
<tr>
<th></th>
<th>quantity</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Inputs:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zinc-coated steel</td>
<td>91.37</td>
<td>%</td>
</tr>
<tr>
<td>Hot-rolled steel</td>
<td>6.86</td>
<td>%</td>
</tr>
<tr>
<td>Connectors</td>
<td>1.77</td>
<td>%</td>
</tr>
<tr>
<td>Energy (AC)</td>
<td>324.24</td>
<td>MJ/t</td>
</tr>
<tr>
<td><strong>2. Outputs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shipment unit</td>
<td>100.00</td>
<td>%</td>
</tr>
<tr>
<td>Steel scraps</td>
<td>5.00</td>
<td>%</td>
</tr>
</tbody>
</table>

Data presented above were collected by producer analysing 1 year production and energy consumption in production plant.
3.2 Impact category indicators for inputs

3.2.1 Zinc-coated steel sheets and connectors
Data were obtain from U.S. LCI Database Project. Due to leak of available particular data for connectors the same data as for zinc-coated steel sheets were assumed.

Table 3. Inputs and outputs for zinc-coated steel sheets and connectors

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Energy</td>
<td>18.6 GJ/t</td>
<td></td>
</tr>
<tr>
<td>2. Raw materials</td>
<td>196.0 %</td>
<td></td>
</tr>
<tr>
<td>3. Emissions to water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COD</td>
<td>83.0E-3 %</td>
<td></td>
</tr>
<tr>
<td>P_{tot}</td>
<td>4.3E-3 %</td>
<td></td>
</tr>
<tr>
<td>N_{tot}</td>
<td>45.0E-3 %</td>
<td></td>
</tr>
<tr>
<td>4. Emissions to air</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>1001.0 %</td>
<td></td>
</tr>
<tr>
<td>CH\textsubscript{4}</td>
<td>1.1 %</td>
<td></td>
</tr>
<tr>
<td>N\textsubscript{2}O</td>
<td>7.8E-3 %</td>
<td></td>
</tr>
<tr>
<td>SO\textsubscript{2}</td>
<td>3.4 %</td>
<td></td>
</tr>
<tr>
<td>NO\textsubscript{X}</td>
<td>1.2 %</td>
<td></td>
</tr>
<tr>
<td>NM\textsubscript{VOC}</td>
<td>15.0 %</td>
<td></td>
</tr>
<tr>
<td>5. Process waste</td>
<td>260.0 %</td>
<td></td>
</tr>
</tbody>
</table>

3.2.2 Hot rolled profiles
Data were obtain from ELCD Data System

Table 4. Inputs and outputs for steel hot-rolled profiles

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Energy</td>
<td>12.91 GJ/t</td>
<td></td>
</tr>
<tr>
<td>2. Raw materials</td>
<td>100.77 %</td>
<td></td>
</tr>
<tr>
<td>3. Emissions to water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COD</td>
<td>39.1E-3 %</td>
<td></td>
</tr>
<tr>
<td>P_{tot}</td>
<td>2.8E-3 %</td>
<td></td>
</tr>
<tr>
<td>N_{tot}</td>
<td>16.5E-3 %</td>
<td></td>
</tr>
<tr>
<td>4. Emissions to air</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>109.96 %</td>
<td></td>
</tr>
<tr>
<td>CH\textsubscript{4}</td>
<td>0.72 %</td>
<td></td>
</tr>
<tr>
<td>N\textsubscript{2}O</td>
<td>162.6E-3 %</td>
<td></td>
</tr>
<tr>
<td>SO\textsubscript{2}</td>
<td>2.05 %</td>
<td></td>
</tr>
<tr>
<td>NO\textsubscript{X}</td>
<td>16.87 %</td>
<td></td>
</tr>
<tr>
<td>NM\textsubscript{VOC}</td>
<td>0.1 %</td>
<td></td>
</tr>
<tr>
<td>5. Process waste</td>
<td>449.8 %</td>
<td></td>
</tr>
</tbody>
</table>

3.2.3 AC Energy (public network in Poland)
Data were obtain from ELCD Data System

Table 5. Inputs and outputs for public AC network in Poland

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Energy</td>
<td>3.6 MJ</td>
<td></td>
</tr>
<tr>
<td>2. Raw materials</td>
<td>23.25 kg</td>
<td></td>
</tr>
<tr>
<td>3. Emissions to water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COD</td>
<td>0.4E-3 kg</td>
<td></td>
</tr>
<tr>
<td>P_{tot}</td>
<td>31.1E-6 kg</td>
<td></td>
</tr>
<tr>
<td>N_{tot}</td>
<td>0.2E-3 kg</td>
<td></td>
</tr>
<tr>
<td>4. Emissions to air</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>12.21 kg</td>
<td></td>
</tr>
<tr>
<td>CH\textsubscript{4}</td>
<td>8.0E-3 kg</td>
<td></td>
</tr>
</tbody>
</table>
Table 5. Inputs and outputs for public AC network in Poland -continued

<table>
<thead>
<tr>
<th>Indicator</th>
<th>quantity</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$_2$O</td>
<td>1.8</td>
<td>kg</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>0.02</td>
<td>kg</td>
</tr>
<tr>
<td>NO$_x$</td>
<td>0.18</td>
<td>kg</td>
</tr>
<tr>
<td>NMVOC</td>
<td>1.1E-3</td>
<td>kg</td>
</tr>
<tr>
<td>Process waste</td>
<td>4.99</td>
<td>kg</td>
</tr>
</tbody>
</table>

3.3 Energy (AC) consumption

Cumulative energy consumption for functional unit was calculated based on energy consumption indicator values for particular material input collected in Tables 3 to 5 and weighted by input indicators presented in Table 2. Total cumulative energy consumption is presented in Table 6.

Table 6. Cumulative energy consumption for functional unit

<table>
<thead>
<tr>
<th>Component</th>
<th>Component Unit</th>
<th>CU consumption</th>
<th>Product Quantity</th>
<th>FU consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>GJ</td>
<td>for FU, %</td>
<td>GJ</td>
</tr>
<tr>
<td>Zinc-coated steel</td>
<td>t</td>
<td>18.60</td>
<td>91.37</td>
<td>16.99</td>
</tr>
<tr>
<td>Hot-rolled steel</td>
<td>t</td>
<td>12.91</td>
<td>6.86</td>
<td>0.88</td>
</tr>
<tr>
<td>Connectors</td>
<td>t</td>
<td>18.60</td>
<td>1.77</td>
<td>0.32</td>
</tr>
<tr>
<td>Process energy</td>
<td>t</td>
<td>0.32</td>
<td>100.00</td>
<td>0.32</td>
</tr>
<tr>
<td><strong>Total (GJ/t)</strong></td>
<td></td>
<td><strong>18.53</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.4 Impact category indicators for Functional Unit (output)

Table 7 summarized impact category indicators analyzed in this study. For cumulative energy consumption, covering both consumption for input materials and production processes (presented in first “numerical” cell of Table 7), the same indicators were calculated. Impact category indicators values for particular input materials (weighted by input factors from Table 2.) were summarized with energy indicators in last column.

Table 7. Calculated impact category indicators for FU

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Unit</th>
<th>Energy (total)</th>
<th>Zinc-coated steel</th>
<th>Hot-rolled steel</th>
<th>Connectors</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Energy</td>
<td>GJ</td>
<td>18.53</td>
<td>16.99</td>
<td>0.89</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>2. Raw materials</td>
<td>t</td>
<td>119.66</td>
<td>1.79</td>
<td>0.07</td>
<td>0.03</td>
<td>121.55</td>
</tr>
<tr>
<td>3. Emissions to water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COD</td>
<td>kg</td>
<td>2.23</td>
<td>0.08</td>
<td>2.7E-3</td>
<td>1.5E-3</td>
<td>2.31</td>
</tr>
<tr>
<td>P$_{tot}$</td>
<td>kg</td>
<td>0.16</td>
<td>3.93E-3</td>
<td>0.2E-3</td>
<td>0.1E-3</td>
<td>0.16</td>
</tr>
<tr>
<td>N$_{tot}$</td>
<td>kg</td>
<td>0.94</td>
<td>0.04</td>
<td>1.1E-3</td>
<td>0.8E-3</td>
<td>0.98</td>
</tr>
<tr>
<td>4. Emissions to air</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO$_2$</td>
<td>t</td>
<td>62.84</td>
<td>0.91</td>
<td>0.08</td>
<td>0.02</td>
<td>63.85</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>kg</td>
<td>41.13</td>
<td>1.01</td>
<td>0.05</td>
<td>0.02</td>
<td>42.21</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>kg</td>
<td>9.18</td>
<td>7.12E-3</td>
<td>0.01E-3</td>
<td>0.01E-3</td>
<td>9.19</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>kg</td>
<td>117.21</td>
<td>3.11</td>
<td>0.14</td>
<td>0.06</td>
<td>120.52</td>
</tr>
<tr>
<td>NO$_x$</td>
<td>kg</td>
<td>964.08</td>
<td>15.47</td>
<td>1.16</td>
<td>0.02</td>
<td>980.73</td>
</tr>
<tr>
<td>NMVOC</td>
<td>kg</td>
<td>5.73</td>
<td>13.71</td>
<td>6.8E-3</td>
<td>0.26</td>
<td>19.71</td>
</tr>
<tr>
<td>5. Process waste</td>
<td>t</td>
<td>25.71</td>
<td>0.24</td>
<td>0.03</td>
<td>4.6E-3</td>
<td>25.98</td>
</tr>
</tbody>
</table>

4 SUMMARY

Presented analysis is the authors’ attempt on this field, based on standard ISO 44040:2006. It covers only part of life cycle of analyzed system, but could be a useful database for Life Cycle Impact Assessment of a case or comparative study of a building constructed with analyzed SUNDAY technology.
ENERGY EFFICIENCY OF OLD AND NEW BUILDINGS IN ROMANIA

D. Dan, V. Stoian, T. Nagy-Gyorgy, C. Dăescu
Politehnica University of Timişoara

ABSTRACT: Once Romania has joined the European Community, environmental protection and energy saving have become top priority domains. European standards have become Romanian reference standards and norms. The present-day housing stock in Romania was mostly built between 1960 and 1989, without the adoption of any efficient solutions for thermal insulation. The operation of buildings more than 30 years old, has led to the occurrence of certain damages, because of the condense phenomenon into the walls. In Romania a governmental programme is carried out for the thermal rehabilitation of blocks of flats built before 1989. The investment for the thermal rehabilitation of buildings is financed equally by the government and the owners. This paper presents the situation of the housing stock in Romania, the requirements regarding the resistance to heat flow for the elements of the building envelope as well as the latest tendencies concerning the erection of durable constructions.

1 GENERAL PRESENTATION

An essential element of the sustained development of constructions is the promotion of efficiency and the rational use of energy. As the specific heat consumption and the consumptions involved in the hot water preparation in Romania are rather double compared to the ones found in the Western countries of the European Union, it seems of utmost necessity that special programmes designed for the increase of the energetic efficiency of buildings should be developed.

The experience of Western European countries, and especially Northern countries, that have carried out, after the energetic crisis they had to face in 1973, national programmes designed for thermal protection, stand out as real examples for the national politics regarding the implementation of thermal rehabilitation of the Romanian housing stock.

Based on the statistic data gathered through the census survey carried out for population and residences in Romania in 2002, the total number of housing stock is 4,846,572 buildings that practically comprise 8,110,407 residences. Out of the mentioned number, 1,138,945 buildings that comprise 4,257,964 residences are situated in the urban areas. 97% of the residences are private property. Most of the residences are situated in buildings aged between 15 and 55 years, with a reduced level of thermal insulation and a high degree of run-out. The structure of the Romanian housing stock depending on the age is illustrated in Figure 1.

The heating supply is being ensured for blocks of flats, at a rather high rate (90%), through a centralized system. In large Romanian cities, there have been created and extended, along the latest 40 years, centralized heating systems, that have as a source either thermal-electric power plants (urban central heating), or a local heating plant, responsible for the area, the neighborhood or a group of blocks. Most of the urban heating supply is connected to sources of heating production that belong to the national private power plant, the rest of the systems belonging to the local administrations and being managed by specialized enterprises controlled by the municipalities.
2 STRUCTURE OF THE ENERGY CONSUMPTION WITHIN THE RESIDENTIAL SYSTEM

The weight of the energy consumption within the annual energetic balance of a medium-size apartment built between 1970-1985 is shown in Figure 2:

Considering the whole Romanian housing stock, the efficiency of the heat use for heating, hot water and cooking rises to only 43% from the total quantity of heat supplied by the sources. There can be noticed that the heating of the space is by far the largest final consumer of energy, both in Romanian and in Western European buildings.

3 TYPES OF ENVELOPE ELEMENTS USED FOR RESIDENTIAL BUILDINGS BETWEEN 1960-1989

The types of walls used for civil buildings until 1984 are different, therefore there are different thermal performances that depend on the composition of the walls. The main types of design used for the envelope walls of buildings built until 1984 are presented in Fig.3. A comparative study of the minimum resistances to heat flow required and the effective resistances to heat flow of the types of exterior walls used shows that the latter didn't meet the minimum requirements of thermal insulation. The walls show resistances to heat flow between the limits $R_0=0.54...0.97$ m$^2$K/W, that is 45...81% from $R_{0,req}$. Table 1 shows the ratios between the effective resistances to heat flow and the resistances to heat flow required by the standards in force on the mentioned date, for each type of wall.

<table>
<thead>
<tr>
<th>Exterior wall type</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal resistance $R_{0,ef}$ [m$^2$K/W]</td>
<td>0.68</td>
<td>0.57</td>
<td>0.54</td>
<td>0.57</td>
<td>0.97</td>
<td>0.93</td>
<td>0.67</td>
</tr>
<tr>
<td>Ratio $R_{0,ef} / R_{0,req}$</td>
<td>0.57</td>
<td>0.48</td>
<td>0.45</td>
<td>0.48</td>
<td>0.81</td>
<td>0.77</td>
<td>0.56</td>
</tr>
</tbody>
</table>
After 1984, the imposing of energy saving has led to a change of the design solutions for exterior walls used in residential buildings. The new solutions adopted have led to the exceeding of the minimum resistances required for envelope elements. Fig.4 gives the design details for exterior walls used for residence buildings starting with 1985.

Table 2 Comparative ratios between the effective and required resistances to heat flow

<table>
<thead>
<tr>
<th>Exterior wall type</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal resistance $R_{0,\text{ef}}$ [m$^2$K/W]</td>
<td>1.84</td>
<td>1.38</td>
<td>1.63</td>
<td>2.43</td>
<td>1.56</td>
<td>1.61</td>
</tr>
<tr>
<td>Ratio $R_{0,\text{ef}} / R_{0,\text{nec}}$</td>
<td>1.53</td>
<td>1.15</td>
<td>1.35</td>
<td>2.02</td>
<td>1.30</td>
<td>1.34</td>
</tr>
</tbody>
</table>

Table 2 shows the comparative ratios between the effective resistances to heat flow and the resistances to heat flow required according to the standards in force on the given date. There can be noticed that the principle solutions proposed for the improvement of the heat flow resistance exceeded the minimum resistance required, but in practice the solutions were not observed, this
resulting in short-comings of the envelope elements, regarding energetic and comfort performances. The thermal insulation materials used were the cellular autoclaved concrete and the mineral wool, with various hygro-thermal characteristics. Polystyrene was considered as an expensive material at the time.

Therefore, we can conclude that, for most of the buildings, the elements of the envelope in contact with the exterior do not meet the thermal and hygro-thermal requirements, and a general rehabilitation is needed, with consequences on the hygro-thermal comfort and the energy saving.

4 THE EVOLUTION OF ROMANIAN STANDARDS REGARDING THERMAL INSULATION

Along the years, the Romanian standards that concern thermo-technics have introduced different values for the minimum resistances to heat flow, but also additional conditions regarding the diffusion of moisture within the constructional elements. The codes valid until 1989 comprised the following requirements regarding the envelope elements:

- the effective resistance to heat flow should be higher than the minimum resistance required determined upon the climate zone that the building is being erected and interior climate parameters;

\[
R_u > R_{0,\text{nc}} \tag{1}
\]

\( R_u \) – Total resistance to heat flow \([\text{m}^2\text{K}/\text{W}]\);
\( R_{0,\text{nc}} \) – Total resistance to heat flow taking into account the massiveness of the material \([\text{m}^2\text{K}/\text{W}]\);
\( m \) – massiveness coefficient in function of the thermal inertia;
\( R_{0,\text{nc}} \) – Minimum required resistance to heat flow \([\text{m}^2\text{K}/\text{W}]\).

- preventing the condense to occur on the interior surface of the envelope element, meaning to satisfy the following condition:

\[
T_{si} > t_r \tag{2}
\]

\( T_{si} \) – Temperature on interior surface \([\degree\text{C}]\);
\( t_r \) – Temperature of dew point \([\degree\text{C}]\).

- limiting the mass of condensed water inside the exterior envelope element, that corresponds to the satisfying of the following conditions:

\[
m_w - m_v \leq 0 \tag{3}
\]

\[
\Delta W_{ef} \leq \Delta W_{allowed} \tag{4}
\]

\( m_w \) – Mass of water condensed during the cold period of the year;
\( m_v \) – Mass of water evaporated during the hot period of the year.
\( \Delta W_{ef} \) – Increase of water percentage condensed during the cold period of the year;
\( \Delta W_{allowed} \) – Increase of water percentage allowed.

Tables 3 shows the time variation of the requirements regarding the resistance to heat flow of the envelope elements of Romanian buildings.

In the past 10 years, there have been developed in Romania a series of new standards, along with their specific guidelines for application. It is essential that there has been introduced a new concept regarding the thermal insulation of buildings, through the evaluation of the global insulating coefficient of the building, respectively through energetic certification.
Table 3  Time variation of the requirements regarding the resistance to heat flow

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>CODE</th>
<th>$R_{\text{min}}$ [m$^2$K/W]</th>
<th>$R'$ [m$^2$K/W]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exterior walls</td>
<td>Flat roof</td>
<td>Floors over base-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ment</td>
</tr>
<tr>
<td>1950 ... 1961</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1962 ... 1968</td>
<td>STAS 6472 – 61</td>
<td>0.76</td>
<td>0.96</td>
</tr>
<tr>
<td>1969 ... 1975</td>
<td>STAS 6472 – 68</td>
<td>0.80</td>
<td>1.02</td>
</tr>
<tr>
<td>1974 ... 1975</td>
<td>STAS 6472/3 – 73</td>
<td>0.80</td>
<td>1.02</td>
</tr>
<tr>
<td>1976 ... 1984</td>
<td>STAS 6472/3 – 75</td>
<td>0.80</td>
<td>1.02</td>
</tr>
<tr>
<td>1985 ... 1987</td>
<td>STAS 6472/3 – 84</td>
<td>0.76</td>
<td>0.87</td>
</tr>
<tr>
<td>1988 ... 1989</td>
<td>NP 15 - 84</td>
<td>1.20</td>
<td>1.55</td>
</tr>
<tr>
<td>1990 ... 1997</td>
<td>STAS 6472/3 – 89</td>
<td>1.00</td>
<td>1.24</td>
</tr>
<tr>
<td>1998 ... 2000</td>
<td>C107/3 – 1997</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>C107/1 – 1997</td>
<td>-</td>
<td>1.40</td>
</tr>
</tbody>
</table>

The Romanian law states that, until the year 2010, all buildings should be energetically certified. Based on the energetic certification, advantages will be obtained concerning the systems of insurance, loans, taxes etc. The graph shown in Figure 5 presents the variation of the standards number and design guides that refer to the requirements of energetic performance.

![Figure 5. Variation of the standards number in the field of energetic efficiency in Romania](image)

4.1 Politics regarding the energetic efficiency. National programme for the rehabilitation of residence buildings

From the analysis of the graph presented in Figure 5, there can be clearly noticed the last decade’s trend to also introduce in Romania the concept of sustainable development directly referring to the energetic efficiency of new and existing buildings.

The Romanian Government has issued the Government Order no. 29/2000 regarding the thermal rehabilitation of the existing buildings and the stimulation of thermal energy saving; the provision sets up the legal framework for the thermal rehabilitation and modernization of all existing buildings and the installations thereof, aiming to the improvement of the conditions of hygiene and thermal comfort, to the decrease of the heat flow, the energetic consumptions, the cost of heating and hot water, and the polluting emissions generated by the production, the transportation and the consumption of energy. It is about the buildings situated in urban and rural areas (residences, public buildings, productions halls, etc.), where there are performed activities that require a certain degree of thermal comfort, according to the technical requirements in
force. Based on the legislation in force, the local administrations financially support the investments that aim to the thermal rehabilitation of the housing stock, by supporting 50% of the investment, the other half being imposed on the owner.

The Government’s programme for thermal rehabilitation of the existing housing stock also comprises some fiscal facilities for the owners. Thus, the ones who decide to rehabilitate their building shall benefit of an expertise, an energetic audit and projected design for thermal rehabilitation funded by the state budget, the relief from taxation when it comes to the issuing of the energetic certificate of the building and of the construction permit regarding the thermal rehabilitation works, respectively the relief from taxation regarding the residence all along the period of reimbursement of the credit obtained for the purpose of thermal rehabilitation.

5 EFFICIENT SOLUTIONS USED IN THE CONSTRUCTION OF THE „IULIUS MALL” COMMERCIAL CENTRE OF TIMISOARA

After 1989, one of the most important investment in the Western part of Romania is the ”Iulius Mall” commercial centre. The completion of the building structure was a decisive stage of the investment. The quality control of the building erection is a component of the quality system.

The commercial centre is made up of several sections, each of them with an independent structure. The first development stage of the area and the building of the commercial centre consists in the construction of 15 blocks and one technical block. The building has a constructed area of 73,000 square meters distributed on 3 levels and one terrace, hosting over 200 shops. Beside the shops, there is a movie theatre with several halls, a supermarket, restaurants, food courts, bars, kids land and sports centers.

A general view of the “Iulius Mall” Commercial Centre at the end of the construction works is presented in Figure 6.

![Figure 6. General view of the main entrance of “Iulius Mall” Centre of Timișoara](image)

The photos included in Figure 7 show aspects from the execution of the exterior walls.
a. Detail from the installation of the envelope walls on the Southern facade
b. General view of the Southern facade
Figure 7. Aspects from the execution of the exterior walls

The application of the thermal protection and hydro-protection on the terrace is shown in Figure 8.

a. Terrace hydro protection
b. Terrace thermal protection
Figure 8. Details from the execution of the terrace hydro and thermal protection.

The most important material used for the constructional work of Iulius Mall Center is presented in the table 4.

<table>
<thead>
<tr>
<th>No.</th>
<th>Material</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Reinforcements and structural steel</td>
<td>&gt; 3,000 t</td>
</tr>
<tr>
<td>2.</td>
<td>Concrete cast in site</td>
<td>&gt; 80,000 m³</td>
</tr>
<tr>
<td>3.</td>
<td>Mineral wool 5 cm thickness</td>
<td>13.847 m²</td>
</tr>
<tr>
<td>4.</td>
<td>Sandwich panels 6 cm thickness</td>
<td>13.847 m²</td>
</tr>
<tr>
<td>5.</td>
<td>Polystyrene 10 cm thickness</td>
<td>18.500 m²</td>
</tr>
<tr>
<td>6.</td>
<td>Windows and doors</td>
<td>&gt; 4,200 m²</td>
</tr>
</tbody>
</table>

Based on the characteristics of the materials used and on the execution details of the „Iulius Mall” commercial centre, there was drafted the certificate of energetic performance of the building, presented in Figure 9.
6 CONCLUSIONS

The reduction of heat loss through the construction elements is necessary in order to increase the energetic efficiency of a building. National and international programmes now in force aim to the thermal rehabilitation of residence buildings, as a priority measure within the sustained development of constructions.

The energetic performances of residential buildings are being evaluated in Romania by authorized energy experts who issue the certificates of energetic performances of a building. The energetic audit of a building requires, beside the energetic certification, the establishment of intervention measures and execution details designed for the improvement of thermal comfort.

The reduction of heat loss leads to the reduction of pollution and of the costs caused by the building maintenance.

REFERENCES

C107/1-3/1007 - Romanian standard for the calculus of the global thermal insulation coefficients for the civil residences
GT 036- 2002 - Guide for the thermal and energetic audit for the existing buildings and for the preparation for the hot water necessary for these buildings
GT 037- 2002 - Guide for the elaboration and assignment of the energetic certificate for the existing buildings
STAS 6472/2-83 - Building Physics. Hygrothermics. External climatic parameters
Thermal rehabilitation of a student’s hostel belonging to the Politehnica University of Timișoara

D. Dan, V. Stoian, T. Nagy-Gyorgy, C. Dăescu
Politehnica University of Timisoara

ABSTRACT: The student’s hostels located in Timișoara-Romania were mostly built from 1970 to 1980 with the adoption of minimum solutions for the thermal insulation required at the time. The hostels are heated by using a district heating station. The use of the buildings without general repair work has led to the occurrence of certain damages, especially because of the asweat on the walls. The technical department of the university has promoted and sustained the improvement of the energetic performances of the hostels located in the campus area. The paper presents one student hostel before and after thermal rehabilitation, along with the solution adopted and the economical study performed in order to sustain the execution of the constructional works. The solutions adopted referred to the improvement of global thermal resistance of the envelope elements in order to reduce the pollution and the energy loss.

1 INTRODUCTION

The "Politehnica" University of Timisoara, Romania is one of the largest and best-known technical universities in Central and Eastern Europe. Located in Western Romania, The "Politehnica" University attracts students both from the city and form the neighboring regions.

During the university years, the administration offers students the possibility to find accommodation in the campus. The students’ campus located in the city centre hosts over 25 hostels. During a university year, over 5,000 students can be accommodated in the hostels of the Politehnica University.

The administration of the University is permanently concerned with the improvement of the accommodation offered to the students, therefore, the investments have been directed especially to the rehabilitation of the students’ hostels. This activity has been carried out during the latest 3 years and the interventions were focused on the reconstruction of the finishing works, as well as the improvement of the comfort conditions. Taking into account the age of the buildings and the installations thereof, the works aimed at the total change of the installations, the complete remaking of the finishing, the improvement of the thermal insulation and installing of one thermal station for each hostel.

2 PRESENTATION OF A TYPICAL STUDENTS’ HOSTEL

One of the students’ hostel that has been rehabilitated is Hostel 20C (Fig.1). The building is included in the accommodation park of the Politehnica University of Timisoara, being erected in 1978. It has a basement, a ground floor and five storeys, each storey hosts ten apartments, each apartment includes two rooms, a shower room and a water closet. The apartments also have a hallway, with two sinks. Figure 2 shows the functional architecture of one apartment.
On each floor, at the end of the hallways, there are the stairways and 2 pantries, nowadays also used for students’ accommodation, although, in the past, they contained electric cookers or washing machines. As a matter of fact, the hostel is part of a chain of 4 similar hostels, related by linking buildings that include the ground floor and two storeys and host the students’ reading rooms. The total surface of the building is about 6566 square meters (out of which the 938 square meters of the technical basement). The surface of one floor is about 938 square meters.

From the point of view of the structure, the hostel has a vertical resistance structure composed by structural reinforced concrete walls made up of large prefabricated panels for the facade walls and cast in place structural reinforced concrete interior walls. The horizontal structure is made of reinforced concrete prefabricated panels. The partition walls between the rooms hallways and the bathrooms respectively the shower rooms are non-structural, made of reinforced light weight concrete blocks. The original roof was initially a terrace-roof. Nowadays, it has a sloping roof. The roof envelope and the envelope accessories are newer than the building, being built after 1985. The interior finishing of the walls is done with lime mortar coating and clay painting, that has to be entirely remade, due to the high level of degradation. On the building side that shows to the park nearby, in several rooms there have been noticed mouldiness caused by the insufficient thermal insulation and to the existing thermal bridge (Figure 3a). The
access hallways to the hostel rooms are partially covered with tiles, that show degradation and need to be entirely replaced. The bathrooms also have tiles that are damaged (Figure 3c). The floor of the main hall is covered with cast mosaic or cast mosaic plates. The floors of the rooms are covered with linoleum, badly run out (Figure 3b). The carpentry is old and badly damaged (Figure 3d).

![Image of mouldiness on the exterior walls](image1)
![Image of degradation of the linoleum floors](image2)
![Image of degradation of the tiles and piping](image3)
![Image of situation of the exterior carpentry](image4)

Figure 3. Aspects of the hostel’s status

3 EVALUATION OF THE ENERGETIC PERFORMANCES OF THE EXISTING BUILDING

In view to the rehabilitation of the hostel, there has been performed a technical and thermo-energetic expertise in order to decide upon the intervention measures. From the structural point of view, the building can take both gravitational and horizontal (earthquake) loads. No structural damages have been noticed during the operation along the years. The thermal-energetic expertise aimed at establishing the level of the energetic performances of the existing building and to decide upon the principle solutions for rehabilitation. The heating of the hostel was done by the centralized city system.
4 REHABILITATION OF THE STUDENTS’ HOSTEL

4.1 Structural solutions

The good behavior in time of the structure led to the lack of imposing special rehabilitation steps. But the proposal to install the hostel’s own heating station required the consolidation of the floor over the basement and the ground level, due to the increased loads brought to the installations. The floor intended to support the boilers of the heating station was made of reinforced prefabricated concrete 9 cm thick, designed for an effective load of 150 daN/m². The structural solution adopted was to build an additional floor over the existing one, the new floor coming with cross beams able to take over the vertical concentrated loads from the equipments and the elements of the station. In order not to overload the existing floor, between the beams of the new floor and the old floor there was laid a layer of polystyrene. The composition details of the proposed solution are shown in Figure 4.

![Figure 4. Details of the proposed structural solution](image)

4.2 Solutions for thermal rehabilitation

The investigation performed led to the conclusion that exterior envelope elements were built as follows (from the interior to the exterior):

- The side panel, concrete 20 cm, Autoclaved Aerated Concrete 12.5 cm, concrete 6 cm, mortar coating 1.5 cm (Precast Panel Type 1);
- Between the windows: concrete 20 cm, Autoclaved Aerated Concrete 12.5 cm, mortar 0.5 cm (Precast Panel Type 2);
- The bottom panel under the window, concrete 10 cm, Autoclaved Aerated Concrete 12.5 cm, concrete 7.5 cm (Precast Panel Type 3);
- The front walls: concrete 15 cm, Autoclaved Aerated Concrete 12.5 cm, face brick work 7.5 cm (Precast Panel Type 4);
- Double-winged coupled windows;
- Single-wing windows;
Metallic single-wing doors;
The flat roof over the fifth storey: concrete 10 cm, vapour barrier made of bituminous membrane of 0.02 cm, autoclaved aerated concrete 12.5 cm, cement flooring 10 cm, waterproof membrane with 5 layers of about 1 cm thick;
The floor over the basement, linoleum 0.5 cm, 10 cm cement flooring, 10 cm reinforced concrete.

Table 1 shows the heat flow resistances of the envelope elements, the minimum required resistances, the ratio between them and the average thermal resistance of the building.

Table 1 – Resistances to heat flow – current situation

<table>
<thead>
<tr>
<th>Type</th>
<th>( R' ) [m²K/W]</th>
<th>( R'_{\text{nee}} ) [m²K/W]</th>
<th>( R'/R'_{\text{nee}} )</th>
<th>( R ) [m²K/W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precast Panel Type 1</td>
<td>0.82</td>
<td>1.4</td>
<td>0.58</td>
<td>0.61</td>
</tr>
<tr>
<td>Precast Panel Type 2</td>
<td>0.78</td>
<td>1.4</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>Precast Panel Type 3</td>
<td>0.77</td>
<td>1.4</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>Precast Panel Type 4</td>
<td>0.9</td>
<td>1.4</td>
<td>0.64</td>
<td></td>
</tr>
<tr>
<td>Double Coupled Window</td>
<td>0.39</td>
<td>0.5</td>
<td>0.78</td>
<td></td>
</tr>
<tr>
<td>Simple Window</td>
<td>0.17</td>
<td>0.5</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>Metallic Door</td>
<td>0.17</td>
<td>0.5</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>Roof floor</td>
<td>0.87</td>
<td>3.00</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>Floor under basement</td>
<td>0.39</td>
<td>1.65</td>
<td>0.23</td>
<td></td>
</tr>
</tbody>
</table>

In order to evaluate the energetic classification, there has been calculated the normal annual heat necessary and the normal annual heat necessary for hot water preparation. Based on the values obtained, there was established the energetic classification according to the Romanian codes in force (Figure 5).

Figure 5. Energetic classification of the existing Hostel C20

Because all the envelope elements of the building show shortcomings regarding the resistance to heat flow, the following measures have been proposed, in order to improve the performances of the building. Thus, concerning the exterior walls, there was proposed the execution of a thermal system, composed of an additional thermal protection applied to the exterior, made of polystyrene, over which there is applied a finishing layer on a support of glass fibre. The building will be painted in pastel colors. The existing carpentry will be entirely replaced by
plastic carpentry and thermally insulated windows. For architectural reasons, the face brick facades will not be altered, in order to comply with the urban regulations of the area. The floor over the basement will be insulated by the application of a layer of polystyrene 5 cm thick, and the floor over the highest storey will be insulated by the application of a polystyrene layer 10 cm thick and a cement flooring minimum 2 cm thick. Based on the solution proposed, there have been recalculated the resistance to heat flow of the envelope elements respectively the average thermal resistance of the building. The values obtained are shown in Table 2.

<table>
<thead>
<tr>
<th>Type</th>
<th>$R_*$ [m²K/W]</th>
<th>$R_{nec}$ [m²K/W]</th>
<th>$R'/R_{nec}$</th>
<th>$R$ [m²K/W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precast Panel Type 1 R</td>
<td>2.17</td>
<td>1.4</td>
<td>1.55</td>
<td></td>
</tr>
<tr>
<td>Precast Panel Type 2 R</td>
<td>2.13</td>
<td>1.4</td>
<td>1.52</td>
<td></td>
</tr>
<tr>
<td>Precast Panel Type 3 R</td>
<td>2.11</td>
<td>1.4</td>
<td>1.50</td>
<td></td>
</tr>
<tr>
<td>Precast Panel Type 4 R</td>
<td>0.9</td>
<td>1.4</td>
<td>0.64</td>
<td>1.37</td>
</tr>
<tr>
<td>Double Window C</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Thermoinsulated Door C</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Roof floor R</td>
<td>3.49</td>
<td>3.00</td>
<td>1.16</td>
<td></td>
</tr>
<tr>
<td>Floor under basement R</td>
<td>1.65</td>
<td>1.65</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

The analysis of the resistance to heat flow obtained after the application of the thermal rehabilitation solutions proved that the resistances to heat flow of the envelope elements exceed the minimum values required, except for the walls of the Eastern and Western facade. Although the solution of the application of a thermo-insulating layer over the interior sides of these walls could be adopted, this has not been done, since the areas neighbouring the non-rehabilitated walls housed the staircase and the common pantries. After the rehabilitation, the average resistance to heat flow of the building doubles.

In order to improve the heating system and to reduce the losses, there has been proposed the installation of a heating station on gas, the overall replacement of the radiators and the heating system. The proposed pipe lines were made of high density polypropylene, pre-insulated in the
basement of the building. Each distribution casing will have devices for evacuation and cleaning.

Figure 6 shows the new classification of the thermally rehabilitated building.

5 ECONOMICAL STUDY OF THE INVESTMENT. CONCLUSIONS

The evaluation of the investment was performed on the basis of the quantity of the determined works according to the proposed interventions. The graphs in Figure 7 show the distribution of the expenses by specialties.

Figure 7. Distribution of the investment costs on specialties [%]

5.1 Comparative study concerning the energy consumption

Based on the theoretical evaluations performed, there can be noticed that the thermal rehabilitation led to the reduction of the heat consumption necessary for the heating of the area by nearly 50% from the initial consumption. The reduction of the total energy consumption is by more than 50% of the initial consumption. The heat consumption for the heating of the areas reduces because the average thermal resistance of the building doubles and because of the thermal station located within the building, thus reducing the losses along the distribution network.

Figure 8. Variations of the heating consumption

The important reduction of the hot water consumption is due to the high efficiency of the thermal station, to the insulation of the distributions pipes and to the installation of timing taps in the shower cabinets. These timing faucets have actually led to a reduction of 40% of the hot
water consumption in the whole building. Figure 8 shows the variations of the heating consumption, based on the real data gathered along two years of operation of the building.

As is shown in the Figure 8 the heating consumption during the winter decrease with 23% from the values registrod before thermal rehabilitation of hostel.

Taking into account the total amount of the termal rehabilitation, that is about 110.000 Euros, and the economy achieved of 2100 Euros/month for heating and hot water, the value of the investment for the thermal rehabilitation is to be amortized in about 6 years. Figure 9 shows aspects of reabilitated hostel.

![Hostel exterior](image1)

a. South facade reabilitated – general view

![Student room and bathroom](image2)

b. General view of student’s room  c. Aspects of bathroom

Figure 9. Aspects of the hostel’s status after reabilitation

REFERENCES

C107/1-3/1007 - Romanian standard for the calculus of the global thermal insulation coefficients for the civil residences

D. Dan, S. Secula, V. Stoian – Technical project for reabilitation of C20, Campus Area Timișoara, Romania 2005

GT 036- 2002 - Guide for the thermal and energetic audit for the existing buildings and for the preparation for the hot water necessary for these buildings

GT 037- 2002 - Guide for the elaboration and assignment of the energetic certificate for the existing buildings
Comparison of the improvement of comfort in Turkish houses which are built by using traditional, conventional and semi-industrialized construction methods

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ABSTRACT: There is a relationship between sustainability and thermal comfort conditions. If a house is thermally comfortable, then it can be called “sustainable”. In Turkish architecture, generally traditional, conventional and semi-industrialized construction systems are used. They have different properties and different construction materials and components are used during their construction process. This leads to different thermal behaviors. Therefore, the aim of this study is to examine and compare the thermal properties of the houses constructed by using these construction methods for İzmir conditions. In the end, the optimum one of them will be proposed.

1 INTRODUCTION

Sustainability and providing thermal comfort conditions are related to each other. That is due to the fact that a building is sustainable and it can be used for a longer time period if it provides comfort conditions to its inhabitants. Therefore it is important to provide comfort conditions in a house in order to maintain its sustainability.

In Turkey, there are generally two kinds of construction methods that are in use for housing. These are traditional construction methods which are generally used in rural areas and conventional construction methods which are generally used in cities and urban areas. In traditional construction, generally thermal comfort conditions are better provided due to the fact that these construction methods have been used, tried and experimented by the local people in that area for a very long time period and in the end the best results have been achieved. But on the other hand, conventional construction methods are in use for a very short time (less than a hundred years) and besides they are being used by the manufacturers, not the actual users of the houses, therefore these houses are generally poor in thermal protection. There are also semi-industrialized construction methods that are being used in housing in Turkey. Even though they are not used as much as the traditional and conventional methods, they still have a potential of being preferred more in the future. Therefore the aim of this study is to examine and compare the thermal properties of houses which are constructed by using different construction methods in Turkey for İzmir conditions. This is going to be done by explaining and examining the wall, roof and ground floor slab sections that are used in traditional, conventional and semi-industrialized construction methods, and then by comparing the thermal behaviour of them for İzmir conditions. In the end, the optimum one will be seen according to thermal comfort conditions for İzmir.
2. EXAMINATION OF DIFFERENT CONSTRUCTION TECHNIQUES GENERALLY USED IN HOUSES IN TURKEY FROM THE VIEWPOINT OF PROVIDING THERMAL COMFORT CONDITIONS

As explained above, generally traditional, conventional and semi-industrialized construction methods are being used in housing in Turkey. Here these are going to be explained and an examination will be done for each of them by giving the detail of the wall section.

A simple building is designed for examining the thermal comfort conditions and the role of the outer walls in providing this as seen in Figure 1.

![Figure 1. The plan of the designed house](image)

2.1 Traditional construction method

In traditional construction method, generally conglomerated houses are constructed. There are also wooden skeleton buildings but they are not used as much as conglomerated ones. Therefore conglomerated construction will be used for examination here. Conglomerated constructions are constructed by using stones, adobe (sun-dried mud brick), bricks and (even though a little) wood. But among these materials, mostly brick is used. They are still preferred more than others. Therefore, brick conglomerated house example will be held in this examination.

In this method, only brick is used to construct the walls of the house. These are generally load-bearing and therefore they have minimum 20 cm width. Mostly solid or vertical-hollowed bricks are used. Inside and outside, a plaster is used to cover and protect the brick walls. Generally no heat-insulating material was being used before year 2000, but since then heat-insulating materials have to be used according to the new Turkish standard TS825 due to the fact that only these constructions are not enough for energy conservation.

In Table 1, Table 2 and Table 3, the layers of a traditional conglomerated house wall construction, roof construction and ground floor slab construction are given respectively. In the tables, the thicknesses and $\lambda$ values (thermal conductivity) are shown.
Table 1. Layers of the wall of traditional construction method.

<table>
<thead>
<tr>
<th>Layers</th>
<th>Thickness $m$</th>
<th>$\lambda$ (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plaster (inside)</td>
<td>0.025</td>
<td>1.4</td>
</tr>
<tr>
<td>Brick (with vertical hollows)</td>
<td>0.20</td>
<td>0.81</td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>0.05</td>
<td>0.028</td>
</tr>
<tr>
<td>Plaster (outside)</td>
<td>0.03</td>
<td>1.4</td>
</tr>
</tbody>
</table>

The total area of this brick wall is 87.2 m$^2$. The $U$-value for this house is calculated as 0.446 W/m$^2$K. This is lower than the value let in the TS825 which is 0.80 W/m$^2$K.

Table 2. Layers of the roof construction of traditional construction method.

<table>
<thead>
<tr>
<th>Layers</th>
<th>Thickness $m$</th>
<th>$\lambda$ (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>0.05</td>
<td>0.7</td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>0.10</td>
<td>0.028</td>
</tr>
<tr>
<td>Concrete (for protection)</td>
<td>0.05</td>
<td>1.74</td>
</tr>
<tr>
<td>Reinforced concrete slab</td>
<td>0.10</td>
<td>2.1</td>
</tr>
<tr>
<td>Plaster</td>
<td>0.025</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Area of the roof is 69.44 m$^2$. The $U$-value is calculated as 0.255 W/m$^2$K. This is lower than the value let in the TS825 which is 0.50 W/m$^2$K.

Table 3. Layers of the ground floor slab construction of traditional construction method.

<table>
<thead>
<tr>
<th>Layers</th>
<th>Thickness $m$</th>
<th>$\lambda$ (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marble</td>
<td>0.03</td>
<td>3.5</td>
</tr>
<tr>
<td>Concrete (for protection)</td>
<td>0.05</td>
<td>1.74</td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>0.05</td>
<td>0.028</td>
</tr>
<tr>
<td>Concrete slab</td>
<td>0.10</td>
<td>1.74</td>
</tr>
<tr>
<td>Hardcore</td>
<td>0.15</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Area of the ground floor is 69.44 m$^2$. The $U$-value is calculated as 0.441 W/m$^2$K. This is lower than the value let in the TS825 which is 0.80 W/m$^2$K.

Area of the doors and windows in total is 12.6 m$^2$. The same materials are used for both of them. Therefore the $U$-value for both doors and windows is used as 1.4 W/m$^2$K.

The room temperature is taken to be 20° C. The maximum heating energy demand of this traditional house is calculated by using these values and the result is 21.23 kWh/m$^3$. But the actual energy demand of this example is calculated as 16.99 kWh/m$^3$. So this is a better result than the maximum energy demand. Annual heating energy demand is 3302 kWh.

2.2 Conventional construction method

In conventional construction method, generally reinforced concrete skeleton buildings are constructed in Turkey. In these buildings, generally brick is used to construct the walls of the houses between the reinforced concrete columns and beams. These are generally between 13-20
cm thick walls and generally they are not load-bearing walls. Mostly horizontally-hollowed bricks are used in the construction of these walls.

In Table 4, Table 5, Table 6, Table 7 and Table 8, the layers of a conventional reinforced concrete skeleton house brick wall construction, column part of wall construction, beam part of wall construction, roof construction and ground floor slab construction are given respectively. In the tables, the thicknesses and $\lambda$ values (thermal conductivity) are shown.

Table 4. Layers of the brick wall of conventional construction method.

<table>
<thead>
<tr>
<th>Layers</th>
<th>Thickness</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plaster (inside)</td>
<td>0.025</td>
<td>1.4</td>
</tr>
<tr>
<td>Brick</td>
<td>0.20</td>
<td>0.45</td>
</tr>
<tr>
<td>(with horizontal hollows)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>0.05</td>
<td>0.028</td>
</tr>
<tr>
<td>Plaster (outside)</td>
<td>0.03</td>
<td>1.4</td>
</tr>
</tbody>
</table>

The total area of this brick wall is 60 m$^2$. The $U$-value for this house is calculated as 0.409 W/m²K. This is lower than the value let in the TS825 which is 0.80 W/m²K.

Table 5. Layers of the column part of the wall of conventional construction method.

<table>
<thead>
<tr>
<th>Layers</th>
<th>Thickness</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plaster (inside)</td>
<td>0.025</td>
<td>1.4</td>
</tr>
<tr>
<td>Column</td>
<td>0.40</td>
<td>2.1</td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>0.05</td>
<td>0.028</td>
</tr>
<tr>
<td>Plaster (outside)</td>
<td>0.03</td>
<td>1.4</td>
</tr>
</tbody>
</table>

The total area of this column part of the wall is 11.20 m$^2$. The $U$-value for this house is calculated as 0.457 W/m²K. This is lower than the value let in the TS825 which is 0.80 W/m²K.

Table 6. Layers of the beam part of the wall of conventional construction method.

<table>
<thead>
<tr>
<th>Layers</th>
<th>Thickness</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plaster (inside)</td>
<td>0.025</td>
<td>1.4</td>
</tr>
<tr>
<td>Beam</td>
<td>0.25</td>
<td>2.1</td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>0.05</td>
<td>0.028</td>
</tr>
<tr>
<td>Plaster (outside)</td>
<td>0.03</td>
<td>1.4</td>
</tr>
</tbody>
</table>

The total area of this beam part of the wall is 16 m$^2$. The $U$-value for this house is calculated as 0.473 W/m²K. This is lower than the value let in the TS825 which is 0.80 W/m²K.
Table 7. Layers of roof construction of conventional construction method.

<table>
<thead>
<tr>
<th>Layers</th>
<th>Thickness</th>
<th>λ (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>0.05</td>
<td>0.7</td>
</tr>
<tr>
<td>Thermal insulation for protection</td>
<td>0.10</td>
<td>0.028</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.05</td>
<td>1.74</td>
</tr>
<tr>
<td>Reinforced concrete slab</td>
<td>0.10</td>
<td>2.1</td>
</tr>
<tr>
<td>Plaster</td>
<td>0.025</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Area of the roof is 69.44 m². Therefore the U-value is calculated as 0.255 W/m²K. This is lower than the value let in the TS825 which is 0.50 W/m²K.

Table 8. Layers of ground floor slab construction of conventional construction method.

<table>
<thead>
<tr>
<th>Layers</th>
<th>Thickness</th>
<th>λ (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marble</td>
<td>0.03</td>
<td>3.5</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.05</td>
<td>1.74</td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>0.05</td>
<td>0.028</td>
</tr>
<tr>
<td>Concrete slab</td>
<td>0.10</td>
<td>1.74</td>
</tr>
<tr>
<td>Hardcore</td>
<td>0.15</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Area of the ground floor is 69.44 m². Therefore the U-value is calculated as 0.441 W/m2K. This is lower than the value let in the TS825 which is 0.80 W/m2K.

Area of the doors and windows in total is again 12.6 m² here as in traditional one. Therefore the U-value for both doors and windows is used as 1.4 W/m²K.

The room temperature is taken to be 20°C. The maximum heating energy demand of this conventional house is calculated by using these values and the result is 21.23 kWh/m³. But the actual energy demand of this example is calculated as 16.71 kWh/m³. So this is a better result than the maximum energy demand, but due to the fact that it is higher than the energy demand of the traditional case study which is 15.43 kWh/m³, traditional one is better than this one. Annual heating energy demand of the conventional case study is 3249 kWh and this is also higher than the traditional case study’s energy demand of 2999 kWh. But only the reinforced concrete columns and beams are added and the type of the bricks used are changed from vertical hollowed ones to horizontal hollowed ones.

2.3 Semi-industrialized construction method

In semi-industrialized construction method, different methods are being used. Here in this study, the lightweight-concrete panel construction systems (known as gazbeton in Turkey) will be examined.

In this method, only light-weight concrete panels are used to construct the walls of the house. The load-bearing types of these panels that have 20 cm width are chosen in this study. Inside and outside, a plaster is used to cover and protect the walls. The roof is constructed by using 10 cm. wide, reinforced light-weight concrete roof slabs.

In Table 9, Table 10 and Table 11, the layers of a semi-industrialized leight-weight concrete (gazbeton) house wall construction, roof construction and ground floor slab construction are given respectively. In the tables, the thicknesses and λ values (thermal conductivity) are shown.
Table 9. Layers of the light-weight wall of semi-industrialized construction method.

<table>
<thead>
<tr>
<th>Layers</th>
<th>Thickness</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plaster (inside)</td>
<td>0.025</td>
<td>1.4</td>
</tr>
<tr>
<td>Light-weight concrete panel</td>
<td>0.20</td>
<td>0.16</td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>0.05</td>
<td>0.028</td>
</tr>
<tr>
<td>Plaster (outside)</td>
<td>0.03</td>
<td>1.4</td>
</tr>
</tbody>
</table>

The total area of this light-weight concrete wall is 87.2 m$^2$. The U-value for this house is calculated as 0.308 W/m$^2$K. This is the lowest of the case studies of the three methods calculated and also lower than the value let in the TS825 which is 0.80 W/m$^2$K.

Table 10. Layers of the reinforced light-weight concrete roof construction of semi-industrialized construction method.

<table>
<thead>
<tr>
<th>Layers</th>
<th>Thickness</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>0.05</td>
<td>0.7</td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>0.10</td>
<td>0.028</td>
</tr>
<tr>
<td>Concrete (for protection)</td>
<td>0.05</td>
<td>1.74</td>
</tr>
<tr>
<td>Reinforced light-weight concrete slab</td>
<td>0.10</td>
<td>0.16</td>
</tr>
<tr>
<td>Plaster</td>
<td>0.025</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Area of the roof is 69.44 m$^2$. The U-value is calculated as 0.370 W/m$^2$K. This is lower than the value let in the TS825 which is 0.50 W/m$^2$K.

Table 11. Layers of the ground floor slab construction of semi-industrialized construction method.

<table>
<thead>
<tr>
<th>Layers</th>
<th>Thickness</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marble</td>
<td>0.03</td>
<td>3.5</td>
</tr>
<tr>
<td>Concrete (for protection)</td>
<td>0.05</td>
<td>1.74</td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>0.05</td>
<td>0.028</td>
</tr>
<tr>
<td>Concrete slab</td>
<td>0.10</td>
<td>1.74</td>
</tr>
<tr>
<td>Hardcore</td>
<td>0.15</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Area of the ground floor is 69.44 m$^2$. The U-value is calculated as 0.441 W/m$^2$K. This is lower than the value let in the TS825 which is 0.80 W/m$^2$K.

Area of the doors and windows in total is 12.6 m$^2$. The same materials are used for both of them. Therefore the U-value for both doors and windows is used as 1.4 W/m$^2$K.

The room temperature is taken to be 20ºC. The maximum heating energy demand of this semi-industrialized house is calculated by using these values and the result is 21.23 kWh/m$^3$. But the actual energy demand of this example is calculated as 16.29 kWh/m$^3$. So this is a better result than the maximum energy demand. Annual heating energy demand is 3166 kWh.
3 COMPARISON OF THE HOUSING CONSTRUCTION TECHNIQUES

Until here, the total annual energy demand calculations are done for three different house construction methods used in Turkey. Here, the results will be discussed.

Table 12. Annual energy demand of the three methods for heating.

<table>
<thead>
<tr>
<th>Construction Methods</th>
<th>Qa (annual energy demand)</th>
<th>Q(^r) (calculated energy demand)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional construction method</td>
<td>3302</td>
<td>16,99</td>
</tr>
<tr>
<td>Conventional construction method</td>
<td>3249</td>
<td>16,71</td>
</tr>
<tr>
<td>Semi-industrialized construction method</td>
<td>3166</td>
<td>16,29</td>
</tr>
</tbody>
</table>

It is seen that the heating energy demand of the house is decreasing with the developing technology. It is the most in traditional construction method, and the least in semi-industrialized construction method.

The results are used in a simulation program in order to calculate the cooling energy demand of the three methods. The results show the cooling energy demand of the three methods. These results are shown in Table 13 below.

Table 13. Annual energy demand of the three methods for cooling.

<table>
<thead>
<tr>
<th>Construction Methods</th>
<th>Qa (annual cooling demand)</th>
<th>cooling demand absolute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional construction method</td>
<td>3,1</td>
<td>171</td>
</tr>
<tr>
<td>Conventional construction method</td>
<td>2,9</td>
<td>160</td>
</tr>
<tr>
<td>Semi-industrialized construction method</td>
<td>5,5</td>
<td>307</td>
</tr>
</tbody>
</table>

It is seen from the tables that the conventional construction method is the best one for the lowest cooling energy demand. But the semi-industrialized construction method is the worst of all for cooling energy demand. This is due to the fact that all parts of the house except the ground floor slab are constructed with light-weight concrete panels. And light-weight concrete is a light construction and has very low heat storing capacity. In the other two construction methods, the walls, the roofs and the ground floor slabs can lose the energy they gain during the day at night and they get cold, and they still can keep cool during the next day when the sun is up in the air. But the walls and the roof of the light-weight concrete house cannot keep that much cool during the day since they have very low mass. This proves that heat storage mass is important not only for heating, but also for cooling. Therefore, light-weight concrete construction can be a good choice for a lower heating energy demand but it is the worst choice for a lower cooling energy demand.

On the other hand, conventional construction method seems to be the best choice for the lowest cooling energy demand. Likewise, traditional construction method is only a little way behind the conventional method. This is just the opposite at heating energy demand. The traditional method is the best for the lowest heating energy demand, and the conventional method is only a little way behind it. Therefore, it is best to choose one of them according to which energy demand is important or a problem for the place of house that is going to be constructed. If cooling
is more important than heating, then conventional method maybe chosen. But if heating is more important, then traditional method maybe chosen.

4 CONCLUSION

According to the results, why traditional construction system have been used in Turkey for such a long time and why it is still being used is explained very well. That is because of the fact that heating the houses was a problem for a longer period in a year (for more than 7 months) and you can keep the house heated for a longer time in a conglomeration house.

With the advancing technology, conventional construction system has entered the construction site. In this system, a worse insulation valued material concrete is being used, but also with a better insulation valued brick-the horizontally hollowed ones. These keep the new construction system equal. Therefore they can be used equally in the constructions. But the worst one is light-weight concrete construction system. It is obvious that this has been seen and not being used a lot in the construction of houses.

This is just an examination done for only one design project of a house. For a better result, more examples should be examined. The second step of this study can be the examination of the actual houses built in the same area with all of the three construction methods. In addition, cost issues maybe held for better choice criteria. In this study, only the thermal comfort conditions are held in order to give an exact result for providing comfort in the houses regardless of the prices. This gives nearly exact results according to the choice of the traditional architecture. And also shows us the reason why traditional architecture houses are still being constructed and being used today. That shows the reason of the sustainability of the traditional Turkish houses, and also the relationship between the thermal comfort conditions and the sustainability. If we want to design and construct sustainable houses, we should be careful to provide thermal comfort conditions in the houses.

REFERENCES

TS825/T3 Binlerarda Islatma Kuralları (Thermal Insulation in Building), April 2002, Türk Standartları Enstitüsü, Ankara
TS825 calculation tool
Energetic audit methods, part of sustainable development process

L. Berevoescu, V. Stoian, & D. Dan
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ABSTRACT: In the context of studying the sustainable development, the energetic audit establishes, from economic and technical point of view, the solutions for thermal-energetic rehabilitation and modernization of the construction. For this problem, engineers have a great responsibility, in the way of finding the most efficient ways and techniques of establishing the energy consumption reduction and low costs, as a result of the investment in the measures of conserving the energy. The paper presents some techniques of the estimation energy consumption used to determine the spares which results from application of some conservation measures of the energy.

1 INTRODUCTION

The concept of sustainable development renounces to be against the nature in exchange of creating a friendship between them, trying to stop any process which may injury the next generations and to repair everything that still could be repaired. It is a solidarity manifestation above the limits of a life, evidence of our civilization maturity in a period of globalization and extra-terrestrial researches. There are requested immediate deep changes in fields of industrial activity, economic activity, educational activity, cultural activity, administrative and political activity; a decision factor being the science and the technology. Under the pressure of the existent situation, it is formed a correct base of thinking and are used synthetically methods of orientation, having catalyst role for engineering activity, their importance is exceptional in the industry of constructions because these are utilized for a very long period: sustainable development – integrated concept of built space and of energetic audit.

2 BUILDING-ORGANISM IN THE CONTEXT OF SUSTAINABLE DEVELOPMENT OF THE ENERGY CONSUMPTION WITHIN THE RESIDENTIAL

A sustainable building or a green building is a construction which utilizes the key resources (energy, water, construction materials, soil, etc) in a more efficient way than the conventional buildings. These buildings are constructed in manner to offer to their inhabitants a healthy environment for working, studying or resting, by using the extensive natural light, fresh air and a high degree of comfort. The sustainable buildings are efficient from the point of view of maintenance and operation costs, and of which value increases in time, through positive impact on the natural and social environment.
3 THE ENERGETIC AUDIT-PART OF SUSTAINABLE DEVELOPMENT PROCESS

Energetic audit of a building – method which establishes, from economic and technical point of view, the solutions for thermal-energetic rehabilitation and modernization of the construction based on the results obtained from thermal and energetic activity of expertise of the building.

In the approved norms by MLPTL, NP 47, 48 and 49 / 2000 it is mentioned a division in three components:
- thermal expertise – in which are established thermal-technical characteristics of the building (elements of construction and installation) and energy consumptions for complying with normal functioning;
- the energetic certificate – which, starting from energetic expertise, establish the “energetic quality” of the construction and offer a qualificative. The energetic certificate is obligatory in different situations;
- the energetic audit – which presents solutions for reducing the energy consumption of the buildings.

For this problem engineers have a great responsibility, in the way of finding the most efficient ways and techniques of establishing the energy consumption reduction and low costs, as a result of the investment in the measures of conserving the energy.

In the next chapters it will be presented, shortly, some techniques of estimating the energy consumption (see Consult, Group, IP. 2003. Reference book of energetic efficiency for the buildings), used usually by buildings experts in order to determine the spares which results from application of some conservation measures of the energy.

4 THE METHODS OF ENERGETIC ANALYSIS

The existing methods of analyzing the energy consumption (applied in so called audits or energetic analysis) differ a lot in complexity and correctness. In order to choose the proper method of energetic audit, the expert / auditor have to consider more factors, which include: fastness, cost, and versatility, possibility of reproducibility, sensibility, precision and easiness in utilization.

There are hundreds of possibilities and methods for analyzing the energy, which are used in the whole world in order to discover the possible reduction in the measures of conservation of the energy.

Generally, the existent methods of analyzing the energy may be:
- direct methods (forward);
- reverse methods (feed-back)

In the direct method, as we may see in Figure 1, the energy estimations are based on physical description of the construction systems, as geometry, placement, construction details, and the type of system and operation HVAC (heating, ventilation and air conditioning). The most existent detailed methods of simulation of energy follow the method of simulation of direct approach.

![Figure 1. Direct approach of an energetic audit](image-url)
In indirect approach, as we may see in Figure 2, the example of analyzing the energy consumptions tries to deduct the representative parameters of the building (as the coefficient Gv of the total losses of the whole building, main task of the building, or time constancy of the building) using the existent utilization of energy, weather and any others relevant data of the performance.

Figure 2. Reverse approach of an energetic audit

Generally the reverse examples are less complex as conception than the direct examples. Although, the flexibility of the reverse examples is limited by formulating the representatives construction parameters and by correctness of the construction performance data. The most existent reverse examples are based on regression analysis (as the examples degrees – days with variable reference), or on integrated approach in identification of construction parameters. (*Number of degrees – days: has influence on annual energy consumption. Defined as difference between one given temperature and daily average temperature).

Among the frequent applications of direct and reverse approaches there are:
- verification of energy reduction which appear with help of measures for reducing the energy;
- establishing the malfunctions at the equipments;
- testing the energetic systems efficiency.

The energetic audit techniques may use either the approaches with stationary simulation or the ones with dynamic simulation.

Generally, the stationary examples are sufficient for analyzing the building performance for a season or for one year. Although the dynamic examples may be necessary in order to evaluate the transitory effects of the energetic systems in constructions, as are the ones seen at the systems of stocking the energy or at the control elements for beginnings optimization.

The energy analysis techniques are grouped, usually, in three categories:
- methods based on indicators (reports), which are approaches of pre-auditing type, based on energy densities / costs which allow a fast evaluation of construction performance;
- reverse methods, based either on stationary simulation or on dynamic one;
- direct methods, which more often constitutes the base for computer programs for energy consumption simulation.

4.1 Methods based on indicators

The methods based on indicators aren’t in fact energetic analysis methods, but approaches of pre-audit type for establishment of the specific energy or of the cost indicators of the building.

These indicators of energy / cost of the building are compared with reference performance indicators (sometimes being known as landmarks) obtained from many other buildings with the same major characteristics. Energetic consumption indicators may offer sometimes relevant information regarding some potential problems of the building, such as leakages in the piping system of water / steam, or inefficiency of cooling system, or high quantity of water consumption.

More exactly, energy density consumption or energetic indicators of the buildings are utilized for:
- establishing if too much energy is consumed and if an energetic audit will be useful.
- verifying if it was realized a certain established level of energetic performance of the building. If not, the energy indicator may be used for establishing energy consumption reduction, needed for achieving the proposed level.
- monitoring the energy consumption evolution of the building and establishing the efficacy and profitability of any energetic management program realized post – audit.

In order to estimate some coherent energetic or cost indicators, are built large data bases, usually for estimating the reference indicators, are needed data for hundreds and thousands of similar buildings.

The cost or energy indicators are reports for which the numerator and the denominator are specific variables.

For the indicators of energetic performance, the present variables at denominator may be:
- total energy consumption of the building (including all the final consumers), in kWh or Gcal.
- The energy consumption per existent final consumer in the building (heating, ventilation and enlightening …)
- Energy needed (kW)

For cost indicators, it is usually used for the denominator a currency value (especially for the energy expense or for the whole building exploitation). For denominator may be used more variables, according to the type of the building and of the scope followed by calculation of indicator. Some of the variables used for the energy or cost indicators denominator are:
- Area or volume of the building (heated area or conditioning volume)
- Consumers of the building ( in buildings of collective use, as hotels, schools)
- Degrees – days (with reference temperature of 20°C)
- Production units (especially for manufacturing units, restaurants)

4.2 Methods of reverse simulation

Methods using reverse simulation are based on the existent performance data of the building in order to identify a certain set of characteristic parameters. The reverse methods may be valuable for increasing the energetic efficiency of the building, being used at:
- finding the malfunctioning, by identifying time periods or by identifying the energetic systems with very high energetic consumption.
- obtaining the estimations on energy reduction resulted after applying a set of distinctive measures,
- verification of energetic reductions as a result of modernizations.

In order to estimate, based on experimental data, the representative parameters of the building and / or of its systems (such as bearing coefficient of the building or effectiveness of the heating system), usually are used regression analysis. In general, stationary reverse simulations are based on monthly and / or daily data and comprise one or more independent variables. The dynamic reverse simulations are usually developed on sets of hour data or under-hour, being capable of rendering transitory effects, as in the case of the buildings where high thermal inertial delays the heating or cooling of the interior area.

4.2.1. Stationary reverse simulations

In general, these simulation search to identify the relation between building energetic consumptions and parameters depending of climate, such as average of exterior temperature (monthly or daily), degrees – days or degrees – hours. As it has been mentioned before, this kind of correlation it is realized by using statistic methods (based on analysis of monthly regression).
The stationary reverse simulations are applicable only for estimation on long term of the final consumptions of energy. So, in order to sustain the regression analysis, the data about energy consumption are collected on long periods of time (one season, one year).

The main advantages of reverse stationary simulations are:
- Simplicity: the reverse simulations may count only on few sets of obtained data, for example, from the building invoices for energy.
- Flexibility: the stationary reverse simulations have lots of applications, being important especially in estimation of residential buildings consumption and of small commercial buildings.

The stationary reverse simulations are recommended especially for measuring and verification of energy reduction after modernizations. There simplified simulations based on degrees – days methods, which can be used in order to determine the energetic impact which some improving energetic measures may have. Bellow, it shall be presented two such simplified reverse simulations:

**Cumulative method degrees – days** which consists of correlation (using a linear regression analysis) of cumulatively energetic consumptions of the buildings with cumulatively degrees – days (using a reference temperature of 20°C). Figure 4 shows the base concept of the cumulative method degrees – days.

![Figure 3. Typical application of cumulatively method degrees – days](image)

It is shown the energy cumulatively consumption by using the relation:

\[
E_{inc} = 0.024 \times \frac{G}{\eta_{inc}} \times V_{clad} \times I \times GZ_{inc} \quad [\text{kWh}]
\]

where \(E_{inc,ln} = \) cumulative energy consumption for heating the building [kWh];
\(G = \) total losses coefficient according to the building volume [W/m\(^3\).K]; \(\eta_{inc} = \) heating system average effectiveness during a season; \(V_{clad} = \) heated volume of the building [m\(^3\)];
\(GZ_{inc} = \) cumulative degrees – days for heating (related to 20°C); \(I = \) correction factor which considers the settled reduction of the thermal charge (for example during the night or during the week-end); if it is no charge reduction, then \(I=1\).

This method it is used in some European countries in order to control the energy consumption variation of the buildings during the warm season. Particularly, using the cumulative degrees – days allows to be aware of every modification of the energetic consumption after the modernization measures, by the curve of linear regression. Any improvement of thermal performances of the building (such as improvement of thermal insulation or increasing the efficiency of the heating system) will reduce the grade.

**Method degrees – days with variable reference temperature** which uses linear regression analysis in order to establish the balance temperature of the building. The method is a base for
lots of analysis instruments and software products for estimation of monthly energy consumption for heating the building.

It is represented by chart, with points, the monthly energy consumption for heating, according to degrees days monthly for a calculation interior temperature of 20°C.

\[ E_{inc,lun} = 0.024 \times \frac{G}{\eta_{inc}} \times V_{clad} \times I \times [GZ_{inc,lun} - (20 - T_{ech}) \times N] \text{[kWh]} \] (2)

where:
- $E_{inc,lun}$ = monthly energy consumption [kWh];
- $GZ_{inc,lun}$ = degrees – days heating for one month (related to 20°C);
- $T_{ech}$ = balance temperature of the building;
- $N$ = number of the day from a month;
- $G$, $I$, $V_{clad}$, $\eta_{inc}$ have the same signification as in equations (1)

In order to correlate monthly energy consumption with monthly degrees – days (related 20°C) it is necessary the development of an linear regression analysis, using only data from the warm season.

The line of regression (dashed in Figure 3) intersects the abscissa in $GZ_{inc,lun,0}$. The balance temperature results from the condition

\[ [GZ_{inc,lun,0} - (20- T_{ech}) \times 30] = 0. \]

Inclination of the regression line it results from $0.024 \times V_{clad} \times \eta_{inc}$

If it is known the volume of the building and the season effectiveness of the heating installation, it may be determined the total coefficient of thermal losses, $G$.

4.2.2. Dynamic reverse simulations

The dynamic reverse simulations may be used for estimating the energy consumption variation, based on date collected in a short period of time (one week). In general, one dynamic reverse simulation is based on a building thermal model which uses a distinctive set of parameters, usually identified by application of a form of linear regression analysis. Besides the stationary models, the dynamic one request a higher degree of interaction with the user and knowing all the details of the building or of the modeled system. Such models are sophisticate and usually are base of some specialized soft.
4.3. Methods of direct simulation

The direct models are, generally, based on physical description of the energetic system of the building. Usually, these methods allow the final energy consumption, as the estimation of any energy reduction resulted after applying the measures of energy conservation.

4.3.1. Stationary direct methods

The stationary direct methods are, generally, easy to be used, and many of the calculations may be done manually or with electronic calculation sheets. It may be distinguished two such typical methods:

- degrees – days methods
- inter-current methods

Degrees – days methods which are using season degree – days calculated at a pre-established temperature (interior temperature of calculation of 20°C or balance temperature) in order to estimate the necessary temperature for heating the building. Usually, these methods aren’t adequate for calculating the needed energy for cooling. Although the method degrees – days with variable reference temperature it is more exact, the method degrees – days for heating, based on a reference temperature of 20°C, it is still used in Europe for residential and commercial buildings.

The methods degrees – days allows the estimation of energy season consumption for heating, with equation 3.

\[
F = \frac{0.024 \cdot G \cdot V_{clad} \cdot f \cdot GZ_{inc}(T_{ref})}{\eta_{inc}} \quad [\text{kWh}]
\]

where: 
- \( F \) – energy consumption (gas, liquid fuel, or electric energy for heating), [kWh];
- \( G \) – total coefficient of losses of the building; \( V_{clad} \) - heated volume of the building \([m^3]\);
- \( f \) – correction factor which includes different effects, as functioning at partial charges, charge reduction during the night or free heating rapport; \( T_{ref} \) – balance or interior temperature of building calculation \([\text{°C}]\); \( GZ_{inc}(T_{ref}) \) – degrees – days heating at reference temperature \( T_{ref} \) \([\text{k x day}]\);

The methods degrees – days with variable reference temperature offers usually correct estimations on the energy consumption for heating in the case of the buildings where are important thermal losses through exterior walls (especially at low buildings, where the air infiltrations are relatively reduced). But, they are not recommended for the buildings where internal thermal matters are prevailing and / or with complex HVAC installations.

The inter-current methods are similar to degrees – days methods with variable reference temperature; in order to estimate energetic consumption for heating and / or cooling of the building, but, they are based on different climate date, on inter-current values for exterior temperature. In classical inter-current methods, the exterior temperatures are grouped in equal inter-currents, usually of 5°C. For each inter-current, it is mentioned static number of the hours of appearances of the values from the inter-current. For the others climate variables are established only average values correspondent to the centered value from the exterior temperatures interval. Climate data from classical interval methods usually represents a one-dimensional set of data (exterior temperatures). The precision of interval methods it is useful only in case of the sensitive heated buildings (without phase changing) and without significant effects of thermal impulse. In order to increase the precision, especially at the buildings with high thermal latent charges, are introduced bi-dimensional sets of climate data based on two variables (as the dry thermometer temperature and relative humidity).

In both types of stationary methods, it is necessary to know the total coefficient of thermal losses, \( G \).
4.3.2 Dynamic direct methods

Analytic dynamic methods are using numbering and analytical models in order to calculate the transfer of energy among the different systems of the building. In general, such models consisted in software products (with hour steps of time or smaller) which estimate accordingly the effect of thermal impulse due to stocking the energy into the building walls and / or into the heating system.

The most important propriety of those models of simulation is their capacity of taking into account more decisive parameters in correct estimation of energy consumption, especially at the buildings with pronounced thermal impulse, with night reduction of the charge, with stocking systems of the energy or prediction control strategy.

In general, a simulation program needs a detailed physical description (geometry, walls details, type of heating and conditioning systems).

5. CONCLUSION

From the sphere of principles, under the pressure of time which is passing, the sustainable development must comprise actions with effects in different fields, and especially, regarding energy consumption savings utilized for assuring comfort inside of the buildings.

Although, science researches may add more results in the field of energy distribution recovery, although the technological solutions which may be applied immediately, exists and should be introduced without delay, with government support.

As a brief conclusion may be retained the following important ideas:

- we are at the beginning of the transition process towards sustainable development which is absolutely necessary and urgent, and the necessary transformations must enter in every activity field, starting with energy and people information and continuing with all fields of national economy, first being constructions field.
- the existing methods of analyzing the energy consumption differ a lot in complexity and correctness. In order to choose the proper method of energetic audit, the expert / auditor have to consider more factors, which include: fastness, cost, versatility, possibility of reproducibility, sensibility, precision and easiness in utilization.
- the methods of analyzing the energy consumption give the possibility to analyze the building performance for a season or for one year, estimation and verification of energy reduction which appear with help of measures for reducing the energy consumption.
- the methods of analyzing the energy consumption is an important criteria for the solution adopted in order to optimize the insulation systems of buildings.

REFERENCES

C107/1/2/3/4-02 Norm for designing and execution of building thermal insulation works
Law no. 10/1995 regarding constructions quality (one of the six requests of the law is “Thermal insulation, waterproofing and energy saving” – request F).
Law no. 325 from 27 of May 2002 for approving Govern Order no. 29/30.01.2000 regarding thermal rehabilitation of the existent constructed found and stimulation of thermal energy saving.
Sealy, Cordelia 2003 April. Materials today
Svenskbyggtjanst & Swedish National Energy Administration
Low energy building design with sustainable energy end use

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ABSTRACT: When designing a low energy building there are always a discussion on how environmental correct the different energy saving measurements are, especially when heat pumps are used. The Swedish building sector and energy sector has conducted a joint project to study this question. The main objective was to identify the most cost- and resource-efficient measures to reduce the built environment’s environmental impact, and to achieve an energy supply system with the least possible environmental impact. The results of this study are presented in Persson A. et all, 2006, show interesting facts to consider when designing low-energy buildings. Primary energy factors and primary CO$_2$ emission factors have been calculated and used as indicators of resource need and environmental impact.

- Environmental impact and cost-efficiency have been calculated for each efficiency measure in combination with sex different energy supply scenarios
- LCC from the end user’s perspective have been used for cost efficiency calculations.
- In addition a comparison of the studied buildings has been made with four well-known Swedish low-energy buildings.

The main issues from studies made Persson A. et all, in 2005 and 2006, will be presented including the background to design of low energy buildings. It will be shown that a system’s perspective including energy supply and energy demand is necessary to achieve a sustainable development.

1 INTRODUCTION

The Swedish building sector and energy sector has conducted a joint study aiming at identifying the most cost- and resource-efficient measures to reduce the built environment’s environmental impact, and to achieve an energy supply system with the least possible environmental impact. In this study primary energy factors and primary CO$_2$ emission factors have been calculated and used as indicators of resource need and environmental impact. Input:

- Primary energy and CO$_2$ emission factors are calculated from a LCA perspective, from excavation through transformation and distribution, and losses in the individual building to actual energy end use.
- Primary energy factors and the primary CO$_2$ emission factors are given in kWh per m$^2$ heated area and kg CO$_2$ per m$^2$ heated area respectively.
- The analysis comprises one recently erected residential multi-family building and one new office building. For each of the two houses a number of efficiency measures have been simulated.
- Environmental impact and cost-efficiency have also been calculated for each efficiency measure in combination with sex different energy supply scenarios.
- LCC from the end user’s perspective have been used for cost efficiency calculations.
In addition a comparison of the studied buildings has been made with four well-known Swedish low-energy buildings.

1.1 The studied buildings

Multi-family building:
- 15 apartments
- Situated in Stockholm
- Families moved in 2004
- Mechanical exhaust air ventilation system
- Good insulation performance
- A-labelled appliances
- Total yearly energy demand is 170 kWh/m²
- Simulations have been made for e.g. balanced ventilation with heat recovery, heat pump, improved insulation standard, high performance (A+ and A++) appliances, and replacing electrical comfort heating in bathroom floors with district heating

Office building:
- New office building
- High performance insulation and windows
- Sun screens in south and west to avoid cooling demand
- Balanced mechanical ventilation with heat recovery with a good COP
- Total delivered energy 182 kWh/m²
- Simulations have been made for e.g. “free cooling” (passive cooling), energy efficient lighting, day lighting solutions and division in building control system zones, high performance ventilation systems, improved sun screens, air born cooling, variable air volume ventilation systems, and decentralised cooling with a higher COP

1.2 The studied supply systems

80 % of all multi-family residential and office buildings in Sweden are supplied with district heating, hence it was natural to choose several supply system scenarios based on district heating.

1. District heating 2010 forecast
2. Biomass based medium sized district heating system
3. District heating based on biomass CHP
4. District heating based on natural gas CHP
5. Ground heat pump
6. Local biomass combustion

In the analysis electrical end use has been seen from an average European and a future marginal (natural gas combination) supply perspective.
Figure 1. Primary energy consumption calculated for all different combinations of energy efficiency measurements and supply system with a multi family building.

Figure 2. Case E-, ESX- and EX-ventilation for multi-family house, all simulated measures. Difference in $LCC_{energy}$ and primary energy consumption.

2 SUSTAINABLE ENERGY END USE FROM A SYSTEMS PERSPECTIVE

2.1 What is most efficient from an integrated energy, environmental and cost perspective – measures in the individual building or in the supply system?

Achieving the societal sustainable development goal requires a system’s perspective including both energy demand and supply. But how should efficiency measures best be prioritised, taken economical and other limitations into account? How can the best possible use of resources be reached from a system’s perspective?
2.2 Should you focus on delivered energy or primary energy?

The Swedish building sector stands for 40% of total energy consumption, CO₂ emissions are lower approximately 25% of the national CO₂ emissions. Delivered energy has decreased by 7% during the past three decades. However, if include all losses from exploiting the energy source and transports, energy transformation and distribution, the result is totally different. Such an analysis shows that the building sector’s relative energy consumption despite all energy efficiency efforts has increased with 11%!

![Diagram](image)

Figure 3. System boundaries for primary energy, delivered energy, and net energy respectively.

![Diagram](image)

Figure 4. The Swedish building sector’s energy end use from 1975 to 2002. The figure shows delivered energy and corresponding losses.

The study clearly shows that a system’s perspective including both energy supply and energy demand is necessary to achieve a sustainable development. The study points out:

1. Measures and combinations of measures leading to both lower LCC costs, decreased primary energy consumption and decreased environmental impact.
2. Measures and combinations of measures which are cost efficient but lead to higher primary energy consumption and increased environmental impact, and
3. Measures which neither are cost efficient nor lead to decreased environmental impact.

The analysis carried out shows that primarily four measures or combination of measures are cost efficient (LCC) and at the same time leading to lower environmental impact compared to the two base case buildings used in the study. These four categories are (in cost-efficiency order):
1. Decreased use of electricity
2. Use CHP produced district heating
3. Reduced energy need for heating
4. Reduced energy need for heating at a minor increase of electricity end use

Some interesting conclusions from the study are:

- Environmental impact and resource need may vary by a factor two in a specific building with application of different measures, although the delivered energy only varies slightly.
- In combination with combined heat and power production (CHP) traditional exhaust air ventilation systems without heat recovery may be almost as resource efficient as balanced ventilation (exhaust and supply air system) with heat recovery, ESX.
- Primary energy consumption of heat pump solutions with an average coefficient of performance (COP) of 2.5 exceed the primary energy consumption of most solutions with exhaust air ventilation systems without heat recovery as well as systems with ESX ventilation (e.g. exhaust air heat pumps and ground heat pumps). To achieve lower primary CO\textsubscript{2} emissions the heat pump’s COP has to exceed 2.5.
- Well-known examples of energy-efficient buildings such as Lindås Park (passive house), the Jöns Ols residential building in Lund, and the “Astronomihuset” office building in Lund show to be relatively normal regarding primary resource use (primary energy as well as primary CO\textsubscript{2} emission).

2.3 How much lower must the energy end use for heating be to balance the use of incremental kWh electricity?

The necessary reduction of heating energy demand to balance the environmental impact of the use of incremental kWh electricity depends on what energy supply system the comparison is based on. In this study the supply system base line is the Swedish District Heating Association’s forecast on average mix of energy sources for 2010 and European marginal electricity production has been used as baseline in this study. With this supply system scenario a reduction of 3 kWh heat is needed to balance each added kWh in terms of electricity primary energy consumption. The corresponding number for primary CO\textsubscript{2} emissions is 5.6. The 2010 district heating forecast includes a certain share of CHP. Should the CHP produced district heating increase compared to the 2010 forecast, an even larger reduction of heat demand is necessary to balance each kWh increase in electricity demand.

In the short term perspective it is reasonable to assume that it is environmentally sound to invest in measures reducing heat demand in accordance with the ratios 3:1 between heat and elec-
tricity demand when discussing primary energy consumption, and 5.6:1 when it comes to primary CO₂ emissions. In a longer term perspective a new forecast of the district heating mix has to be made. Given the current Swedish development it is probable that such a forecast would include a larger share of CHP.

The general conclusion from the study is that to reach a sustainable energy system, it is not sufficient to focus on delivered energy only. There has to be a shift of focus towards CO₂ emissions and primary energy consumption, over the whole chain from excavation of energy sources to end use.

3 CONCLUSIONS

The main conclusions from the study are:

Primary energy consumption of heat pump solutions with an average coefficient of performance (COP) of 2.5 exceed the primary energy consumption of most solutions with exhaust air ventilation systems without heat recovery as well as systems with ESX ventilation (e.g. exhaust air heat pumps and ground heat pumps). To achieve lower primary CO₂ emissions the heat pump’s COP has to exceed 2.5.

The necessary reduction of heating energy demand to balance the environmental impact of the use of incremental kWh electricity depends on what energy supply system the comparison is based on. In this study the supply system base line is the Swedish District Heating Association’s forecast on average mix of energy sources for 2010 and European marginal electricity production has been used as baseline in this study. With this supply system scenario a reduction of 3 kWh heat is needed to balance each added kWh in terms of electricity primary energy consumption.

The general conclusion from the study is that to reach a sustainable energy system, it is not sufficient to focus on delivered energy only. There has to be a shift of focus towards CO₂ emissions and primary energy consumption, over the whole chain from excavation of energy sources to end use.

4 REFERENCES

Persson A et al, 2006, Energianvändning och försörjning av byggnader ur ett systemperspektiv, ett samverkansprojekt mellan bygg- och energibranschen,

Persson A et al, 2005, All teller inget – Systemgränser för byggnaders uppvärmning, ÅF
Chapter 3

LIFE-TIME STRUCTURAL ENGINEERING

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Life-time structural engineering

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INTRODUCTION

Life-time structural engineering is the subject of the Working Group 3 of COST Action C25. The evaluation of life-time of structures is a key issue for the assessment of sustainability of built-up areas. In order to develop an integrated approach to life-time structural engineering, it is important to define a design procedure based on performance levels, considering different types of limit states which include not only mechanical safety but also durability and obsolescence of structures. The assessment of durability and obsolescence of new and existing structures involves different issues related both to the calculation methods and monitoring techniques of life-cycle performance.

With this regard, WG3 has been organized in three Working Packages, namely WP8, WP9 and WP10. The first one is concerned with the analysis of verification methods for durability of constructions. The subject of WP9 is the monitoring of life-cycle performance. WP10 is devoted to sustainable construction assessment and classification systems with reference to selected case studies.

The main aim of WP8 is to define the different phases of a durability design procedure based on performance levels. In particular, its main tasks are the survey of the state-of-the-art in verification methods for durability of constructions and the analysis of degradation models for prediction of service life of structures. According to performance based durability design, the safety of constructions is satisfied if the failure event corresponding to the maximum allowable value of degradation occurs after the design service life has expired, with a proper safety margin. In particular, the calculation of life-time of constructions requires the identification of the environmental loads affecting durability that will likely act on the structures. On the basis of the identification of environmental loads, the degradation factors and mechanisms have to be evaluated. Once deterioration mechanisms that could act on the structures during the life cycle have been identified, corresponding damage models have to be selected which provide degradation as a function of time on the basis of statistical formulations. The probabilistic characterization of the damage development over time is necessary since it influences the value of the safety factor to be considered in design phase. The definition of the maximum allowable degradation values for different limit states represents the final step of development of a durability design procedure. Both serviceability and ultimate limit states related to basic requirements such as functionality in use and structural safety need to be defined. With respect to mechanical limit states, more specific performance levels can be classified for durability design. In particular, serviceability limit states can be related to changes in functionality or aesthetics on the basis of maintainability, economy and environmental impacts. Finally, ultimate limit states have to be defined for the damage of structural material which compromises the mechanical safety of constructions.
WP9 is concerned with another important issue for the evaluation of actual safety factor and residual service life of structures, that is the monitoring of life-cycle performance of constructions. Its main tasks are: the analysis of maintenance, repair and rehabilitation techniques and planning; the survey and condition assessment of structures in terms of safety and functionality; the classification and planning of demolition and deconstruction systems. Different techniques and numerical methods for damage monitoring of materials and evaluation of actual structural safety are available in the literature. The aim of monitoring analysis is to define the actions to avoid or defer obsolescence, that is the inability to satisfy the changing of functional and structural requirements. Generally these actions, such as maintenance, demolition and repairing, have the purpose of minimising the impacts of obsolescence before costs become substantial. In particular, the final objective is to reduce demolishing of facilities that have not reached their mechanical or durability limit states, and thus promote the sustainable development. In a performance based approach, the factors and causes of obsolescence should be defined and identified, both in quantitative and qualitative terms, selecting different limit states for functionality of different structural typologies. The different methods for decision making such as life cycle costing method and risk analysis have to be used to select the proper intervention strategy.

WP10 is devoted to the application of analysis methods developed in other WPs to case studies selected within C25. In particular, the main objective is to compare different structural systems in terms of sustainability, on the basis of the results provided by previous WPs. With this regard, both new and existing constructions have been selected. For each case study, different structural solutions will be analyzed on the basis of a performance based design approach, considering both mechanical, degradation and functional limit states.

In this context, the present chapter collects some contributions by WG3 members, after first year of activity of COST Action C25. The papers are concerned with different issues of lifetime structural engineering and have been organized according to the subjects of relevant WPs.
ABSTRACT: This paper gives a brief introduction into the concepts related to service life planning. Service Life Planning is subject of international standardization, and the ISO 15686 series identifies the elements need to perform service life planning of construction works. The standardization work was initiated partly on the basis of the requirements expressed in the European Directive on Construction Products, and establishes valuable links to the concepts of performance based building and sustainability in building construction.

1 INTRODUCTION

During the last 25 years, the subject field of service life prediction, service life planning and service life declaration has gained intensive attention of the international research and development as well as the international standardization community. In the European Union, this interest manifested in the formulation of the Construction Products Directive (CPD), in which six essential requirements to be fulfilled by construction products are established. These requirements are to be fulfilled throughout the working life of the construction works. Essentially, this necessitates that a service life planning exercise is being conducted.

The topic was in parallel being developed through activities in CIB, and gained the attention of international standardization, first through CEN activities which due to the international attention to the subject rapidly resulted in ISO activities. At the brink of completion, the ISO standard series 15686 on "service life planning" provides standards on methodologies for service life planning, including items such as life cycle costing, the link between LCA and service life planning, data demands, feedback from practice, and methods to transfer and adapt information between different scenarios.

The standards of the 15686 series are applied within the emerging ISO and CEN standards concerning sustainability of construction works. The concept of service life is at the very core of any "life cycle" consideration; additionally, it relates to the concept of performance-based building, which itself is another field of growing international attention.

This paper gives a brief introduction to the concepts of:

- service life planning,
- service life declaration,
- factor method
- failure mode and effects analysis
- deterministic methods
- feedback from practice (experience based information)
- CE marking
- CPD
- current ISO and CEN standards relating to service life
2 SERVICE LIFE PLANNING

The International Standardization Organization (ISO) standard series on service life planning (SLP) for buildings and constructed assets (ISO 15686) developed by ISO/TC59/SC14, as well as the European Union thematic network on performance-based building (PeBBu), respond at least partly to the European Union Construction Product Directive (CPD) (CEC, 1988). Particularly, they respond to a horizontal requirement of the CPD, necessitating that buildings and constructed assets be the subject of planning activities that reflect their performance throughout their operating life, or in other words, require SLP.

The concept of SLP aims to enable planners to design buildings that meet or exceed identified project-specific targets and performance requirements. Requirements may concern a variety of issues, stretching from lifecycle costs and technical performance to environmental considerations. To enable this, planners also have to assess information available for materials or components in the light of the requirements for the building in its entirety – including aspects of usage. In other words, they must consider and merge performance requirements and performance properties at different scales. Planners may handle the task intuitively. However, due to the increasing demands imposed by clear documentation of planning activities and the need for verification (especially when tendering is performance based), a clear relationship between requirements and performances on various levels needs to be established. (Sjöström et al) argue, that one difficulty is that the object on a higher system level (e.g. the building) is comprised of objects from lower system levels (e.g. components and materials), but the application in this higher system level decides their ultimate functionality. Requirements originate from the highest system level, where fitness for purpose must be sustained. The performance and functionality on the higher system level is substantially different from the sum of the functionalities on the lower system levels.

The procedure of service life planning, involving the analysis of the preconditions, through the identification and the setting of requirements to the assessment of design options in relation to these requirements is indicated in Figure 1.

![Figure 1: Service Life Planning according to ISO 15686-6](image)

3 SERVICE LIFE DECLARATION

The concept of service life planning relies on the availability of product and component related service life information. Together with the application context of a product or a component, the ability of these products and components to withstand deterioration agents and to maintain per-
formance forms the information basis on which the routine of service life planning can be performed. A declaration of the reference service life, a service life declaration, needs to indicate the development of performance over time, for a set of well-identified reference conditions.

A general limitation to the application of service life planning is the fact, that despite the increasing awareness of product manufacturers that information on life performance of their products may be a persuasive argument in the market, such information is not typically disclosed. Additionally, the majority of product standards do not include declarations of product life performance.

If service life information, or information on life performance pf products and components is provided, such information typically may have two origins. It can be based on experience gained from product application, or "feedback from practice", or it can be based on qualified indications, possibly based on testing, and provided by the manufacturer or qualified third parties. In either situation, the conditions for which the provided information is valid necessarily needs to be communicated alongside the service life information, as otherwise no scrutinization of the information and no analysis as to the relevance to a given application situation could be performed.

4 FACTOR METHOD

The existing empirical models are usually described for some given (reference) case e.g. regarding material quality, maintenance and environment; and the same holds true for service life information in general. At the time being, the design team is therefore generally required to use the information from a reference in-use condition (e.g. declared service life from producer). The process of service life estimation aims to transfer reference service life information to the current design case, and to enable the designer or other decision maker to estimate service life information relevant to his specific application situation, reflecting the current in use conditions, see Figure 2.

<table>
<thead>
<tr>
<th>Manufacturer’s Task</th>
<th>Designer’s Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>Testing &amp; experience, ISO 15686-2</td>
<td>Verification of demand to adapt RSL</td>
</tr>
<tr>
<td>Reference service life (RSL)</td>
<td>Modification of RSL</td>
</tr>
<tr>
<td>Reference scenarios</td>
<td>Estimated service life (ESL)</td>
</tr>
<tr>
<td>Reference requirements</td>
<td>Specific scenarios</td>
</tr>
<tr>
<td>Reference context</td>
<td>Performance requirements</td>
</tr>
<tr>
<td>Reference exposure etc</td>
<td>Specific context</td>
</tr>
<tr>
<td>Identification of differences in scenarios</td>
<td>Specific exposure etc</td>
</tr>
</tbody>
</table>

Figure 2: The route from Reference Service Life to Estimated Service Life

Where the conditions for which a reference service life has been established significantly differ from the intended application situation, the information will need to be modified in order to better reflect the given context. Such modulation of the information has then to take into account the differences between the reference situation and the intended design situation, see ISO/DIS 15686-8. One available procedure for this, called the Factor method, is described in ISO 15686. The Factor method has been criticized for being too simple and that the results will not be reliable enough. Due to its character and its potential applicability even as a simple checklist, the method though is practical for designers.
The factor method addresses a set of factor classes, each representing a typical set of aspects having an influence on the service life or products and components, when being integrated into a building or other construction works. These factor classes are:

A. Inherent Performance Level
B. Design Level
C. Work Execution Level
D. Indoor Environment
E. Outdoor Environment
F. In-Use Conditions
G. Maintenance Level

5 FAILURE MODES AND EFFECTS ANALYSIS

The methodology of failure modes and effects analysis (FMEA) has recently been adapted to an application to building products and components. The methodology is based on the apprehension of degradations and failures of building products. An identification of degradation scenarios and an assessment of their relevance allows the generation of a multi-performance profile. A system analysis establishes a functional model of a building product, and the FMEA allows an analysis of various relevant failure route scenario. For each scenario, information can be gathered, but as this information does not originate from harmonized information sources, fusion of data is another essential step of the methodology. A temporal quantification of the failure scenarios ultimately leads to the establishment of the desired service life information, reflecting the modelled failure modes and the chosen performance aspects and performance requirements. (Talon et al 2005).

6 PREDICTION MODELS AND DETERMINISTIC METHODS

Chemical or physical deterioration or corrosion mostly causes the performance loss of building products considered here. Other important reasons for, sudden, performance failures may be fundamental abuse of products, fire, or explosion, etc. Degradation can normally be expressed as mathematical models. With a limiting value - a minimum performance requirement - the service life can be calculated. Figure 3 shows generically some performance over time functions.

Figure 3: A spread of performance measure with its mean value, printed relative to a requirement on the performance measure, resulting in a lowest, average and highest expected service life. The performance curve and requirement curve are simplified to illustrate the concept. (Trinius et al 2005)
Performance over Time (POT) models are often called Damage Models. POT or Damage Models are characterised by the inclusion of a minimum performance requirement which enables determining the service life. The establishment of POT models requires knowledge and data on the degradation environment and the essential degradation factors, the properties of the material under study, and a established Performance Requirement relevant to the studied in-use situation.

Important sets of models are Dose-Response functions, which are normally used to describe corrosion processes. These can be expresses as a power function of degradation factors and elapsed time:

\[ M = a \cdot t^b \]

where

- \( M \) = corrosion rate at time \( t \);
- \( a \) = a rate constant, e.g. expressed by the deposition of pollutants or other degradation factors to a material surface;
- \( b \) = a power exponent governed by e.g. diffusion processes.

Dose-Response functions can only be used for service life prediction when an agreed performance requirement is applied. POT and Dose-Response models are established through field and laboratory experiments in interaction with analyses of feedback from practice studies.

Degradation processes have a stochastic character, most easily understood by considering the stochastic behaviour of e.g. climate and weather, and ideally POT models should cover stochastic variations. Most degradation models do, but it is also true that in engineering applications they are mostly used in a deterministic way, i.e. with fixed mean values of parameters introduced in the calculation process.

7 FEEDBACK FROM PRACTICE

ISO 15686 provides a separate part (part 7) of the standard series aiming at the topic "feedback of service life data from practice". Acknowledging that significant experience with numerous materials, products and components has been gained, and will continuously be made available, this immense source of information is intended to be made applicable for service life planning.

As for the application of reference service life information from manufacturers, the user of information must be aware that information based on experience from a singular application necessarily includes the strengths as well as the weaknesses of that case from which the information has been drawn. Information representing the conditions of product application need to be communicated together with the service life information itself, otherwise the value of the information is unclear. With an increasing number of well-documented cases however, it can be assumed, that information sets for numerous applications of common products can be made available.

A significant restriction remains the general unavailability of feedback information related to innovative products, or for very specific applications. While it is not intended to stifle innovation nor to stifle creativity, while sustaining the requirement that innovative solutions need to meet the same requirements as established solutions, is must however be recognized, that the non-availability of feedback information related to innovative products may be an obstacle difficult to overcome.

8 CE-MARKING AND THE CPD

Within the European market for construction products, also innovative products are to meet the generic requirements stated by European directives and resulting codes and regulations. The basis for CE-marking of innovative building products is, as for all products, compliance with the CPD.
The goal of the CPD is the removal of technical barriers in the construction products sector, through:

- compliance of works with the six Essential Requirements;
- transformation of the six Essential Requirements to product requirements by means of Interpretative documents;
- determination of performances for products used in the works by technical specifications;
- attestation of conformity of the product.

The six essential requirements established in the CPD are to be fulfilled throughout the "working life" – consequently a resulting horizontal requirement is the ability to handle service life and life performance information.

Products are "fit for their intended use" if they comply with a Harmonised European Standard (hEN), a European Technical Approval (ETA) or a non-harmonized technical specification recognized at EC level.

9 CURRENT ISO AND CEN STANDARDS RELATING TO SERVICE LIFE

According to ISO 15392 Sustainability in Building Construction – General Principles, "sustainable" buildings bring about the required performance and provide value while minimizing adverse impacts. The understanding of "value" includes non-monetary value considerations, and the "adverse impacts" include impacts on economic, environmental as well as social aspects. The life cycle of a building or other construction works, including the processes required to obtain and to maintain a building, plus any legacy, is the basis for the quantification of impacts and for the consideration of sustainability. Addressing the life cycle and the performance provided throughout the life cycle defines the prominent link of sustainability considerations to the concepts of performance-based building and to service life planning. Other ISO standards developed under ISO TC59 as well as the standards under development within CEN TC350 do apply the same conceptual view, setting assessments in relation to performance, including the consideration of life performance. The conceptual inter-linkage between performance based building, service life planning and declaration and assessment of sustainability aspects is illustrated in Figure 4.

![Figure 4: Performance based building, service life planning and declaration and assessment in their common context](image-url)
10 CONCLUSIONS

Service Life Planning as well as performance-based building can be considered to be pre-requisites for the move towards a more sustainable development of the built environment and its elements. The international standards on sustainability in building construction very well demonstrate this connection. The information demand to be fed in order to enable service life planning to be performed is immense and requires highly transparent and comprehensive information, communicated in a way that enables designers and other building-sector actors to work with that information. A good understanding of life performance aspects of construction works and their parts is a necessary requirement when striving to increase performance, while minimizing undesired impacts.

REFERENCES


1 General Principles (under review)
2 Service Life Prediction Principles (published)
3 Performance Audits and Reviews (published)
4 Data Requirements (under development)
5 Maintenance and Life Cycle Costing (close to publication)
6 Procedures for considering Environmental Impacts (published)
7 Performance Evaluation and Feedback of service life data from practice (published)
8 Reference Service Life (final editing)
9 Guide on the inclusion of requirements of service life assessment and service life declaration in product standards (final editing)
10 Performance standards in building (under development)


Modelling of corrosion damage for metal structures

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University of Naples “Federico II”, Naples, Italy

ABSTRACT: The durability of metal structures is strongly influenced by damage due to atmospheric corrosion, whose control is a key aspect for design and maintenance of both new constructions and historical buildings. Nevertheless, only general provisions are given in European codes to prevent the effects of corrosion during lifetime of metal structures. In particular, design guidelines such as Eurocode 3 do not provide models for the evaluation of corrosion depth which are able to predict the rate of thickness loss as a function of different influencing parameters. In this paper, a report is presented on the modelling approaches of atmospheric corrosion damage of metal structures which are available in both ISO standards and the literature. A comparison among the selected degradation models is shown in order to evaluate the possibility of developing a general approach to the evaluation of thickness loss due to corrosion.

1 INTRODUCTION

The growing attention that the scientific community has paid in the last decades to the corrosion phenomena is related to the huge economic, social and environmental losses consequent upon spread damage on several metal constructions.

During the 1970s and 80s, several studies on the cost of corrosion were carried out. It was showed that the corrosion impact on the domestic economy of various countries accounted for 3% of the GDP (C.C. Technologies Laboratories & NACE International 2001). When the damage has greatly enlarged, expensive maintenance and replacement are required for the safe and reliable use of constructions and, even if the serviceability of the structure is not compromised, the deterioration of appearance produces reduced value of constructions.

From the structural point of view, the thickness loss of the cross section due to corrosion attack leads to a smaller resistant area, producing a decrease of the structural performances in terms of strength, stiffness and ductility. In some cases, the local failure of a member or joint could affect the stability of the whole structure. In addition, in case of cyclic loads, the corrosion phenomenon can produce a significant reduction in the fatigue strength, mainly in zones with high stress concentrations (Landolfo et al. 2005).

In order to prevent failures due to corrosion, a durability design of metal structures is necessary, both for ultimate and serviceability limit states.

With this regard, the main European structural design codes provide only general protective measures, such as the use of weathering or stainless steel, of surface protection systems and of structural redundancy. It should be also noted that no predictive models, which are able to estimate the corrosion depth of structural material, are provided but only general recommendations concerning the minimum thickness to be used for structural members are reported.

Nevertheless, several models concerning the evaluation of the damage produced by corrosion are available in the literature and standards, even if they refer to different parameters and conditions.
The object of this study is to present a report on the predictive models relevant to atmospheric corrosion which are available in the literature in order to evaluate their suitability with respect to use in a durability design procedure based on lifetime safety factor method (Landolfo et al. 2007). The procedure is composed of different phases which are the analysis of environmental loads, selection of influencing parameters and the evaluation of thickness loss by means of corrosion models and related safety factors.

With this aim, corrosion rates and classification methods of environmental corrosivity considered in standards are reported in the following. Moreover, several models are shown which take into account the different factors affecting the evolution of damage, such as the presence of chlorides, sulphates and pollution in the atmosphere.

Finally, a comparison among considered dose response curves corresponding to selected corrosion classes and metals is presented and main differences are described with respect to degradation rates reported by ISO standards.

2 CORROSION OF METALS AND ALLOYS

The corrosion phenomena of metals and alloys involve mainly two elements: the material and its environment. In particular corrosion is defined as the deterioration of a material, usually a metal, that results from a reaction with its environment (NACE 2002), causing the degradation of both.

Corrosion attacks could manifest in different forms and several classification system are provided by the international scientific literature.

A first classification is made on the basis of the reaction that takes place on the metal surface. In this case, it is possible to distinguish between chemical and electrochemical corrosion, the latter involving at least one cathodic-anodic reaction.

Another traditional classification system (NACE 2002, EN ISO 8044, NPL et al.) characterizes corrosion phenomena according to their appearance and the basic forms of corrosion, which could be uniform or localised (Figure 1), are defined as follows:

- **general corrosion**: corrosion that is diffused more or less homogeneously over the surface of a material;
- **uniform corrosion**: it is a kind of general corrosion that proceeds at the same rate onto the metal surface;
- **pitting corrosion**: localized corrosion that is restricted to a small area, taking the form of pits;
- **crevice corrosion**: localized corrosion of a metal surface at or close to an area that is protected by another material;
- **erosion corrosion**: a conjoint action involving a corrosive flowing which leads to accelerated loss of material;
- **cavitation corrosion**: development and rapid collapse of cavities or bubbles;
- **galvanic corrosion**: corrosion of a metal due to a contact with a more noble metal in a corrosive electrolyte;
- **fatigue corrosion**: cracking of metal caused by repeated stresses in a corrosive environment;
- **stress corrosion**: brittle cracking caused by the parallel occurrence of an applied stress and a specific environment.

Finally, on the basis of the corrosive environment, degradation mechanisms are categorized in **microbial and bacterial corrosion**, **gaseous corrosion**, **marine corrosion**, **underground corrosion** and **atmospheric corrosion**. The first one is usually associated with the presence of micro-organism and/or bacteria on the metal surface that occurs in natural and sea water as well as in soils. **Gaseous corrosion** occurs when a dry gas is the main corrosive agent and there is not a liquid layer on the surface. **Marine corrosion** refers to sea water acting in an immersion and/or a splash zone, while **underground corrosion** is related to corrosion in soils.

This paper focuses on the **atmospheric corrosion** of metal structures in outdoor atmospheres, that represents one of the most severe form of corrosion, resulting in huge economic and structural performance losses.

3.12
The atmospheric corrosion phenomena comprise three different forms of corrosion, particularly dry, damp and wet corrosion. Damp and wet corrosion usually occur in indoor and outdoor atmosphere, as a consequence of wet and dry cycles induced by rainfall and condensation, which produce thin water films at the metal surface. In damp corrosion, the thin film of electrolyte is formed on metal surface by adsorption of water molecules when a critical humidity level is reached, while wet films are associated with water flowing (Roberdge 2000).

Atmospheric corrosion is mainly an electrochemical process that occurs in the presence of thin film electrolytes formed on the metal surface. The attack proceeds by balancing anodic oxidation reaction, which involves the dissolution of the metal in the electrolytic film, and cathodic reactions, involving the oxygen reduction reaction. The anodic process controls the overall rate of atmospheric corrosion and it is represented by equation (1):

\[ M \rightarrow M^{n+} + ne^- \]  

The electrolyte films tend to form only when a certain critical humidity level is reached. For example, in the case of iron a threshold value for humidity of about 60% in a pure atmosphere can be defined. Corrosion rate can be neglected for lower values of RH while for higher ones it rapidly increases.

The overall rate of the metal dissolution process is strongly influenced by the formation of corrosion products, their solubility in the water film and the formation of passive coatings as well as by the corrosiveness of the environment. These phenomena processes are influenced by several factors, that could be divided into two different classes: the endogenous factors, which are related to the metal itself (the effective electrode potential of a metal in a solution, the composition of the metal, the chemical and physical homogeneity of the surface, etc.), and the exogenous factors that are connected to the atmospheric composition (Landolfo, Di Lorenzo, Guerrieri 2005).

Among these factors, important practical environmental variables are the time of wetness (TOW) and the concentration of contaminants, such as sulphur dioxide and chlorides.

The time of wetness represents the average period of time during which the electrolyte is on the corroding surface (Roberdge 2000), for practical purpose it could also be defined as the number of hours during which the relative humidity is greater than 80% and the average temperature T>0° (ISO 9223, 1992). The negative effect of the humidity is exacerbated by the concentration of the atmospheric pollutants, mainly sulphurs and chlorides.

Chlorides in the atmosphere can definitely increase the corrosion rate, such as in the case of marine environment, where the critical humidity level is about 30-40%. The main effect of chlorides is to prevent formation of protective oxide films on the metal surface, thus increasing the overall corrosion rate.

As far as sulphurs are concerned, small concentrations could dissolve in the thin electrolyte, the relative humidity being over 60-70%, and the acidic electrolyte that is formed seems to stimulate both the anodic and the cathodic reactions (Roberdge 2000). It has been shown that there is an increase in rate at about 60% relative humidity even in pure air, and a further sharp increase at 80% in the presence of 0.01% of sulphur dioxide (NPL).
3 STANDARDS AND CODES

With respect to corrosion phenomena, the European structural design codes provide only general recommendations and basic principles that are mainly concerned with the use of coating protective systems, the choice of corrosion resistant materials and structural redundancy. Such specifications aim to prevent the initiation and propagation of the corrosion attacks by means of design detailing, surface protective systems and proper inspection and maintenance programmes, but no references are reported to models able to predict the damage effects during service life.

The EN 1993-1-1 states few common principles, such as the opportunity of providing corrosion protection measures by means of surface protection systems, improving the use of weathering and stainless steel and by structural redundancy. It should be noted that in this case no references are made to models able to estimate the corrosion depth.

Nevertheless, in the new Italian structural code (DM 2005) an important innovation has been introduced concerning corrosion, which is expressly included among the different loads acting on constructions. Corrosion is classified as a type of entropic load, which comprises deteriorating actions, caused by natural degradation mechanism of materials and environmental loads, which affects the structural integrity. With respect to durability, it is recommended to adopt a 2mm extra thickness in aggressive environment if maintenance and inspection can not be performed for design life up to 100 years.

The European Standard EN 12500-2000, edited by the European Committee for Standardization (CEN), defines the procedure to be adopted for the classification, determination and estimation of corrosiveness of atmospheric environments by assessing the mass loss of standard samples, after 1 year exposure. The procedure is described in detail the next section. Important references to the corrosion of metals and alloys are reported in the almost 40 standards compiled by the ISO Technical Committee TC 156. The TC working group 4 worked on categorization of the corrosivity of environment in terms of practical environmental variables, atmospheric corrosion testing and classification of corrosivity of atmosphere.

In particular, EN ISO 9223 provides the classification of the corrosivity of atmospheres on the basis of three key factors: the TOW (time of wetness), the deposition rate of chlorides and sulphur dioxide concentration. It defines five corrosivity classes, ranging from C1 to C5.

EN ISO 9224 (1992) provides guiding values for the corrosivity categories of atmospheres. EN ISO 9225 (1992) is concerned with the methods of measurement of pollution data, while EN ISO 9226 (1992) gives the corrosivity rates of standard specimens for the evaluation of corrosivity of atmospheres. In EN ISO 14713 (1999), specific recommendations are provided for each corrosivity class with respect to different coating typologies. In particular, the life duration of zinc and aluminium coatings is related both to thickness loss and corrosiveness of environment.

Other references can be found in international standards, but a design procedure has still to be codified for predicting and preventing the potential damage that a specific environment could lead to both coatings and structural materials, during the entire service life.

4 CORROSIVITY OF ATMOSPHERIC ENVIRONMENTS

As far as the corrosivity of atmospheres is concerned, EN 12500 (2000) defines five outdoor environments on the basis of the presence of corrosive agents in the air, namely:

- **Rural atmosphere**: countryside and small towns, minor corrosive agents contamination (carbon dioxide, chlorides, artificial fertilizers).
- **Urban atmosphere**: densely populated areas, few industrial activities, medium corrosive agents contamination (sulphur dioxides);
- **Industrial atmosphere**: intensive industrial activities, high corrosive agents contamination (sulphur dioxides);
- **Marine atmosphere**: areas close to the sea, or internal zones strongly affected by airborne salinity. Corrosion effect are influenced by topographic conditions, prevailing wind direction.

3.14
Marine Industrial atmosphere: complex environment, areas close to both the sea and industrial districts, or internal zones located in the prevalent wind direction. Medium and/or high corrosive agents contamination (sulphur dioxides, chlorides).

The methodology for the quantitative evaluation of the corrosivity of a specific environment standard is provided in EN 12500 on the basis of guiding values of the mass loss of standard flat specimens (rectangular shape, 50x100 mm) of four materials (carbon steel, copper, zinc, aluminium), after one year of exposure. The corrosivity classification is defined according to Table 1.

Although it is strongly recommended to follow the previous procedure, a qualitative classification of the corrosiveness of atmosphere has been established whether field test data are not available (Table 2).

Table 1. Mass loss (g/m²) for one year field test exposure in the five corrosivity classes C1-C5, the order being from the least to the most corrosive. (EN 12500/2000).

<table>
<thead>
<tr>
<th>MASS LOSS g/m²</th>
<th>Corrosiveness category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Steel</td>
<td>Zinc</td>
</tr>
<tr>
<td>≤ 10</td>
<td>≤ 0,7</td>
</tr>
<tr>
<td>10-200</td>
<td>0,7-5</td>
</tr>
<tr>
<td>200-400</td>
<td>5-15</td>
</tr>
<tr>
<td>400-650</td>
<td>15-30</td>
</tr>
<tr>
<td>650-1500</td>
<td>30-60</td>
</tr>
</tbody>
</table>

Table 2. Corrosivity qualitative classification. An extract of EN 12500.

<table>
<thead>
<tr>
<th>Corrosiveness category</th>
<th>Typical outdoor atmospheric environments</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 Very low</td>
<td>Dry or cold zones; very low pollutants contamination; time of wetness very low. E.g.: Desert, Antarctic zone.</td>
</tr>
<tr>
<td>C2 Low</td>
<td>Temperate zone; low pollution (SO₂ [µg/m³] &lt;12). E.g.: rural areas and small towns. Dry or cold zones; short damp periods. E.g.: desert, sub-artic zones.</td>
</tr>
<tr>
<td>C3 Medium</td>
<td>Temperate zones; medium pollutant contamination (12 &lt;SO₂ [µg/m³] &lt;40); low chloride influences. E.g.: urban areas, coastal area characterized by low chlorides deposition rate. Tropical zones with low pollution.</td>
</tr>
<tr>
<td>C4 High</td>
<td>Temperate zones; high pollution levels (40 &lt; SO₂ [µg/m³] &lt;80); important chloride influences. E.g.: polluted urban areas, industrial areas, coastal areas (no splashing zones), deicing salt influence. Tropical zones with medium pollution level.</td>
</tr>
<tr>
<td>C5 Very high</td>
<td>Temperate zones; very high pollution levels (80 &lt; SO₂ [µg/m³] &lt;250); strong chlorides deposition rates. E.g.: industrial zones, coastal and sea areas (no splashing zones). Tropical zones with high pollution levels and/or strong chlorides influences.</td>
</tr>
</tbody>
</table>

As an alternative to this qualitative classification, it is possible to refer to ISO 9223 corrosivity chart where each class is defined by the guiding values of TOW, sulphur dioxide concentration and the chloride deposition rate. The time of wetness (hours/year) is defined as the number of hours per year during which RH is greater than 80% and the average temperature exceed 0°C. Five TOW classes are identified (T1÷T5), ranging from the indoor environment with climate control (TOW ≤ 10 hours/year) to the most corrosive damp climate (TOW ≥ 5500 hours/year). Finally, four sulphur dioxide (P0÷P3) and chloride (S0÷S1) deposition rates classes have been stated for the classification of environmental corrosivity. An application of ISO 9223 is presented in Table 3.
Table 3. An application of the ISO 9223 chart to carbon steel for TOW = T3

<table>
<thead>
<tr>
<th>Sulphur dioxide concentration [µg/m³] or deposition rate [mg/m²day]</th>
<th>P3</th>
<th>C2</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2</td>
<td>C1-2</td>
<td>C1-2</td>
<td>C2-3</td>
<td>C3-4</td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>C1</td>
<td>C1</td>
<td>C2</td>
<td>C3-4</td>
<td></td>
</tr>
<tr>
<td>P0</td>
<td>C1</td>
<td>C1</td>
<td>C2</td>
<td>C3-4</td>
<td></td>
</tr>
<tr>
<td>S0</td>
<td>S1</td>
<td>S2</td>
<td>S3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chloride deposition rate [mg/m²day]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5 CORROSION MODELLING

Several models concerning the evaluation of the damage produced by atmospheric corrosion are available in the literature. They are formulated according to different approaches which depend on the objectives of the model itself. Such models can be classified as 1st level and 2nd level models. The first ones are based on laws of physics and chemistry (Landolfo, Di Lorenzo, Guerrieri 2005). In this case the dissolution of metal and the formation of corrosion products is evaluated at microscopic level in the sense of current (Roberdge 2000). The 2nd level models are useful for engineering application and allow to evaluate the corrosion rate as a function of mass and/or thickness loss with time, being obtained from the observation and the interpolation of experimental data.

In the following a review of 2nd level corrosion models for structural applications is presented. In this case the relationship between the corrosion rate and the levels of pollutants is expressed in combination with different climatic parameters (Kucera 2004). Considered variables affecting the corrosion rate over time are the time of wetting, the frequency and duration of drying out periods, relative humidity, temperature and temperature variation, and the composition of the atmosphere. The corrosion rate is usually expressed as the mass loss per unit area per unit time, or as the rate of penetration, by means of the thickness loss. It is important to note that the thickness loss reported in corrosion studies is usually the average of the thickness losses of the exposed and ground ward surfaces of a specimen (Albrecht & Hall 2003).

Corrosion models usually describe the corrosion depth as a function of time in the form of a power model:

\[ d(t) = A \cdot t^B \]

where \( d(t) \) = corrosion depth [µm, g/m²], \( t \) = exposure time [years], \( A \) = corrosion rate in the first year of exposure, \( B \) = corrosion rate long-term decrease.

Because of the formation of corrosion products on the metal surface, the initial corrosion rate usually decreases on long term period. If \( B \) is smaller than 0.5, the corrosion products show protective, passivating characteristics, otherwise \( B \) is greater than 0.5.

Some simplified models have been proposed which take into account the environmental effects influencing the corrosion rate by means of constant values of coefficients \( A \) and \( B \). Such models express the thickness loss only as a function of time and are usually calibrated on data obtained from short and long term field test exposure. As a consequence, if they are used for environments which differ from the one where the model has been calibrated, the predicted value of the corrosion rate is often inaccurate.

A first attempt to develop general models has been provided by International Standard ISO 9224 (1992), which specifies the long term corrosion rates for standard structural materials in the five corrosivity classes C1–C5. According to the Standard the average corrosion rate of each material follows a bi-linear low. During the first 10 years the corrosion depth is given by formula:

\[ d_i(t) = r_{av} \cdot t \] \hspace{1cm} t < 10 \text{ years} (3)
where \( d_1(t) \) = corrosion depth after the first 10 years of exposure (micrometers); \( r_{av} \) = average corrosion rate (micrometers per year); \( t \) = time at which the exposure ends.

After 10 years of exposure, the corrosion rate is assumed to be constant with time and the thickness loss is given by formula:

\[
d(t) = r_{av} \cdot 10 + r_{lin} (t-10) \quad t \geq 10 \text{ years}
\]

where \( d(t) \) = corrosion depth for the considered time interval (micrometers); \( r_{lin} \) = steady state corrosion rate (micrometers per year); \( t \) = time in the linear region of the curve of uniform corrosion as function of time.

The standard provides the guiding values of both \( r_{av} \) and \( r_{lin} \) for carbon steel, weathering steel, zinc, copper and aluminium. In Figure 2 a representation of corrosivity band for carbon and weathering steel is shown.

![Figure 2](image1)

Figure 2. An application of ISO 9224. Thickness loss as a function of time for carbon steel (a) and weathering steel (b) for different corrosiveness classes.

Some adjustment to these corrosion laws have been reported in Albrecht et Hall (2003), where the authors have proposed a new bi-linear model which accounts for a modified corrosion rate during the first year of exposure and a steady state during the subsequent years. An application of the modified bi-linear law for carbon and weathering steel for the upper and lower bound in the medium corrosivity category C3 is reported in Figure 3.

![Figure 3](image2)

Figure 3. Thickness loss as a function of time for carbon steel (a) and weathering steel (b) for corrosivity class C3.

Recently, different models have been developed with the aim to generalize the corrosion loss over time for different environments, reporting the climate and pollutants variables as independent factors. In the following two of these models are presented.

Several dose-response functions have been developed within the International Cooperative Programme on “Effects on Materials, including Historic and Cultural Monuments” in the
framework of the UN ECE convention on long range transboundary air pollution (Kucera 2004). These functions have been formulated for different metal materials (Table 4) and are based on both long term exposures and trend analysis based on repeated 1-year measurements, taking also into account the unsheltered (eq. 5.1-5.4) or sheltered (eq 5.5) exposure.

Table 4. Dose response function, ICP Materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass loss [g/m²]</th>
<th>Equation n°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weathering steel (unsheltered)</td>
<td>ML = 34[SO₂]³⁴×exp(0.020Rh + f(T))t⁰.³³</td>
<td>(5.1)</td>
</tr>
<tr>
<td>Zinc</td>
<td>ML = 1.4[SO₂]⁻²²×exp(0.018Rh + f(T))t⁰.⁸⁵ + 0.029Rain[H⁺]t</td>
<td>(5.2)</td>
</tr>
<tr>
<td>Aluminium</td>
<td>ML = 0.0021[SO₂]⁴²×Rh exp{f(T)}t¹.⁷⁸ + 0.00023Rain[Cl⁻]t</td>
<td>(5.3)</td>
</tr>
<tr>
<td>Copper</td>
<td>ML = 0.0027[SO₂]⁻²⁷×[O₃]⁰.⁷⁹×Rh·exp{f(T)}t⁰.⁷⁸ + 0.050Rain[H⁺]t².⁵⁹</td>
<td>(5.4)</td>
</tr>
<tr>
<td>Weathering Steel (sheltered)</td>
<td>ML = 8.2[SO₂]⁻²⁴×exp(0.025Rh + f(T))t².⁶⁶</td>
<td>(5.5)</td>
</tr>
</tbody>
</table>

Klinesmith et al. (2007) developed a model for the atmospheric corrosion of carbon steel, zinc, copper and aluminium, taking into account the effects of four environmental variables (TOW; sulphur dioxide, salinity and temperature). The data of the ISOCORRAG program have been used to calibrate the coefficients of the proposed models.

The general form of the degradation model is the following:

$$y = A \cdot t^B \left( \frac{TOW}{C} \right)^D \cdot \left[ 1 + \frac{SO₂}{E} \right]^F \cdot \left[ 1 + \frac{Cl}{G} \right]^H \cdot e^{(f(T)+T_0)} \tag{6}$$

where $y$=corrosion loss ($\mu$m); $t$=exposure time (years); $TOW$=time-of-wetness (h/year); $SO₂$=sulphur dioxide concentration ($\mu$g/m³); $Cl$ is chloride deposition rate (mg/m²/day); $T$=air temperature (°C); and A, B, C, D, E, F, G, H, J, $T_0$ =empirical coefficients (Table 5).

Table 5. Coefficients of Eq. (6) calibrated with ISO CORRAG data (Dean & Reiser 2002) for carbon steel and zinc materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>J</th>
<th>$T_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon steel</td>
<td>13.4</td>
<td>0.98</td>
<td>3800</td>
<td>0.46</td>
<td>25</td>
<td>0.62</td>
<td>50</td>
<td>0.34</td>
<td>0.016</td>
<td>20</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.16</td>
<td>0.36</td>
<td>3800</td>
<td>0.24</td>
<td>25</td>
<td>0.82</td>
<td>50</td>
<td>0.44</td>
<td>0.05</td>
<td>20</td>
</tr>
</tbody>
</table>

In order to evaluate the differences among the selected corrosion models, a comparison has been carried out for carbon and weathering steel. The considered corrosivity class is C3 which is characterized, according to EN12500 (Table 2), by a temperate climate, medium pollutant contamination and low chloride influences. The TOW selected levels range from 2500 to 4200, while sulphur dioxides and chlorides have been chosen within class P1 and S1 respectively, as defined in ISO 9223. In Figures 4 and 5 the comparison among selected models and corrosion rates is shown.

A good agreement among standards and selected corrosion models can be observed in the case of weathering steel for both short and long term exposures.

On the contrary, as far as carbon steel is concerned, it can be noted that Standard ISO 9224 underestimates the corrosion loss for both short and long term exposures, as also observed by Albrecht & Hall. With this regard, it should be observed also that the corrosion rates for carbon
The damage models available in literature have been compared with corrosion depth considered by standards, selecting the different influencing parameters in order to simulate similar classes of environmental corrosivity. Comparison performed with standard provisions showed a large scattering of predicted corrosion depth. In particular, with regard to carbon steel, it has been shown that standards underestimate the value of thickness loss.
Of course, the scattering of results influences the reliability of models and the value of related safety factors in a durability design procedure.

The probabilistic characterization of the corrosion development over time, relating the average value of the corrosion depth with the standard deviation, represents the further step of this study. Once the degradation models have been determined, it could be possible to upgrade the ordinary mechanic design with durability based performance design by defining the lifetime safety factors relevant to characteristic service life both for serviceability and ultimate limit states.

REFERENCES


National Physical Laboratory (NPL) UK. Guide to the conservation of metals. http://www.npl.co.uk

1 INTRODUCTION

The service life of new and existing bridges is invariably governed by their fatigue performance. Fatigue, as one major degradation process of steel, is therefore a key issue within the life cycle assessment of steel bridges. Appropriate and efficient fatigue design of various elements and details in bridge structures is thus important but however often a complex procedure. Current fatigue design rules e.g. provide a classification system that allocates structural details to particular S-N curves representing the fatigue resistance of the corresponding detail based on nominal stresses. These design rules combined with present construction guidelines are in many cases inadequate for modern types of bridge structures as they do not offer enough information and possibilities in order to take into account e.g. specific detail arrangements or the use of high strength steels. This paper thus aims to give a short overview of the fatigue design concept for steel and composite bridges according to Eurocode and to summarise some recent research results focusing on several fatigue aspects such as fatigue of high strength steels and post-weld improvement methods, application of advanced fatigue assessment methods e.g. for hollow section joints and headed studs as shear connectors.

2 FATIGUE DESIGN CONCEPT FOR STEEL AND COMPOSITE BRIDGES

The fatigue design of steel and steel-concrete composite bridges is covered in the relevant Eurocode application parts: for steel bridges in EN 1993-2 (2005) and for composite bridges in EN 1994-2 (2005). However, these application parts themselves cover, related to their particular fields, only specific aspects concerning e.g. fatigue loading, whereas for the general fatigue design concept or the fatigue resistance both parts refer to EN 1993-1-9 (2005) as part of the general rules for steel structures.
The fatigue design procedure according to Eurocode is based on the rule of linear damage accumulation in line with Miner’s law. The verification itself can be done using either a general procedure based on a damage verification or a simplified procedure based on a stress verification, see Figure 1. Within the general procedure the fatigue verification should be done using a representative fatigue load model that results in a certain stress history at the specific detail, where then - by using a cycle counting method (e.g. reservoir method) - the design stress range spectrum is determined for the final damage verification, based on a S-N curve for the relevant constructional detail, see Figure 1 left hand side. Since this method is very time consuming for a standard fatigue design process, a simplified fatigue verification procedure, see Figure 1, right hand side, has been set up and included as standard procedure within the code. For road bridges this procedure uses e.g. a simple single vehicle model consisting of 4 axes á 120 kN for determining the relevant fatigue stress range $\Delta \sigma_p$. This stress range is subsequently transformed into the so called equivalent constant-amplitude stress range $\Delta \sigma_{E,2}$ that would result in the same fatigue damage for $2 \cdot 10^6$ cycles as the real design spectrum, provided that the comparison is based on a Miner’s summation. Within the design process $\Delta \sigma_{E,2}$ can easily be calculated using the equivalent factor $\lambda$ that has been derived based on the General Procedure. Knowing the equivalent constant-amplitude stress range $\Delta \sigma_{E,2}$ the fatigue verification can consequently be performed based on a stress level, showing that $\Delta \sigma_{E,2}$ is smaller than the corresponding value of $\Delta \sigma_C$ of the relevant S-N curve.

Figure 1. Fatigue verification procedures according to Eurocode (characteristic level)

According to EN 1993-1-9 (2005) the fatigue resistance is given by a series of 14 standardized fatigue strength curves (S-N curves) for direct stresses and two for shear stresses, each applying to a typical detail category. For direct stresses the S-N curves are defined for detail categories...
ranging from 36 to 160, where the number indicates the characteristic fatigue strength $\Delta \sigma_C$ at $N = 2 \cdot 10^6$ cycles. For direct stresses a two-slope curve with $m = 3$ and 5 is used in combination with a cut-off-limit at $1 \cdot 10^8$ cycles, see Figure 2.

The detail catalogue of EN 1993-1-9 (2005) currently comprises about more than 70 different constructional details.

For composite bridges the fatigue resistance of shear connectors between the reinforced concrete slab and the steel girder is dealt in EN 1994-2 (2005). However, currently the fatigue resistance is only given for headed studs with a detail category of $\Delta \tau_C = 90 \text{ N/mm}^2$ in combination with a rather flat slope of $m = 8$, see Figure 2.

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Figure 2. S-N curves according to Eurocode for the detail of a transverse stiffener and headed studs

The fatigue verification uses the so-called nominal stress which is defined as a stress adjacent to the potential crack location calculated in accordance with elastic theory excluding all stress concentrations. For constructional details that are not covered within the detail catalogue or for which it is difficult to define a nominal stress the fatigue verification can also be done using the hot-spot-stress method, see also section 4.3.

Regarding safety and reliability EN 1993-1-9 (2005) offers the possibility to choose the partial safety factor for fatigue strength $\gamma_M$ between 1.0 to 1.35 depending on the safety concept and the consequence of failure. Thereby it is foreseen to give the designers and the owners the chance to decide by their own where to put the effort in: either by using a low safety factor in combination with a mandatory inspection program or to use a high safety factor without maintenance and inspection.

3 FATIGUE OF HIGH STRENGTH STEELS AND POST WELD TREATMENT METHODS

3.1 High strength steels in bridges

Over the past decades high strength steels (HSS) have gained ground in the market of steel structures. This is because they combine the beneficial properties of a high static yield strength, a low self-weight, a good weldability and a high ductility. However, in welded structures subjected to fatigue, as e.g. bridges, the advantage of the higher static strength can only be exploited in a limited way because slender structures lead to comparatively higher fatigue stresses and the fatigue strength of welded structures does not increase in the same manner as the steel tensile strength. Consequently, the possibility that the fatigue criteria become decisive for the dimensioning of a structure increases with the application of high strength steels.
Within the field of bridge design it has been shown that the application of HSS is likely to be economically interesting especially for the case of composite road bridges Kuhlmann et al. (2006), because of the lower proportion of live load to dead load. These investigations however also showed that in order to achieve a maximum utilization of the higher yield strength of HSS an improvement of fatigue strength is necessary. In general, it is sufficient to improve the fatigue strength at critical construction details locally limited in regions of high stress ranges $\Delta\sigma$.

Very effective methods to enhance the fatigue resistance of welded structures are post-weld treatment methods. However, up to now it has not been possible to apply their positive effects on the fatigue resistance according to missing rules in the present fatigue design standard EN 1993-1-9 (2005).

3.2 Investigations of fatigue resistance of HSS in the as-welded and post-weld treated condition

In order to get a deeper inside into the beneficial effects of post-weld treatment methods on the fatigue resistance, a test program was set up by Kuhlmann et al. (2006) especially focusing on high strength steels. This test program comprised two post-weld treatment methods: first the well-known TIG-dressing method and secondly the relatively new post-weld treatment method called “Ultrasonic Impact Treatment” (UIT), see Figure 3. UIT is a mechanical hammering technique at a frequency of around 200 Hz superposed by a ultrasonic treatment at a frequency of around 27 kHz. These combined impacts result in plastic deformations at the treated surface leading to beneficial compressive stresses in the surface layer and a smoothening of the weld toe transition.

![weld toe before and after TIG-dressing](image)

![UIT tool and application](image)

Figure 3. Post-weld treatment methods

The overall test program comprised about 250 small scale specimens and 12 large scale girder tests. Within the experimental test program various aspects, e.g. the steel grade S355, S460 and S690, the post-weld treatment condition, the stress ratio as well as the plate thickness were varied. All investigations took place on the constructional detail of a transverse stiffener, as it was found out in the aforementioned investigations, that this detail is typically located in critical sections of steel and composite bridges.

The results of the tests showed that for all steel grades the application of post-weld treatment methods leads to a considerable improvement of the fatigue resistance, especially in the region of high-cycle fatigue. For steel grade S460 some test results are shown in Figure 4 in form of S-N curves as mean life lines obtained by a linear regression analysis. The tests were conducted with a constant amplitude fatigue loading on a stress ratio of $R = 0.1$. One can see that in comparison with as-welded state the beneficial influence of a post-weld treatment method on the fatigue strength can be represented by a transition and/or a rotation of the fatigue resistance curve. Regarding the fatigue strength at $2 \times 10^6$ cycles and compared to the as-welded state an increase of about 50% could be achieved by applying TIG-dressing and increase of about 80% when applying UIT.

Concerning the UIT method it could further be observed that the fatigue resistance increased with increasing yield strength. The improvement of the fatigue strength for the steel grade S690 was even so high, that the failure of the specimens did not occur anymore in the region of the weld but moved in the base material, see Figure 4.

Based on the experimental test program and additional numerical simulations within the thesis of Dürr (2006) it was finally possible to derive simple design recommendations for the application of the UIT method on the construction detail of the transverse stiffener. According to
these recommendations, the fatigue strength for the as-welded state can be improved by one detail category for the steel grade S355, by 2 detail categories for the steel grade S460 and by 3 detail categories for the steel grade S690, in combination with a change of the slope of the fatigue strength curve from $m = 3$ to $m = 5$.

Figure 4. S-N curves and test specimen with base material failure

4 FATIGUE OF WELDED CIRCULAR HOLLOW SECTION JOINTS

4.1 General

The application of circular hollow sections (CHS) in highway-bridge design is relatively new. For about 15 years steel-concrete composite bridges including CHS trusses have developed as an innovative and aesthetic alternative to conventional all-steel bridges. Outstanding examples are the bridges of Lully (1997) and Dättwil (2001), both Switzerland.

CHS trusses with diagonals and without verticals have turned out to be most efficient. In this case the braces run at an angle of 45° to 60° toward the continuous bottom chord forming K-joints in planar trusses and KK-joints in spatial trusses. The top chord (in case of spatial trusses: the two top chords) may be integrated within the concrete slab of the bridge, see Figure 5.

Figure 5. Composite bridge with KK-joints and hot spots of a welded joint (FE-plot)

4.2 Truss joints

From the viewpoint of economics and ease of construction it is preferable to weld the braces directly to the bottom chord. The resulting welded joints lead to high stress concentrations (hot-spot stresses) because of the coincidence of the metallurgical discontinuity due to the weld and the stress-rising effect caused by the geometrical intersection of the truss members. Therefore, welded joints demand a precise adjustment of design, fabrication and quality assurance.
In cast-iron joints the welds are located outside the critical chord-to-brace intersection and are of simpler shape. Aside of the economical aspect one disadvantage of cast iron compared to welded joints is that the bottom chord is cut for each joint twice. That may cause a drawback on the reliability of the entire structure.

4.3 Verification

The fatigue verification of cast iron joints is generally based on the S-N method providing that the detailed joints are covered by an existing detail category. The influence of backing rings, scale effect etc. has to be taken into account. Eventually, the nominal stresses have to be modified accounting for offsets etc. In order to verify a welded CHS joint the S-N method does not suffice any more because no nominal stress can be defined. Due to the non-uniform and complex stress field in proximity of the weld along the brace-to-chord intersection the more sophisticated hot-spot stress method has to be performed. For more than 30 years positive experiences have been gathered in off-shore structures using this method.

The hot-spot stresses can be computed by a Finite-Element analysis. This approach requires a sufficient expertise of the analyst and is rather time spending. The application of stress concentration factors (SCF) can be considered as a facility. The SCF are highly dependent on the so-called non-dimensional geometrical parameters (for example: ratio of brace and chord diameter, ratio of wall thicknesses etc.). Unfortunately, highway bridges fall out of the application range of current design specifications such as CIDECT etc.

Highway-bridge specific SCF for K-joints are given in Schumacher (2003). In contrast to K-joints, SCF for KK-joints are not available in tables for the adequate range of geometrical parameters typical of highway bridges. In an on-going research project fostered by the German federal authority Bundesanstalt fuer Strassenwesen highway-bridge specific SCF-tables are set up. The underlying approach is based on Schumacher (2003). In addition construction rules will be summarised.

5 FATIGUE OF COMPOSITE BRIDGES WITH HORIZONTALLY LYING SHEAR STUDS

5.1 General

Regarding composite bridges, the fatigue behaviour of the shear connections devices, which are in most cases headed studs, are of major importance. While a lot of research has already been done on headed studs in a normal vertical position, till now only few knowledge is available on headed studs in a horizontally lying position.

In comparison to normal vertical headed studs, horizontally lying headed studs feature a small edge distance $a_e$ of the headed stud to the concrete surface. Depending on the load direction parallel or orthogonal to the free concrete edge the behaviour and resistance are different. They allow for new interesting cross sections and applications, see Figure 6.

Numerous experimental and numerical investigations e.g. in Kuhlmann & Kürschner (2006) lead to design rules for static resistance for both load directions and furthermore for fatigue resistance under longitudinal shear which meanwhile have been implemented in EN 1994-2.

The resistance is influenced by the reinforcement. Therefore beside the load direction the resistance is specified depending on the effective edge distance $a'_e$, see Figure 6. With decreasing of the effective edge distance cracking of the concrete becomes more important and stud failure is dominated by the concrete cracking.

![Figure 6. Loading of horizontally lying headed studs and geometrical parameters](image-url)
5.2 Investigations on the fatigue strength under transverse loading

Substantial fatigue loads in vertical direction derive from concentrated loads like wheel loads, see Figure 6. Two test series on push-out specimens with different effective edge distance $a_e$ were performed to investigate the influence of the effective edge distance $a_{er}$. The specimens were loaded with a constant amplitude load range at similar maximum load levels and different load ranges.

The existing experiences concerning the fatigue behaviour of headed studs only show shearing of the studs as stop criterion. Contrarily, in these tests three different failure modes occurred. Some specimens failed by shearing of the studs, too. But most specimens failed by concrete outbreak. Two specimens showed a fatigue failure of the reinforcement. In both cases one stirrup failed in the upper bend.

Contrary to headed studs without an edge influence only a slight concrete crushing at the weld collar could be observed. Concrete cracking at an early stage is essential for the fatigue behaviour. The resulting increasing slip causes bending in the stud shank.

A statistical evaluation comes to S-N curves for the 95%-fractile. A comparison with the fatigue strength of headed studs without edge influence is given in Figure 7. The effective edge distance $a_{er}$ obviously has a significant effect on the fatigue strength which is lower as the fatigue strength of headed studs without an edge influence.

![Fatigue strength comparison](image)

Figure 7. Comparison of the fatigue strength of horizontally lying studs under vertical loading and headed studs without edge influence and typical failure mode

5.3 Residual static resistance

The design code EN 1994-2:2005 gives rules to determine the static resistance of headed studs independently from the fatigue strength. This implies the assumption that the entire static resistance is valid over the whole life time. The design rules are derived from push-out tests which use shearing of the studs as failure mode. A crack may appear much earlier. This leads to the question whether a separate determination of the static resistance and fatigue strength may lead to unsafe results.

First systematical investigations were made by Oehlers (1990). To this day Hanswille et al. (2007) carried out the most comprehensive test program concerning this topic. With increasing number of cycles there is a decreasing residual static resistance observed.

To investigate the residual static resistance for horizontally lying shear studs under vertical loading a further test series has been performed. After a variable range of load cycles the different test specimens were tested statically in controlled manner. Although there is a slight decreasing residual static resistance with increasing number of cycles, all specimens exceeded the expected static resistance on mean level. Despite the great residual static resistance the headed studs showed remarkable fatigue cracks.

The high residual static resistance of horizontally lying shear studs under vertical loading after a high cycle preloading may be explained with the low resistance of the concrete for a mere static loading. As for horizontally lying shear studs under vertical shear concrete failure limits
the static loading decisively, the utilization of the partially cracked stud sections under cyclic loading is not very high and allows for a higher residual strength compared to studs without an edge influence.

6 SUMMARY

Fatigue is a major aspect within the design and maintenance of bridges during the whole life time. The current fatigue design procedure for steel and composite according to the Eurocodes offers a quite up to date concept including e.g.: - different verification procedures ranging from simplified to quite sophisticated, - different safety concepts taking into account the owner’s strategy concerning maintenance and inspection and - a detail catalogue with more than 70 different constructional details that allows in most cases a proper and durable design over the whole life time. All these are vital elements with regard to a sustainable engineering.

However, modern trends within the design of steel and composite bridges take place in the area of lightweight, slender and aesthetically attracting structures, e.g. by using high strength steels, hollow section joints or new shear connection devices for composite bridges. In this context an overview of ongoing research work has been presented showing that: - the application of high strength steels in combination with the allowance of modern post-weld treatment method is very beneficial in order to reduce the self-weight and thereby the vast of natural resources, - the application of circular hollow sections leads to very economical and durable bridge structures, when refined methods are used that allow for a proper fatigue design of welded joints, and that - the existing regulations concerning the fatigue resistance of shear connection devices in composite bridges have to be modified in order to take into account e.g. the position and loading direction of the headed stud (horizontally lying studs).

REFERENCES


Durability assessment modeling of reinforced concrete elements

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ABSTRACT: In this paper, the construction components, the durability of which is under study, are the concrete elements. In the first part of the paper, the connection between the deterioration of concrete elements and the moisture conditions inside them is stressed and some basic information about the methods used for the calculation of moisture profiles in construction elements are presented. The second part of the paper refers to deterioration mechanisms affecting the concrete elements’ durability. A short overview of deterioration processes is given and there is a focus on chloride initiated corrosion. In the last part of the paper, the probabilistic methods for durability assessment of reinforced concrete elements are presented.

1 INTRODUCTION

The assessment of construction components’ and materials’ durability has been the objective of many studies and extensive research projects, since it is an essential step towards the prediction of the components’ and the construction’s (as a whole) life duration. The durability of a construction material can be described as its ability to withstand deterioration caused by environmental conditions (Rendell et al. 2002). A measure for a material’s durability is usually the time until the material deteriorates to a limit level of functionality, beyond which its performance is not acceptable. This minimum level of performance, when durability assessment is concerned, is usually identified with regard to the main purpose that a material is supposed to serve in the component or the construction itself. In this context, the usual approach for the assessment of the concrete’s durability is to consider the limit levels of performance with regard to its strength. Similarly, a component’s or an element’s durability expresses its ability to maintain through time, and subjected to environmental conditions, its performance above or at an acceptable level.

The durability of construction materials and components is closely related to the sustainability of the construction itself. Indeed, sustainability in construction, as it is currently viewed, extends far beyond the sole consideration of energy and resources consumption during the operation of a construction and embraces every aspect of a construction’s operation and every stage of its life cycle. Among the issues that are related to the sustainability of construction are the maintenance, the repair and the replacement of its components. It is now clear how durability of construction components is related to sustainability of constructions. Durable constructions lead to a much smaller need for repair or even replacement of various components. Consequently, the cost and the resource consumption for such interventions is noticeably reduced. Furthermore, the multi-level cost resulting from repeated interruptions of the construction’s function (that is sometimes necessary for the repairs to be done) is also reduced. Also, a reliable durability assessment would lead to well-programmed, timely inspections and interventions.
2 DURABILITY OF CONCRETE ELEMENTS AND ENVIRONMENTAL CONDITIONS-
CALCULATION OF HYGROTHERMAL PROFILES

2.1 Introductive discussion

Every construction and, consequently, all of its components are exposed to the environmental
conditions of the region where it operates. The air’s temperature and relative humidity ranges,
extreme values and fluctuations are decisively influencing, among others, the levels, as well as
the fluctuations, of temperature and moisture on the surface and inside the construction ele-
ments. Furthermore, events such as repeated rainfalls and snowfalls, as well as extended dry pe-
riods, can drastically alter the hygrothermal conditions on the surface and inside construction
components.

The levels of moisture on the surface and inside a construction component are of decisive
importance for its life duration. Indeed, the water that is accumulated inside a construction
component and the periodic variations of a construction’s element water content are strongly
related to numerous materials’ deterioration mechanisms. Water inside or on the surface of a con-
struction element can act either directly, being the main aggressive agent, or indirectly, facilitat-
ing the action of other degradation mechanisms and factors and accelerating the progress of
numerous deterioration processes (Fagerlund 1996). There are many types of destructive proc-
cesses, in the context of which water is the direct aggressive agent. Frost attack on several con-
struction materials and components (masonry, concrete elements, etc.) and mould growth
(mainly on wood but sometimes observed on surfaces with different substrate) can be listed in
this category of deterioration processes. The types of destruction in the progress of which water
holds a supporting role are also numerous. Chemical attacks on natural stones and dissolution of
corrosive substances can be mentioned as examples.

Similarly, water in reinforced concrete elements contributes to the initiation, propagation and
acceleration of various deterioration mechanisms. Apart from the frost attack, that has already
been mentioned, the corrosion of the reinforcement bars is a process in which water has a major
contribution. The rate of the chloride ion diffusion, the time needed for the carbonation of the
concrete cover, as well as the propagation of the bars’ corrosion are all influenced from the

2.2 Analysis of construction components’ hygrothermal performance

The analysis of construction components’ hygrothermal performance is based on the calculation
of the simultaneous heat and moisture transport through and inside these elements. During the
last decades, a lot of methods have been developed for the solution of this problem. At first, the
proposed methods employed several, and sometimes crude, simplifications and assumptions
(assuming steady-state flows and invariable material properties, not taking into account several
heat and moisture transport mechanisms in the formulation of the model, etc.). As the scientists
were gaining more knowledge on the subject and as the calculating capacity provided by the
developing computer systems was growing, the models formulated for the simulation of the si-
multaneous heat and moisture transport through and inside construction components were be-
coming more sophisticated and accurate.

Nowadays, there are numerous such methods the use of which provides reliable results. The
ones that perform calculations assuming unsteady flows (dependence on time and space) are
thought to simulate more accurately the dynamic nature of the problem. These methods usually
calculate the simultaneous heat and moisture transport through and inside construction compo-
nents by solving a set of two coupled partial differential equations. The one of these equations
is the mathematical formulation for the heat transport and the other one is the mathematical
formulation for the moisture transport. They are frequently based on conservation principles
(energy and mass respectively). A set of boundary and initial conditions is required for this sys-
tem to be solved. The calculations are usually performed on the basis of the discretisation of the
calculation domain (using methods such as finite elements method, finite difference method,
etc.) and on the consideration of sufficiently small time steps. The solution for each time step is
acquired with the use of an iterative method.

The heat transport mechanisms that are taken into account in various methods are thermal
conduction, latent heat of evaporation/ condensation, radiation, etc. The moisture transport
mechanisms that are taken into account in various methods are vapour diffusion, capillary conduction, surface diffusion etc.

Of course, the lately developed methods and tools do not all have the same characteristics. In fact, they have major differences in the transport mechanisms and phenomena (e.g. convection, latent heat of phase change etc.) that they are taking into account, in the mathematical model they use (e.g. the driving potentials for the moisture transport equation), in the consideration or not of the materials’ properties dependence on their water content, etc. Another aspect of the calculations that varies from case to case is the dimensions (in space) of the analysis performed. For example, there are tools that perform an one dimensional analysis of the simultaneous heat and moisture transfer processes in construction components (WAND, WALLDRY, WUFi Pro 4.0, 1-D hygIRC, MOIST 3.0, GLASTA, 1-D HAM (Hagentoft & Blomberg 2000), MATCH, etc.) and others that extend to two dimensions (WUFi StOpStar, Latenite-VTT (Geving et al. 1997), etc.). There are also tools that perform a 3-d calculation. An overview of building components’ hygrothermal performance analysis tools can be found in (Canada Mortgage and Housing Corporation).

3 MECHANISMS OF DETERIORATION OF CONCRETE

3.1 Introduction

Deterioration of concrete elements is a normal consequence of the ageing process. However, a number of parameters like the quality of construction, the climatic conditions, or the lack of maintenance, can greatly influence this process. The following mechanisms will be briefly introduced in this chapter: (1) freeze-thaw deterioration, (2) deterioration due to aggressive chemical exposure and (3) reinforcement corrosion. Deterioration mechanisms are discussed with measurements taken at the Krk Bridge in Croatia. This is the largest conventional reinforced concrete arch bridge in the world completed in 1980 and set in very aggressive maritime environment (Adriatic sea salinity is 3.5%) with frequent high wind carrying sea-salt and spray ing exposed concrete elements.

3.2 Freeze-thaw deterioration

Freeze-thaw deterioration is due to repeated cycles of freezing and thawing of water contained within the concrete matrix. Damage is due to expansion that occurs when water is converted into ice, as this will cause forces exceeding the tensile strength when concrete is critically saturated. Additionally, smaller pores will be more or less freeze-dried by the ice in the larger pores, and consequently the ice in the larger pores will grow. If temperatures subsequently rise, the ice will expand and due to the five times larger temperature expansion coefficient of ice than concrete, it will exert force (Bijen 2000). Surface deterioration will occur in form of spalling, scaling and cracking, leading to loss of structural strength and integrity. Freeze-thaw damage is aggravated by the use of de-icing salts. Salts lower the freezing point and due to hygroscopic character increase the water content of the pores.

The temperature on the Krk Bridge drops below 0°C 10 to 15 times during winter period. Testing core samples taken from the concrete cover showed failure after only 50 freeze-thaw cycles. It should be noted that the concrete cover is of compressive strength above 75 MPa and is contaminated with chlorides. Only 3 samples showed resistance to 300 cycles, but with 50% reduction in strength, and a single sample not contaminated with chlorides kept the strength after 300 cycles (IGH 2000).

Measures to prevent freeze-thaw deterioration include air-entrainment, use of frost-resistant aggregates, low water/cement ratio and surface treatment with hydrophobic agents.

3.3 Deterioration due to aggressive chemical exposure

Chemical attacks may be categorized in four types: (1) acid, (2) sulphate, (3) alkali and (4) other.
Acid attack is due to reaction of acid with cement paste. The consequence of this reaction is that the layer by layer conversion of the hardened cement and destruction of microstructure. If not removed, converted layer is more permeable than sound concrete. Reaction products are removed by dissolution or abrasion. Once the cement paste is removed, exposed or loose aggregate remains, and eventually total disintegration will occur. Acid attack weakens the structure, and can thus contribute to other deterioration mechanisms. For instance, the removal of concrete cover can lead to steel reinforcement corrosion in concrete. Acid attack may be caused by atmospheric pollutants (i.e. acid rain), or gaseous acids (i.e. sour gas in a sewer pipe).

Sulphate attack (Skalny J. et al. 2002) is due to sulphates reacting with calcium and aluminate ions. The reaction causes expansion and formation of cracks, thus speeding up the deterioration process, as cracks allow further sulphate penetration. As with acid attack, the sulphate attack can also lead to other deterioration mechanisms, as it damages the concrete cover.

Alkali attack (Swamy 1992) is due to alkalis reacting with silica aggregates. The reaction causes expansion and leads to surface “map” cracking.

The permeability of concrete is a critical measure to prevent the deterioration of concrete due to chemical exposure. Mix design should be appropriate to exposure of the concrete element. Remediation generally comprises the repair and removal of damaged concrete and application of a protective surface treatment.

3.4 Reinforcement corrosion

New concrete is highly alkaline (pH between 12.5 and 13.5) and steel reinforcement appears to passivate in such environment with a formation of $10^{-3}$-$10^{-1}$ µm thick layer (Baroghel-Bouny et al. 2007) of iron oxides and hydroxides which prevents further corrosion. Depassivation occurs due to two processes: (1) carbonation and (2) chloride attack.

Carbonation is a reaction of the carbon dioxide penetrating the concrete with hydrated cement paste in the presence of water. The reaction occurs at the water-air frontier in the pores and is thus strongly linked to the drying of concrete (Bijen 2000). The reaction transforms hydration products into calcium carbonates (CaCO$_3$), and due to consumption of the base reserve, the alkalinity of concrete is lowered to around pH 9, when steel will no longer be passivated. Factors accelerating the carbonation are high water-cement ratio, cements with low initial strength, cements with slowly reacting pozzolans and latently hydraulic agents (powder coal fly ash and blast furnace slag) and poor curing practice. The rate of progress of the carbonation front decreases with time. It should be noted that carbonation decreases the porosity of concrete which increases the strength and modulus of elasticity. Some authors (Baroghel-Bouny et al. 2007) report that the mechanical properties of concretes containing the blast furnace slag cements deteriorate after carbonation as their porosity increases. However, the Krk Bridge in Croatia experienced an increase in compressive strength of concrete after 25 years of service, from around 40 MPa to around 75 MPa. Cement used for the Krk Bridge contained around 20% of blast furnace slag.

Chloride attack, unlike carbonation, does not induce the overall decrease of pH. Chloride ions destroy the passivation layer locally. Chloride ions penetrate the concrete, or can be present in the concrete due to use of salt water or contaminated aggregate for mixing the concrete. If the concrete is saturated with water, chloride ions penetrate the concrete by diffusion. If the concrete is in tidal or spray zone, the chlorides penetrate the concrete by capillary absorption and migrate with liquid phase by convection. Chloride ion penetration is affected by the cement type used, temperature and curing practice (porosity). For instance, due to use of blast furnace slag cement in the Krk Bridge the chloride penetration has been slowed down significantly. Thus, the main reinforcement has not corroded yet in spite of very small concrete cover (designed 2.5 cm, executed 1-4 cm). Chloride concentration profiles depending on concrete cover depth, location of the concrete element with respect to sea level, and exposure time are shown in figure below (Beslac et al. 2007).
Once the passivation layer is dissolved, the corrosion propagation starts. Corrosion (Broomfield, 1997, Raupach et al. 2007) is electrochemical mechanism requiring presence of ions in aqueous phase in contact with the metal. Carbonation leads to uniform corrosion with gradual reduction in steel cross-section. Corrosion products are of substantially larger volume than steel, leading to expansion and tensile stresses in concrete cover and finally to cracking parallel to the reinforcement and spalling of concrete cover. Chloride ions lead to localized corrosion (pitting). The pit acidifies and attracts chloride making the micro-environment even more corrosive.

On the Krk Bridge there are locations where the chloride ion concentration has reached the threshold level of 0.4% on cement mass, meaning that the reinforcement corrosion has entered the propagation period. Chloride ion concentrations differ significantly depending on the location relative to the sea level, but also on the surface orientation due to wind turbulences at the specific location. The corrosion process on the Krk Bridge is accelerated by relatively high moisture conditions, high temperatures during summer and occasional freezing temperatures during winter. Frost is weakening transition zone between cement stone and coarse aggregate, and increases the diffusion coefficient. Since the concrete quality is high, the corrosion damage appears mainly due to insufficient depth of concrete cover or errors of design and construction (Radic et al. 2005).

4 PROBABILISTIC DURABILITY ASSESSMENT METHODS

4.1 Probabilistic methods for durability assessment of reinforced concrete elements - General overview

Generally, two different approaches to the durability assessment of deteriorating structures can be distinguished: (a) approach based on implicit rules and modification factors, (b) approach based on the mathematical models of degradation.

In contemporary standards (EN 1990 Eurocode, 2002, ISO 2394:1998 (E)) the required performance during the intended service period under the influence of degradation factors is usually formulated by means of states of a structure that should be avoided, namely: carbonation, leaching and abrasion of concrete, corrosion of reinforcing steel, corrosion cracking and spalling of concrete cover, etc.

Mathematical modeling of reinforced concrete elements deterioration is based on the Fick’s laws of diffusion that control the aggressive media penetration of concrete, and the model of rust products expansion that control initial cracking, evolution of cracks and concrete spalling. These models are used to calculate the time to initiation of reinforcement corrosion and the time to critical deterioration of reinforced concrete elements. Deterioration mechanisms are treated in that cases in similar way to mechanical failure mechanisms.

Due to the uncertainty in prediction of the external and internal environmental influences and the material’s properties as well as probabilistic format of contemporary design code, the use of
the probabilistic models seems to be essential for realistic assessment of reinforced concrete elements durability.

By quantifying durability performance, the reliability measures could be set to make sure of the reliability level by means of:

- partial safety factors $\gamma_m = R_k / R_j$ and $\gamma_f = S_d / S_k$, where: $R_k, S_k, R_j, S_d$ are characteristic and design values of material properties and actions,
- reliability index $\beta = m_Z / \sigma_Z$ where: $Z = R - E$ is a performance function, $R$ is the resistance, $E$ is the action effect, $m_Z$ and $\sigma_Z$ are the mean value and the standard deviation of a random variable $Z$,
- probability of survival $q_f = 1 - p_f = 1 - \int_{F} f(z) \, dz$, where $p_f$ is the probability of failure and $F$ is a failure domain.

Within the Partial Factors Design the effect of deterioration of structural components is usually considered by multiplying the partial safety factor $\gamma_R$ by modification factors corresponding to different types of deterioration processes and the degree of knowledge about the future degradation (Faber & Melchers 2001):

$$\gamma_R = \gamma_{R_0} \times \varphi_D \times \varphi_p \times \varphi_M$$  

where: $\gamma_{R_0}$ is the initial value of partial safety factor corresponding to a certain design service life and a specific safety class, $\varphi_D, \varphi_p, \varphi_M$ are the modification factors corresponding to a given deterioration process, protection and maintenance strategy, respectively.

Using the reliability index measure $\beta$, the influence of uncertainty can be taken into consideration by means of the resistance correction (Faber & Melchers 2001, Thoft – Christensen 2000):

$$\beta = \frac{\varphi_1 \times \varphi_2 \times \ldots \times \varphi_n \times m_R - m_E}{\sqrt{(\varphi_1 \times \varphi_2 \times \ldots \times \varphi_n)^2 \times \sigma_R^2 + \sigma_E^2}}$$

where: $m_R, m_E, \sigma_R, \sigma_E$ are the mean values and standard deviations of the resistance and action effects, $\varphi_1, \varphi_2, \ldots, \varphi_n$ are correction factors.

When the mechanisms of deterioration are known in advance and can be expressed in the form of degradation function $g(t)$ describing evolution of the structural deterioration in course of time, the time-variant resistance $R(t)$ may be defined by:

$$R(t) = R_0 \times g(t)$$

where $R_0$ is the initial resistance, and the full probabilistic approach to durability assessment may be applied. Preventive and mitigating measures can also be introduced by differentiation the time of degradation initiation, and the maintenance or repair may be taken into account by modification of the initial resistance.

Generally, the resistance $R$ of an element and the effect of actions $E$ are the stochastic process of random variables $X_i, Y_j$ and time $t$: $R(X_1, X_2, \ldots, X_n, t), E(Y_1, Y_2, \ldots, Y_m, t)$, thus the performance function is also the stochastic process $Z = R - E = Z(X_1, Y_j, t)$. The direct calculations of the failure probability from the integration of equality $p_f = \int_{F} f(z) \, dz$, using analytical integration can only be eligible in few simple cases and numerical integration is feasible only for a limited number of random variables (Karadeniz & Vrouwenvelder 2003). Time dependent failure modes may in some cases be transferred into corresponding time independent mode. There are known several methods of such a transformation (Karadeniz & Vrouwenvelder 2003).

Application of the simulation-based Monte Carlo method makes possible to obtain approximate solutions in case time-variant problems, highly nonlinear performance functions, unknown
in advance area of integration and large number of random variables taken into account (Marek et al. 2003). Risk is a measure of the danger or hazard that undesired events represents for people, economy and environment, and can be defined as a combination of the probability of occurrence and the consequence of a specified hazardous or undesired event. The risk associated with a hazard of corrosion deterioration may be considered an alternative measure of reinforced concrete structures durability (Woliński 2006).

4.2 Some new strategies and methodological approaches on the probabilistic integrated safety and durability prediction in sustainable structural design practice.

The time-dependent quality of structures may be closely defined only by quantitative durability parameters using available probabilistic approaches, concepts and methods (Kudzys 1992, ISO 2394:1998 (E), Melchers 1999).

The intention of this paragraph is to recommend some new strategies and methodological approaches on the probabilistic integrated safety and durability prediction in sustainable structural design practice.

4.2.1 Long term survival probability of members

The structural members (beams, slabs, columns, walls, joints) of buildings and civil engineering works are represented in design practice by their particular members (normal or oblique sections, connections) for which the only possible failure mode exists. According to probability-based approaches (design level III), the time-dependent safety margin as the performance of deteriorating particular members may be presented as follows:

\[ Z(t) = g [\boldsymbol{0}, \mathbf{X}(t)] = \theta_\mathbf{R}(t) - \theta_\mathbf{S}_g - \theta_\mathbf{S}_q(t) - \theta_\mathbf{S}_w(t) + \theta_\mathbf{S}_n(t) \]  \hspace{1cm} (4)

where \( \mathbf{X}(t) \) is the vector of basic variates; \( \theta \) is the vector of additional variables characterizing uncertainties of models which give the values of resistance \( R \), permanent \( S_g \), sustained \( S_q \) and extraordinary \( S_w \) service or snow and extreme wind \( S_n \) action effects of members (Fig. 2a).

Figure 2. Real (a) and conventional (b) models for safety analysis of particular members of deteriorating structures
This vector may represent also the uncertainties of probability distributions of basic variables.

\[ R(t) = \eta_m R_{ld}(t) \phi(t) \]  

(5)

is the member resistance process, where \( R_m \) is its resistance at the initiation period of deteriorating structures; \( \eta_m = R_{mid}/R_m \) is the factor of latent defects; \( \phi(t) \) is the resistance degradation function (Enright & Frangopol 1998).

The variable action effects may be treated as rectangular renewal pulse processes. The time dependent safety margin (4) may be expressed as the finite rank random sequence as follows:

\[ Z_k = R_{ck} - S_k, k = 1,2,...,n-1,n \]  

(6)

There

\[ R_{ck} = \theta_k R_k - \theta_k S_k \]  

(7)

\[ S_k = \theta_k S_k - \theta_k w_k S_k \text{ or} \]  

\[ S_k = \theta_k S_k - \theta_k w_k S_k \]  

(8)

are the conventional resistance and action effect of members at k-th cut of this sequence; \( n = \lambda t \), is the number of sequence cuts as critical events (situations) during design working life, \( t \), of members (Fig. 2), where \( \lambda = 1/\text{t} \) is a mean renewal rate of these events per unit time when their return period is \( t_k \). When \( R_{ck} \) and \( S_k \) are statistically independent, the instantaneous survival probability of the member at k-th extreme event, assuming that it was safe at the events 1, 2,..., k-1, is:

\[ P_k = P(t_k) = P\{g[\theta(X(t_k))] > 0\exists t_k \in [t_1,t_n] = P\{R_{ck} > S_k\} = \int_0^\infty f_{R_{ck}}(x)F_{S_k}(x)dx \]  

(9)

where \( f_{R_{ck}}(x) \) is the density and cumulative distribution functions of \( R_{ck} \) by (7) and \( S_k \) by (8), respectively.

The cuts of random sequences of safety margins of members must be considered statistically dependent. The time-dependent survival probability of members may be calculated by Monte Carlo simulation and the numerical integration methods. However, it is more reasonable to use the method of transformed conditional probabilities. The resistance is non-stationary process, therefore the survival probability of members may be written in the form:

\[ P_i = P[T > t_i] = P\left\{\bigcap_{k=1}^{n} Z_k > 0\exists Z_k \in [Z_1,Z_n]\right\} \approx \prod_{k=1}^{n} P_i \left[1 + \rho_{ak,...ak} \left(\frac{1}{P_{ak}} - 1\right)\right] \times \left[1 + \rho_{a1,...ak} \left(\frac{1}{P_{a1}} - 1\right)\right] \times \left[1 + \rho_{a1,a2} \left(\frac{1}{P_{a1}} - 1\right)\right] \]  

(10)

where \( P_i \) is the instantaneous survival probability by (9); \( \rho_{ab} = \text{Cov}(Z_a,Z_b)/(\sigma Z_a \times \sigma Z_b) \) is the coefficient of correlation of rank sequence cuts the correlation factor of which is \( \rho_{n,n-1,...1} = (\rho_{n,n-1} + ... + \rho_{n})/(n-1) \); where \( \text{Cov}(Z_a,Z_b) \) and \( \sigma Z_a, \sigma Z_b \) are an auto-covariance and standard deviations of these cuts; \( a_k = 4.5/(1 + 0.98\rho_{ak-1,...1}) \) is the bond index of this factor.

The generalized reliability index \( \beta_i \) of members as the inverse Gaussian distribution of their survival probability \( P_i \) is defined as:

\[ \beta_i = \Phi^{-1}(P_i) \]  

(11)

the components of the other orientations. This fact explains the results that were presented above.

4.2.2 Probabilistic models in technical service life prediction

The technical service life \( t_r \) or the time in survival of structural members without major repair at a target reliability index \( \beta_{\text{min}} \), is the main durability parameter for members of deteriorating sustainable structures. The target reliability index \( \beta_{\text{min}} \), as basis in sustainable durability and
safety predictions, must be related to the failure consequences and functional working classes of structural members (Table 1).

Table 1. Failure consequences and functional working classes of structural members.

<table>
<thead>
<tr>
<th>Consequence class</th>
<th>Functional working class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FC1</td>
</tr>
<tr>
<td>CC1</td>
<td>3.1</td>
</tr>
<tr>
<td>CC2</td>
<td>3.3</td>
</tr>
<tr>
<td>CC3</td>
<td>3.8</td>
</tr>
</tbody>
</table>

The values presented in the Eurocode EN 1990 correspond to the members of the functional working class FC2. It is expedient to correct these directions. Besides, the index \( \beta_{\min} \) may be reduced for existing or overloaded structures under construction since premature failures cannot be any longer caused by rough human designers to achieve a higher quality and economy of structures.

Figure 3. Determination of structural element technical service life \( t_t \) using the time-dependent reliability index curve.

The technical service life \( t_t \) as a quantitative durability parameter of deteriorating members may be calculated from Equation (10). The computation is iterated until the value \( t_t \) corresponds the target probability \( P_{t,\min} = \Phi(\beta_{\min}) \) (Fig.3).

5 REFERENCES


Systematic monitoring of civil structures

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**ABSTRACT:** Monitoring techniques develop rapidly due to enhancements in the field of sensor technology, data acquisition and transmission, storage capacity and evaluation methodologies. Furthermore, the acceptance by building owners increases because monitoring becomes an efficient instrument to reduce inspection and maintenance costs and it helps to extend significantly the service life. However monitoring activities yield only to reasonable results if the monitoring concept is coherent and the aims of the campaign are clearly defined. That comprehends that the consequences arising out of the monitoring results are treated with a well-defined package of measures. This contribution regards the general aspects of monitoring outlining how a systematic approach in terms of monitoring civil structures is achieved. In addition two projects currently conducted by the authors are presented to outline the wide application area of monitoring activities. The first example deals with two concrete bridges in Croatia, which are set in highly aggressive maritime environment. They are equipped with monitoring systems to observe the structural behaviour and the environmental influence to facilitate bridge maintenance during service. Within the second example a monitoring campaign of a filler beam railway bridge in Germany is presented. The medium span bridge is part of a high-speed line, which allows for velocities up to 250 km/h. The aim of this campaign is to get more information about the dynamic system behaviour and to improve the current design concept.

**1 INTRODUCTION**

**1.1 Definition of Monitoring**

The technical monitoring focused on in this paper is defined as the observation of parameters or a process with the use of technical tools. Monitoring differs from a measurement as monitoring is a goal-oriented activity. By installing a monitoring system a special aim in a campaign is intended to be achieved. Therefore, depending on the monitoring results, the monitored process has to be modified if it does not develop as desired. If it is not possible to change the process other measures must be initiated.

Monitoring activities can be divided into different categories. Carrying out a representative monitoring means to monitor one single object, which is “representative” for similar details or structures. It is assumed, that the behaviour of the monitored object is analogue to the behaviour of the other structures.

In contrast to the representative monitoring an individual monitoring is limited to draw conclusions for the monitored object only, e.g. due to unique boundary conditions.

Further monitoring can be differentiated in the time range of a monitoring campaign. Long-term monitoring is carried out permanently or in intervals. Short-term monitoring is performed to observe a process during a special event, e.g. the monitoring of bridge deflections due to one abnormal heavy load to avoid collapse.
1.2 The advantages of technical innovations

The quality of the technical monitoring depends highly on the quality of the used devices and evaluation methodologies. The development in these fields is enormous and the costs of high-end technologies decline more and more. It ranges from powerful sensors and GPS tools to laser or robotic theodolit devices, which are only few examples for the huge amount of modern monitoring tools available, see e.g. (Feltrin et al. 2004). Furthermore storage capacities and data transmission standards like UMTS simplify the data management. New evaluation methodologies like output only methods for system identification provide considerable advantages within the post processing.

The possibilities in the field of engineering by using these new techniques are extensive. The number of engineers, who wants to benefit from these varieties, increase extensively, too. Therefore it gets more and more important to prove whether a monitoring campaign is the best answer to a problem related to a civil structure (see e.g. Hechler et al. 2006). Even if monitoring is cheaper than in the past, the monitoring concept needs to be coherent and the aims of the campaign must be clearly defined.

1.3 Applications

The applications for the monitoring of civil structures range from damage detection, observing sensitive system parameters and checking design assumptions to acquisition of structure relevant statistical data like fatigue data, climate data or load characteristics. Some examples are given in Table 1.

In the last decade structural health monitoring (SHM) has become very popular. Often it is used as an instrument to estimate the structural effects of earthquakes and to avoid sudden collapses of sensitive structures in earthquake zones. But even though SHM develops rapidly and the results are promising these techniques can only support the regular visual inspections or other local testing methods.

<table>
<thead>
<tr>
<th>No.</th>
<th>Object</th>
<th>Monitored parameter/process</th>
<th>Conclusions</th>
<th>Consequence</th>
<th>Aim</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Public building</td>
<td>Smoke emission</td>
<td>Fire in the building</td>
<td>Audible signal, evacuation, fire brigade is alarmed</td>
<td>Protecting human life and the structure</td>
</tr>
<tr>
<td>2</td>
<td>Traffic Bridge in an earthquake zone</td>
<td>Accelerations at several points to determine dynamic system properties of the bridge structure after earthquakes</td>
<td>Structure Damages</td>
<td>Repairs, Closing of the bridge</td>
<td>Protecting human life and the structure</td>
</tr>
<tr>
<td>3</td>
<td>Steel structure with fatigue cracks</td>
<td>Ultrasonic response signal near the cracks due to ultrasound</td>
<td>Fatigue crack propagation</td>
<td>Maintenance activities</td>
<td>Determination of service life, Ensuring the durability of the structure</td>
</tr>
<tr>
<td>4</td>
<td>Concrete structure with large cracks</td>
<td>Digital image data of the surface</td>
<td>Crack propagation</td>
<td>Maintenance activities</td>
<td>Determination of service life, Ensuring the durability of the structure</td>
</tr>
<tr>
<td>5</td>
<td>Cable stayed bridge</td>
<td>Accelerations of the cables due to ambient vibrations</td>
<td>Forces in the cables</td>
<td>Maintenance activities</td>
<td>Checking design assumptions, Avoiding a collapse</td>
</tr>
<tr>
<td>6</td>
<td>Traffic steel bridge</td>
<td>Strains at critical details using strain gauges</td>
<td>Dynamic loads/stresses at the critical details</td>
<td>Maintenance activities</td>
<td>Collecting fatigue data for determination of service life, optimization of maintenance acts, reducing costs</td>
</tr>
<tr>
<td>7</td>
<td>Chloride exposed concrete structure</td>
<td>Chloride concentration in surface areas</td>
<td>Corrosion risk</td>
<td>Maintenance activities</td>
<td>Ensuring the durability of the structure</td>
</tr>
<tr>
<td>8</td>
<td>Excavation with stiffening</td>
<td>Strains in the stiffeners</td>
<td>Loads on the excavation</td>
<td>More stiffeners, reducing loads if possible</td>
<td>Avoiding a collapse</td>
</tr>
<tr>
<td>9</td>
<td>Bearings of a bridge (Elastomer pot sliding bearings)</td>
<td>Distance between sliding slab and covering slab</td>
<td>Level of deterioration</td>
<td>Changing of the bearings</td>
<td>Optimization of maintenance activities</td>
</tr>
<tr>
<td>10</td>
<td>Aerial mast</td>
<td>Strains at several points of the structure</td>
<td>Wind loads</td>
<td>Adjustment of the design rules</td>
<td>Verifying the load assumptions, improving the design process</td>
</tr>
</tbody>
</table>
In many cases the application area for monitoring campaigns is the field of bridge construction since this structure type has to satisfy the criteria of safety exceedingly. The prediction of dynamic effects and its resulting loads is difficult especially with respect to the more and more increasing volume of traffic. Furthermore bridges are often set in aggressive environment, exposed to climate influences. Many parts of the structure can hardly be inspected visually but the regular inspections are imperative as a part of the maintenance regulations. Thus it is often necessary to close a bridge for carrying out visual inspections. Avoiding these extensive procedures a monitoring system can be used as an instrument to reduce maintenance costs and to optimize date and extent of repair work.

2 INSTALLATION OF A MONITORING SYSTEM

2.1 A Systematic Approach

The main goal of monitoring civil structures is to observe a process sufficiently. Often the monitored process can develop critically and results into threatening of life or the decrease of the durability of a structure. Monitoring can be used efficiently to avoid consequences like these. However a systematic approach should be applied when planning, preparing and managing the monitoring system. But even the post processing has to be handled systematically. Three aspects are of great importance:

- Clearly defined aims of the monitoring campaign;
- A proved coherence between the measured parameters and the linked process in the structure;
- Predefined measures, if required, resulting from the evaluation of the monitoring results.

2.2 Difficulties to accomplish

Each structure has its typical behaviour and almost every monitoring campaign has a different motivation resp. goals. Thus in the majority of cases the design of a monitoring system is individual. An advanced knowledge on the design of the monitoring is required as various aspects have to be considered. (e.g. see Hechler et al. 2005). In the following some aspects are discussed.

Data management is a very important aspect, particularly in case of dynamic measurements within the monitoring campaign. The intention should be, to produce as much data as needed but as little as possible. This may be achieved by choosing reasonable sampling rates and also by applying triggering mechanisms to reduce the measurement periods. Further the effort of data management is reduced by simplifying the post processing. Often only a selection of special events is of interest and the identification of the corresponding data is time-consuming. In this case the implementation of a messaging system for event detection is useful as it indicates maximums in the measurement data. Further automatic evaluation routines for post processing are helpful. However these procedures have to be adjusted individually as every structure and every aim of the monitoring system is different.

In many cases unexpected difficulties arise after installing the monitoring system, e.g. problems with the sensors, unsuitable measurement ranges, disturbing signals, unsuitable sensor positions, defective contacts or damaged cables. Therefore on-site changes of the monitoring system should be possible to solve these problems. If a system change is not possible due to the structural characteristics, the operational reliability of the system has to be assured before the installation. Therefore laboratory tests have to be carried out imperatively. They have to be considered within the cost calculation.

Much better than on-site changes is the possibility to change the system with online tools. Mostly this is possible in regard to the controlling and timing of the system; e.g. modifications in terms of sensor calibration, measurement ranges, signal amplification or trigger settings. Also hardware defects can sometimes be handled online. An example is the avoidance of a system stop due to a defect of the power supply adapter (one of the most critical components of a connected computer) by the implementation of a second adapter. This backup power device is
switched on when the first one breaks down. Other alternative installations are possible. However in many cases on-site activities will be required to solve problems concerning the monitoring system. Here, at least online remote diagnosis tools should be installed.

Another important aspect is the power supply of a monitoring system. In case of long-term monitoring campaigns, which are performed outdoors and where an electricity network is not available, this task requires much effort and financial budget. The capacity of batteries is limited, even if computer systems are on stand-by for a long period. Apart from using expensive and sensitive wind or solar energy tools the combination of batteries with a gasoline-driven generator recharging them periodically is useful.

If dynamic vibration measurements are carried out often both ambient and strong motion data are requested for the analysis of the structure. In this case the monitoring system should have the capacity of automatic selection of the most adequate measurement range, so that the low amplitude vibrations are measured with high precision, but also strong motion data will be measured correctly in the case of an event. Otherwise the resolution of the measured vibration signals must be very high. The technical equipment to provide such resolutions is expensive.

2.3 Limitations of monitoring

As already mentioned above, monitoring campaigns can often only support other local testing methods. Particularly if the coherence between the measured parameters and the linked process in the structure is not proved or in question (see 2.1), it is not possible to draw reliable conclusions. Also other problems can occur limiting a reliable interpretation of the monitoring results:

- Technical problems like sensor failure, lack of data transmission, software errors;
- Lack of information about the structure for example due to unavailable or incorrect plans;
- Bad assumptions of material properties or foundation characteristics;
- Inadequate evaluation tools.

Additional information can be found in (Hechler et al. 2005).

3 CASE STUDY 1 - MONITORING CONCRETE BRIDGES IN MARITIME ENVIRONMENTS

3.1 Introduction

Croatian Adriatic coastal area is a very harsh environment in terms of frequent strong winds (gust speeds of 300 km/h have been recorded) which carry sea-salt and spray exposed structural elements thus speeding up bridge deterioration due to chloride corrosion of reinforcement (Radic et al. 2006). There are six large reinforced concrete arch bridges in this region, which were constructed over the past four decades with spans ranging from 200 m to almost 400 m: Sibenik (1966), Pag (1968), Krk I (largest conventional RC arch span of the world), Krk II (1980), Maslenica (1997) and Skradin (2005) bridges. Over the years many deficiencies and advanced stage of deterioration processes were identified on older Adriatic Bridges. Chloride attack due to maritime exposure, followed by cracking, delamination, splitting and peeling off of concrete is identified as major deterioration mechanism, but the observed defects are also attributed to design errors, construction faults and inadequate maintenance (Radic et al. 2005).

3.2 Maslenica Bridge

Many problems encountered in performance of four older Adriatic arch bridges and huge financial resources spent on solving these problems, urged for different approach in planning monitoring the performance of bridges built from 1990 onwards. For the first time in Croatia, a monitoring system for long-term control of stresses, deformations and corrosion progress was installed on Maslenica bridge, which was completed in 1997. The system consists of 92 strain-gauges (18 on concrete and 74 on reinforcement), 40 sensors to measure temperature and 21 corrosion sensors mounted at carefully chosen spots on the arch as well as girders and deck of
the superstructure. Sensors layout is showed in Figure 1. The intention of installing this comprehensive system was to closely monitor both structural performance and durability related performance in order to facilitate the future maintenance activities by triggering timely adjustments and interventions. The system was used to record the stresses and strains at different construction stages and under load-testing prior to opening bridge to the service (Simunic et al. 1999a,b). During the bridge construction the following measurements were performed:

- Initial measurements before and immediately after the concreting of girders;
- Measurement of strain and stresses in reinforcement and deflections due to dead load and pre-stressing;
- Measurement of dynamic parameters;
- Determination of modulus of elasticity based on experimental data;
- Measurement of stresses in the arch during construction by cantilever method;
- Load-testing prior to setting the bridge in service included measurements under static and dynamic loading.

These documented the initial condition of the structure needed as a reference for future measurements. Unfortunately, the funding of the monitoring project was stopped soon afterwards, but currently there is an initiative from the bridge owner to restart the system. This would provide valuable data on reinforcement corrosion progress which would be of relevance not only to the subsequent maintenance works on the Maslenica Bridge, but also for the other existing bridges in the Adriatic region as well as those planned to build in the future.

![Figure 1: Strain-gauges (top) and corrosion sensors (bottom) installed on Maslenica Bridge.](image1)

3.3 Skradin Bridge

More recently, another attempt was made to ensure continuous data on structural performance of an Adriatic arch bridge, with the instrumentation of Skradin Bridge that was opened to traffic in 2005. The bridge (Savor et al. 2006) provides the crossing of the new Zagreb-Split motorway over Krka River canyon in environmentally protected area, and near the estuary, where sea and river waters mix, in a somewhat less aggressive maritime environment than at the location of the Maslenica Bridge. A concrete arch with composite steel-concrete superstructure was finally selected for this location.

Sensors for measuring strains, humidity and temperature were installed on the bridge as the construction progressed so part of the monitoring system was used for measuring strains during the construction. Monitoring corrosion progress on Skradin Bridge is also anticipated. This should result with determination of relevant parameters for modelling concrete deterioration mechanisms. As on the Maslenica Bridge, corrosion sensors are anode-ladder-system (Schießl & Raupach 1992). Total of 6 anode ladders have been installed: two at each springing point, one
at the quarter of the span, and one at the arch crown. The first measurements defining the “reference state” were taken in May 2004, followed by measurements in September 2004 and February 2005 (Rak et al. 2006). Frequency of future measurements shall be decided by the bridge owner.

3.4 Future development

Croatia is currently placing large efforts to develop a reliable and efficient motorway asset management system, and as a continuation of this work Croatian Motorways Ltd. (Radic et al. 2007), which manage and operate most of the motorways in Croatia, initiated development of monitoring programme for their bridges. The intention is to hand-pick major bridges that require out-of-ordinary care and equip them with monitoring systems. The undergoing study is aimed at defining criteria which bridges should be monitored, selecting suitable monitoring systems and sensor setup. The study should be completed within three months, and followed by the implementation on site.

4 CASE STUDY 2 - THE DYNAMIC BEHAVIOUR OF A FILLER BEAM BRIDGE

4.1 Introduction

In the framework of an European research project (DETAILS) a long-term monitoring campaign of a railway bridge will be carried out for ca. two years. The composite filler beam bridge “Erfttalstraße” in Germany was built in the year 2000 next to an old steel bridge crossing the Erfttalstraße near Kerpen. It is part of the high-speed line between Cologne and Aachen where velocities up to 250 km/h are possible for ICE and the TGV trains. But not only passenger, also freight trains are using the bridge frequently.

Figure 2: View on the filler beam bridge Erfttalstraße near Kerpen, Germany

The structure consists of two parallel sections divided by a 2.0 cm wide gap (Figure 3), where the ballast on the bridge is continuous. That means that interaction effects between the two substructures have to be expected. Each part of the bridge is a single span system with a span width of 24.6 m and in both parts of the bridge eleven steel sections HEM 1000 are used. The depth of the cross section is about 1.10 m. Both substructures of the bridge are supported by four elastomer bearings, so that the substructures are not fixed in horizontal track direction.

For the design of composite filler beam railway bridges several codes, both European and national, have to be considered. Eurocode 1 defines the load models LM71 and SW/0 which are taken into account within the design process. Dynamic effects are considered by using a load factor \( \Phi \) given also in Eurocode 1 to increase the static loads. However this approach is only allowed in case that resonance effects are not expected; if resonance effects might occur a dynamic analysis has to be carried out. Eurocode 1 provides a flow chart for determining whether
a dynamic analysis is required. One of the main input values in this procedure is the first natural frequency.

Figure 3: Cross section of the filler beam bridge Ernttalstraße

Based on practical experience resonance effects are observed even though Eurocode indicates that there is no resonance to be expected; on the contrary bridges where resonance effects have been predicted show a favourable dynamic response. The reason for this incorrect prediction of the dynamic behaviour is probably a false estimation of the first eigenfrequency. Also a detailed dynamic analysis is often insufficient in terms of unrealistic results. The main problem is the assessment of realistic system properties within the design procedure, so that the calculated dynamic reactions induced by train loads become reliable. In this regard e.g. the correct consideration of the ballast contribution is of great importance.

4.2 Aim of the project, consequences of the monitoring campaign

Within the project the dynamic behaviour of the bridge and the changes in the dynamic behaviour due to long effects are to be investigated. Aspects like concrete behaviour, slip between concrete and steel, contribution of tracks and ballast, bearing characteristics and climate influence are focused on.

The main goal of the project is to improve the current design concept, so that a better prediction of the dynamic behaviour of filler beam bridges is possible. Recommendations to estimate the first natural frequency more precisely would be a successful outcome in this project. The knowledge of the first eigenfrequency would allow a better adjustment of the design rules to the comfort criteria within the bridge design. In this case the consequences of the monitoring campaign would be the consideration of the results within the design rules.

But not only filler beam bridges, also other bridge types with similar properties are investigated within the monitoring campaigns. Especially for bridges with fatigue relevant details the expected results are of high interest. It is intended to provide methods for damage detection and to improve design and calculation methods for the prevention of fatigue damages. These methods will be based on the knowledge of realistic loads and bridge response gained by the monitoring. Other research activities are also engaged in this issue.

4.3 The monitoring system

The long-term campaign has not yet been started since it is now planned and prepared. However a “short-term campaign” has been carried out in April 2007 to determine system properties in terms of system identification. Accelerations at 40 points (measurements carried out in a set of four configurations) at the bottom of the bridge have been measured due to ambient loads and due to train passages. By using output only methods (EFDD- and SSI-algorithms) applied to measured ambient vibrations the first mode shapes have been identified successfully. They have
been used to calibrate the FEM-model of the bridge. Also information about damping properties and maximum accelerations during train passages have been gained, so that a fundamental knowledge of the dynamic behaviour for preparing the long-term campaign is given.

Regarding the circumstances of the project the design of the monitoring system is a very complex task. As mentioned above there are a lot of parameters that have influence on the dynamic properties of the bridge and the importance of each parameter is not yet known. Thus it is challenging to implement the described systematic approach into the monitoring design. Particularly the question if the coherence between a measured parameter and a process in the structure is really given is hard to predict. For example if higher strains in the steel girders due to long-term effects are measured, it is difficult to estimate if it results from a settlement, from climate influence, from shrink effects, from changed composite behaviour or from changed ballast behaviour. The main question is: How many and what kind of monitoring devices have to be installed to gain sufficient information about the bridge behaviour and about the reasons for this behaviour. Regarding the dynamic properties the following aspects will be focused:

- Composite effects between steel girders and concrete,
- Interaction effects due to ballast behaviour, non-linear system behaviour,
- Damping properties,
- Climate influence,
- Influence of train loads and train velocities, resonance effects.

To gain information about these aspects the following parameters are of interest:

- Accelerations due to ambient loads and due to train loads,
- Strains of steel and concrete, strains of the tracks,
- Climate data, temperature of the structure,
- Slip between steel girders and concrete,
- Displacements,
- Train loads and train velocities, characteristics of different train types.

Aside from the decision how many and what kind of monitoring devices to install some of the difficulties mentioned in chapter 2.2 are met within this project. First of all an effective data management will be of great importance. To carry out sufficient acceleration or strain measurements during train passages a sampling rate of about 500 to 1000 Hz is needed. Thus a respectable amount of data is produced when about ten train passages are measured the day. Furthermore ambient vibrations are also to be measured so either a switching between different measurement ranges for ambient and train loads or a sufficient resolution is necessary. For starting the measurements during train passages and for switching the measurement ranges a trigger mechanism is needed.

It is expected that important knowledge how to design an optimal monitoring system is gained not before first measurements are carried out. Thus continuous improvement of the system in terms of adjustments and modifications will take place.

5 CONCLUSIONS

The efficient use of monitoring systems in the field of civil engineering requires a systematic approach. This comprehends that the aims of the campaign are well defined, the coherency between the measured parameter and the related process in the structure is proved and that the consequences arising out of the monitoring results are treated with a well defined package of measures.

This concept of having a systematic approach in terms of monitoring civil structures is described within this contribution and monitoring aspects are demonstrated in two quite different monitoring projects.
REFERENCES

RFCS-project: DETAILS. DEsign for opTimal life cycle costs (LCC) of high-speed rAILway bridges by enhanced monitoring systems. 2006 - 2009.
INTRODUCTION

The dynamic behaviour of small to medium span railway bridges for high speed traffic is still difficult to foresee during the design, since the influence of the non-structural environment and of the super-structure composed by rails, sleepers and ballast is not well known. This conditions the practical use of the norms, namely the Eurocode 1 part 2, not only for the design of new structures but especially when existing bridges must be checked for increasing traffic speeds [1,3].

A number of such bridges in the track between Linz and Wels in Austria had to be reevaluated [6] in order to permit the increase of train speeds up to 200km/h in accordance with guidelines shown in the ERRI report [2]. In a preliminary numerical evaluation very high vertical accelerations were computed for some of those structures. An experimental program was thus carried out in order to get a better estimation for the dynamic behaviour of the bridges, concerning mainly the first vertical eigenfrequency and the corresponding viscous damping. The paper reports on the results of this experimental investigation and identifies some areas where further research is necessary.

1 INTRODUCTION

The dynamic behaviour of small to medium span railway bridges for high speed traffic is still difficult to foresee during the design, since the influence of the non-structural environment and of the super-structure composed by rails, sleepers and ballast is not well known. This conditions the practical use of the norms, namely the Eurocode 1 part 2, not only for the design of new structures but especially when existing bridges must be checked for increasing traffic speeds [1,3].

A number of such bridges in the track between Linz and Wels in Austria had to be reevaluated [6] in order to permit the increase of train speeds up to 200km/h in accordance with guidelines shown in the ERRI report [2]. In a preliminary numerical evaluation very high vertical accelerations were computed for those structures using the software system RM2000, showing the need for better estimates of the natural frequencies and viscous damping. Resonance under train speeds between 200km/h and 240km/h led to maximum accelerations of up to 20 m/s² in some cases.

An experimental program was therefore implemented, which included the measurement of the vertical accelerations at up to eight points under the bridge decks during normal railway operation and its modal identification based on those measurements. Two to four hours of continuous data recording, depending on the structure under consideration, was considered to be sufficient for the dynamic identification. This included a number of at least ten train passages, which were considered to be the most important source of excitation for the modal identification.

In this way the first natural frequency and the corresponding modal damping could be estimated for all structures. For the more flexible structures, with longer spans, higher natural frequencies, mode shapes and damping could be obtained as well. In some cases measurements of the accelerations on the rails and in the ballast were also carried on, although those results are not presented here.
2 DESCRIPTION OF THE BRIDGES

2.1 Reinforced concrete frames

A set of four monolithic reinforced concrete frames with spans varying from 2.5 to 5.0 meters were measured. The corresponding geometrical characteristics are shown in Table 1 and Fig. 1. Bridge 2 is the only one of the ‘box’ type and is composed by two twin boxes laying side by side, one for each direction of railway traffic. The other bridges are of the ‘frame’ type and are composed by only one monolithic structure for both railway tracks.

Table 1 – Geometrical characteristics of the reinforced concrete frames according to the structural layout

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Span L [m]</th>
<th>Width B [m]</th>
<th>Thickness dRF [m]</th>
<th>Thickness dRR [m]</th>
<th>Thickness dS [m]</th>
<th>Structural Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.50</td>
<td>2x4.25</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>box</td>
</tr>
<tr>
<td>4</td>
<td>2.50</td>
<td>9.30</td>
<td>0.30</td>
<td>0.25</td>
<td>0.25</td>
<td>frame</td>
</tr>
<tr>
<td>5</td>
<td>5.00</td>
<td>9.0</td>
<td>0.40</td>
<td>0.38</td>
<td>0.40</td>
<td>frame</td>
</tr>
<tr>
<td>10</td>
<td>5.00</td>
<td>9.0</td>
<td>0.32</td>
<td>0.32</td>
<td>0.32</td>
<td>frame</td>
</tr>
</tbody>
</table>

Figure 1 – Structural layout of small span bridges

2.2 Single-span slabs

Another set of six bridges with spans varying from 5.75 meters to 23.5 meters have the common characteristic of being composed of single-span simple supported twin slabs, laying side by side, one for each track. The geometric characteristics are summarized in Fig. 2 and in Table 2.

The ballast depth has an average of 0.60 m, varying between 0.55 m and 0.65 m depending on the slab thickness, and spans over the entire width of the twin decks.

The structural layout of the prestressed concrete decks (Bridges 1, 3, 8 and 12) corresponds to one-span simply supported slab with slightly variable depth. In the case of Bridge 7 the simply supported slab is made of HEB360 steel bars filled with concrete. Bridge 11 is also simply supported and made of reinforced concrete.

The support conditions, although defined generally as simple supports, are of two types. In bridges 1, 3, 8 and 12, the bearing supports, two at each extremity of the deck, are made of steel pots filled with rubber material and can be considered free to rotate. For the other structures no specific apparatus have been used and the slab lies directly on the top of the abutment.

Table 2 – Geometrical characteristics of the slab-type bridges

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Span [m]</th>
<th>Width [m]</th>
<th>HL [m]</th>
<th>H [m]</th>
<th>HR [m]</th>
<th>α [°]</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23.50</td>
<td>5.14</td>
<td>0.92</td>
<td>1.14</td>
<td>0.91</td>
<td>90°</td>
<td>Prestressed</td>
</tr>
<tr>
<td>3</td>
<td>19.50</td>
<td>6.49</td>
<td>0.97</td>
<td>1.10</td>
<td>0.84</td>
<td>90°</td>
<td>Prestressed</td>
</tr>
<tr>
<td>7</td>
<td>9.00</td>
<td>4.52</td>
<td>0.43</td>
<td>0.43</td>
<td>0.43</td>
<td>90°</td>
<td>Mixed</td>
</tr>
<tr>
<td>8</td>
<td>21.00</td>
<td>4.23</td>
<td>1.05</td>
<td>1.15</td>
<td>1.05</td>
<td>90°</td>
<td>Prestressed</td>
</tr>
<tr>
<td>11</td>
<td>5.75</td>
<td>4.44</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
<td>90°</td>
<td>Reinforced</td>
</tr>
<tr>
<td>12</td>
<td>11.44</td>
<td>4.54</td>
<td>0.7</td>
<td>0.90</td>
<td>0.70</td>
<td>63.9°</td>
<td>Prestressed</td>
</tr>
</tbody>
</table>
There is no continuity of the slab over the supports to the abutments, except the one materialized by the superstructure composed of ballast, sleepers and rails. It is also to emphasize the fact that in bridges 1, 3 and 8 the line of supports is not collinear when considering both decks, as illustrated in Figure 2-b, and that the line of supports in Bridge 12 is skew relatively to the axis of the bridge.

3 MEASUREMENT PROCEDURES

3.1 Measurement layout

The main concern of the measurements was to identify the first eigenfrequency for which the respective eigenmode is characterized mainly by vertical deflections of the deck. Although for the slab-type bridges this corresponds to the lowest frequency, it would not be the same for the frame-type bridges, as it was already evidenced in the numerical models.

In that sense, for the frame structures, the vertical accelerations along the middle span line (Fig. 3-a) and the horizontal acceleration at about middle height of the vertical slabs were measured. For the slab type structures, according to the expected eigenforms and to the symmetry conditions, only one half-side of each deck was instrumented (Fig. 3-b). Although a maximum of eight channels were available only a number of them were used to capture the vertical accelerations of the deck at mid-span and at ¼ of the span (see Fig. 3-b and Table 3). In this case the remaining sensors were used to measure accelerations on the rails, in the ballast and under the twin deck.

The response data was acquired using the Brüel & Kjær PULSE® multi analyser platform and recorded for post processing [4]. In addition, the type of train, number of carriages and velocity measured with a speedometer were manually recorded [8].

3.2 Identification methods

Two methods were considered for the identification of eigenfrequencies, eigenforms and damping: (i) free vibration after train passages and (ii) natural ambient vibration between train passages. It was decided to capture and record the signal during enough time in order to obtain a significant number of at least ten train passages, corresponding to two to four hours of continuous signal recording.

The signal post processing consisted of two types of power spectra analyses. On the one hand the free vibration immediately after each train passage was collected for all trains and used to build the average spectra. Time histories with a fixed time length were considered, starting from the instant when each train leaves the bridge. Considering the longest eigenperiod expected for the structures, that time length should be enough for the free response to decay significantly.

Taking into account for each structure the entire sequence of all the time histories described above, it is possible to use a method for the parameter identification in the frequency domain such as the Peak Picking Method implemented in the software ARTeMIS®.

However, attention had to be paid to the effective time after which there is no more excitation on the bridge in order to prevent the distortion of the results and the erroneous identification of load harmonics. This was particularly sensitive in the case of the small span bridges, for which the free decay is quite short.
On the other hand, the ambient free vibration caused by unidentified natural excitation during the interval of train passages was collected and analyzed using the frequency domain decomposition method implemented in the referred software.

Although for the medium span bridges both procedures were able to identify the first natural frequency and damping, for the smaller bridges the measurement duration was not enough in order to allow for the natural ambient vibration to build significant spectral peaks. Besides that, the higher natural frequencies and modes could only be reliably identified for the medium span bridges.

As a complement, after the modal identification, selected measured responses during train passages were analyzed and compared with numerical results obtained for equivalent load sets crossing the bridge at about the same speed as it was registered for the respective train during the measurements (see [7,8]).

4 MEASUREMENT RESULTS

4.1 Free decay analysis

Examples of the modal identification in the frequency domain are show in Fig. 4 and the estimated values for the eigenfrequencies and damping ratios resulting are summarized in Table 4.

During the identification process it was noticed that both the natural frequencies and the damping ratio varied according to the amplitude of vibration, that is, for the same structure significantly different values were obtained if time shifts of up to 1,5 seconds were introduced in the starting point of the time histories, maintaining the same total time length, when comparing with the original time histories defined in the paragraph above. This effect is most probably due to non-linear effects provided mainly by the track, ballast and supports.

When the modal parameters obtained from the time shifted response histories are compared with those from the non-shifted histories two tendencies can be recognized: (i) the frequency
increases and (ii) the damping factor decreases. These results are more evident in the lower modes and must be, therefore, related to the amplitudes of vibration. In fact, the higher amplitudes in the lower modes mobilize mechanisms of energy dissipation related to friction in the supports and internal friction in the ballast in a stronger way than they are mobilized in the higher modes, for which the amplitudes of vibration are much lower. This also stresses the idea that the friction forces, probably mainly inside the ballast, become more important for lower amplitudes having an effect of increasing the overall stiffness of the structure. Again, this effect is less important for the higher modes.

Table 4 – Eigenfrequencies and damping considering non-shifted time series

<table>
<thead>
<tr>
<th>Type</th>
<th>Bridge</th>
<th>Mode</th>
<th>Frequency [Hz]</th>
<th>Damping Ratio [%]</th>
<th>Mode type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>1</td>
<td>1st</td>
<td>4.8</td>
<td>7.8</td>
<td>1st Bending</td>
</tr>
<tr>
<td></td>
<td>2nd</td>
<td>13.3</td>
<td>4.9</td>
<td>2nd Bending</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3rd</td>
<td>16.9</td>
<td>2.0</td>
<td>1st Torsion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4th</td>
<td>27.7</td>
<td>1.9</td>
<td>3rd Bending</td>
<td></td>
</tr>
<tr>
<td>2nd</td>
<td>1st</td>
<td>14.7</td>
<td>4.5</td>
<td>1st Torsion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2nd</td>
<td>16.5</td>
<td>2.5</td>
<td>2nd Bending</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4th</td>
<td>33.7</td>
<td>2.8</td>
<td>3rd Bending</td>
<td></td>
</tr>
<tr>
<td>3rd</td>
<td>1st</td>
<td>16.9</td>
<td>4.7</td>
<td>1st Bending</td>
<td></td>
</tr>
<tr>
<td>Medium span slab</td>
<td>2</td>
<td>1st</td>
<td>5.4</td>
<td>6.1</td>
<td>1st Torsion</td>
</tr>
<tr>
<td></td>
<td>2nd</td>
<td>18.8</td>
<td>2.8</td>
<td>2nd Bending</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3rd</td>
<td>19.2</td>
<td>1.8</td>
<td>1st Torsion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4th</td>
<td>37.4</td>
<td>1.2</td>
<td>3rd Bending</td>
<td></td>
</tr>
<tr>
<td>4th</td>
<td>1st</td>
<td>15.0</td>
<td>2.0</td>
<td>1st Bending</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2nd</td>
<td>36.4</td>
<td>1.4</td>
<td>1st Torsion</td>
<td></td>
</tr>
<tr>
<td>1st–2nd</td>
<td>13.7</td>
<td>7.7</td>
<td>4.7</td>
<td>Bending</td>
<td></td>
</tr>
<tr>
<td>3rd–4th</td>
<td>26.2</td>
<td>3.0</td>
<td>1.5</td>
<td>Torsion</td>
<td></td>
</tr>
<tr>
<td>5th–6th</td>
<td>41.4</td>
<td>2.1</td>
<td>2.2</td>
<td>Bending</td>
<td></td>
</tr>
<tr>
<td>7th–8th</td>
<td>50.7</td>
<td>0.2</td>
<td>0.2</td>
<td>Bending</td>
<td></td>
</tr>
<tr>
<td>5th</td>
<td>1st</td>
<td>17.9</td>
<td>3.2</td>
<td>Main vertical deflection of the horizontal slab</td>
<td></td>
</tr>
<tr>
<td>6th</td>
<td>1st</td>
<td>39.0</td>
<td>1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7th</td>
<td>1st</td>
<td>27.5</td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8th</td>
<td>1st</td>
<td>27.3</td>
<td>8.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The effect of coupling between both twin plates originated by the ballast was clearly identified in Bridge 12, which is skew. The influence of the interaction between the plates is shown in the duplication of the frequency peaks (Fig. 4) corresponding to symmetrical and non-symmetrical shapes with reference to the contact plan between the plates. This effect allows the quantification of the ballast shear stiffness since this depends only on the frequency gap between the peaks [5].

A consequence of this effect of coupling between the twin plates is the overestimation of the damping ratio when both frequency peaks are closer than the frequency resolution of the auto-spectra. This is probably the reason for the high first damping ratio measured in Bridges 1, 3 and 8 (see Table 4), whose line of bearing supports is not collinear (see Fig.2-b) inducing a skew type effect between the twin slabs.
Figure 4 – Peak Picking method applied to bridges 1, 7, 10 and 12 (Frequency Domain Decomposition - Peak Picking; Average of the Normalized Singular Values of Spectral Density Matrices of all Data Sets)

4.2 Ambient vibration

Ambient vibration methods are based on the assumption that all the dynamic excitation in the structure is of such a random type that all modes in the relevant frequency range are excited in the same way. Although this is not a typical problem for the application of such methods, the length of the time histories corresponding to the free vibration considered before can be extended for several minutes, depending on the railway traffic, so that the effect of the free vibration induced by the train passage is dimmed.

The results are summarized in Table 5. Because of the insufficient total measuring time and the fact that the maximum signal peak input had to be set up for the expected maximum acceleration during the train passages, conditioning the goodness of the signal for low amplitudes, the results are limited to the first natural frequency and to the longer span bridges.

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Mode</th>
<th>Frequency [Hz]</th>
<th>Damping Ratio [%]</th>
<th>Mode type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>5.2</td>
<td>2.0</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; Bending</td>
</tr>
<tr>
<td>3</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>8.6</td>
<td>1.9</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; Bending</td>
</tr>
<tr>
<td>8</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>5.8</td>
<td>2.7</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; Bending</td>
</tr>
</tbody>
</table>

Comparing these results with those given in Table 4, the difference is to be found in the damping ratio, resulting from the ambient vibration much lower damping values, and in the eigenfrequencies, which are higher than those given in Table 4. Both tendencies are in accordance with the explanation given above, concerning the probable influence of non-linear effects.

4.3 Response to train passages

The maximum acceleration measured during train passages is highly dependent on the frequency window used. Since the phenomenon under consideration is the risk of ballast desegre-
gation in consequence of vibration, a frequency window of 0-25 Hz was used to investigate whether that limit was exceeded during the measurements.

For the dynamic structural identification the measured response to train passages is not of much use, unless a numerical structural model is fitted according to the identified modal characteristics and the numerical response to the real train is computed and compared with those measurements. This was done for several trains and bridges [7,8].

The comparison between the measured and the computed acceleration at the mid-span, shown in Fig. 5, concerns the passage of a locomotive over Bridge 1. Analysing the evolution of the time histories, it is obvious that, during the load application the initial part fits very well but the final part shows some differences. They are probably related to the interaction between train, superstructure and structure as shown e.g. in the UIC leaflet [10], which was not considered in the computations. With respect to the free vibration, the initial close correspondence between the two lines is lost because of a higher damping in the measured response than the one assumed in the computations, and because of the variation of the first natural frequency in the measured time series, as discussed above.

![Figure 5 - Computed and measured response for Bridge 1.](image)

5 CONCLUDING REMARKS

The main difficulty concerning dynamic measurements is usually the excitation. In the present case the vibration provided by the train passages could be used successfully. The resulting free vibration proved to be sufficient for the parameter identification methods to be applied.

The results show the existence of important non-linear effects, since the natural frequencies vary according to the amplitude of vibration, that is, growing amplitudes of the free vibration signal correspond to the decrease of the first natural frequency.

Damping factors are always difficult to be estimated exactly, since the sources for energy dissipation are various and different from the viscous type used in the theoretical formulation of the vibration problems. Particularly the damping due to friction between ballast particles and eventually the friction in the supports can play an important role in the type of structures under analysis. The tendency for the damping to increase with the vibration amplitude could be observed in the analysis. Also, the coupling effect between twin slabs developed through the ballast was clearly identified in the skew bridge and is most probably the responsible for the high measured damping ratios in the first eigenmode of bridges 1, 3 and 8.

The contribution of the ballast to the overall dynamic behaviour of this type of bridges is not yet well known. Since the problem of excessive accelerations in railway bridge results, in many cases, from a resonance situation in one of the lower natural frequencies, a better understanding of the damping mechanisms could be very useful for a more precise evaluation of the dynamic response during the design.
AKNOWLEDGEMENTS

The authors would like to thank Austrian Railway Authorities ÖBB for the technical support and the facilities needed for the measurement setup, as well as Eng. Helena Gervásio from GI-PAC, Lisbon for the experimental support.

REFERENCES

Sustainable bridge construction through innovative advances

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ABSTRACT: Sustainability is now recognised as a key issue which much be addressed in the design, construction and life long maintenance of civil engineering structures. In this lecture, generic aspects of sustainability will be briefly discussed, but the main focus will be on its application to bridges. Motorway bridges built in the 1960’s/70’s had design lives of 120 years; however many were showing signs of deterioration after only 20-40 years.

This led to much debate on the issue of initial versus full life cycle costing which is still ongoing today. In order to address the highly complex issue of the sustainability of bridges the following specific areas which impinge on this important subject will be considered:

1. The impact on sustainability of different forms of bridge construction and maintenance/repair/replacement strategies.
2. The utilisation of innovative in-situ testing equipment for assessing the long term durability of concrete.
3. The development of innovative structural designs for bridges which inherently have greatly extended lives at minimal, if any, additional cost.

1 INTRODUCTION

The built environment has to co-exist with the natural environment with which it is inseparably linked. Energy, materials, water and land are all consumed in the construction and operation of buildings and infrastructure to such an extent that sustainable development can be said to depend on the built environment. The world’s cities have a major impact on emissions of ‘green house gases’ and global warming: they take up around 2% of the earth’s surface but account for nearly 80% of the carbon emissions from human activities. The urban environment influences our living conditions, social well-being and health. Thus the performance characteristics and quality of our infrastructure are of fundamental importance to urban sustainability and the well-being of our environment. The significance of this should not be underestimated especially if it is borne in mind that our infrastructure accounts for at least 50% of our national wealth.

The burden placed by construction on our natural resources can be estimated from the embodied energy i.e. the total primary energy that has to be extracted from the earth to produce a specific product – usually measured per m² of plan area. In addition the operational energy used during their lifetime has to be taken into account. The relative proportion depends on the form of construction. In general, a bridge has high embodied energy and low operational requirements whereas a hospital with its demanding service conditions has a high proportion of operational energy. However for bridges the relative proportions for these energies depends on the extent of maintenance/repair during their lifetime. If minimal maintenance/repairs are required the operational energy may be only marginal however if extensive repairs are necessary and considerable disruption/congestion results the energy consumed can increase dramatically. Thus the challenge for designers is to achieve the minimum total energy used over the 120 year de-
sign life and to persuade the client that a sustainable approach is preferable to a minimum initial
cost design.

In order to contribute to a better understanding of the highly complex issue of the sustainabil-
ity of bridges a number of specific aspects which impinge on this important topic will be dis-
cussed:

1. The relative merits of different forms of construction from the sustainability view-
point.
2. The utilisation of innovative in-situ testing equipment which will allow the durabil-
ity of concrete bridges to be assessed.
3. Technological innovations which could lead to much more durable and sustainable
forms of construction for concrete bridges based on:
   (a). The enhanced strength of deck slabs arising from arching action
   (b). A novel flexible concrete arch system

In the latter two instances the approach adopted in research at Queen’s University Belfast,
carried out with the industry, will be placed in context.

2  SUSTAINABILITY ISSUES AFFECTING BRIDGES

2.1  The Environmental Impact of New Bridges

The embodied energy from the use of construction materials is a source of concern to engineers
when planning, designing and constructing a bridge. However relatively little advice or guid-
ance is given in the literature as to the relative merits of different forms of construction. In this
context a recent paper by Collings[1] presents the results of a comparative study, derived from an
actual project. A bridge in the UK over a river of width 120m with 66m of approach spans on
each side was considered. The total deck area was over 4000m$^2$ and this bridge allowed consid-
eration of the shorter spans on the approaches as well as the main river span. Three basic forms
of construction were considered for the river span; a profiled girder; a tied arch; and a cable
stayed bridge. Constant depth girders were use for all the approach spans. Temporary works
were included as was an estimate of the likely repair, maintenance during the life time of the
three basic forms of construction; steel; concrete; and composite construction.

Useful comparative tables and graphs are included in the paper by Collings[1] however the re-
results summarising the impact of the span and the form of construction on the embodied energy
are only included in this paper. The estimates of the embodied energy during construction (per
m$^2$ for bridge deck) are tabulated in Table 1. Values vary from approximately 16 to 75 GJ/m$^2$ of
deck with the short span concrete structural form giving the lowest values and the all steel or
composite, longer span structure the highest. The embodied energy is also presented graphically
in Fig. 1, where it can be clearly seen that longer spans consume greater embodied energy/ m$^2$
(not unexpected as the cost/m$^2$ also follows these trends). Figure 1 also implies that a well engi-
eeered longer span bridge using local materials, recycled steel and sustainable cement can be
almost as environmentally friendly as a shorter span structure where sustainability issues are not
considered. Table 1 and Fig. 1 also indicate that at the spans under consideration the more archi-
technical solutions (arches, cable stayed) have a higher environmental burden for all materials (as
well as a cost premium). Further comparative studies of this nature, by experienced designers,
need to be encouraged so that the most appropriate forms of construction, from the sustainabil-
ity viewpoint, are selected.
Table 1. Embodied energy during construction (GJ/m²) for various structural forms and materials (from Collings[1])

<table>
<thead>
<tr>
<th>Energy</th>
<th>Type</th>
<th>Steel</th>
<th>Concrete</th>
<th>Composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>viaduct</td>
<td>17.8</td>
<td>15.7/16.6</td>
<td>16.6</td>
</tr>
<tr>
<td></td>
<td>girder</td>
<td>30.9</td>
<td>23.6</td>
<td>29.1</td>
</tr>
<tr>
<td></td>
<td>arch</td>
<td>49.8</td>
<td>34.3</td>
<td>48.8</td>
</tr>
<tr>
<td></td>
<td>cable-stay</td>
<td>40.3</td>
<td>21.1/22.1</td>
<td>37.7</td>
</tr>
<tr>
<td>Minimum</td>
<td>viaduct</td>
<td>17.8</td>
<td>15.7/16.6</td>
<td>16.6</td>
</tr>
<tr>
<td></td>
<td>girder</td>
<td>30.9</td>
<td>23.6</td>
<td>29.1</td>
</tr>
<tr>
<td></td>
<td>arch</td>
<td>49.8</td>
<td>34.3</td>
<td>48.8</td>
</tr>
<tr>
<td></td>
<td>cable-stay</td>
<td>40.3</td>
<td>21.1/22.1</td>
<td>37.7</td>
</tr>
<tr>
<td>Average</td>
<td>viaduct</td>
<td>23.5</td>
<td>21.1/22.1</td>
<td>22.1</td>
</tr>
<tr>
<td></td>
<td>girder</td>
<td>39.3</td>
<td>30.6</td>
<td>37.0</td>
</tr>
<tr>
<td></td>
<td>arch</td>
<td>61.9</td>
<td>49.1</td>
<td>60.8</td>
</tr>
<tr>
<td></td>
<td>cable-stay</td>
<td>50.6</td>
<td>43.9</td>
<td>47.7</td>
</tr>
</tbody>
</table>

Figure 1. Variations in embodied energy with span and material type (from Collings[1])

2.2 Repair, Maintenance and Congestion

All bridges will require some form of intervention during their lifetime and ideally this, as well as all other aspects, should be taken into account in the design process. Even the most basic maintenance will cause congestion but the impact of replacement can be much greater as exemplified by the Tinsley Viaduct.

The Tinsley Viaduct is a twin deck steel/concrete composite beam girder bridge which carries the M1 motorway and the A631 trunk road across the Don valley near Sheffield. The 1km long structure has 20 spans and crosses two railway lines, the River Don and a canal. As a strategic part of the motorway network, the viaduct carries approximately 115,000 vehicles per day. However in the late 1990’s it failed to satisfy the requirements for the introduction of 40t lorries and decisions had to be taken on whether to strengthen or replace the structure.

A replacement bridge was estimated to cost £200 m however the associated cost of congestion over the 2-3 years period of construction was considered to be around £1400m. This enormous additional cost, not to mention the associated environmental impact of congestion, was
clearly unacceptable and in the end it was decided to carry out a complex strengthening process whilst keeping the viaduct open for traffic except for a short time each night. In the end the Viaduct was repaired for £80m with minimal congestion resulting – a net saving of £1,500m.

From the viewpoint of the impact of congestion this extreme example demonstrates the importance of having bridges which can be repaired whilst effectively remaining in service. In this regard steel is more amenable to strengthening however the availability of carbon fibre composites allows comparable action to be taken for concrete bridges. It should also be noted that he cost/environmental impact of congestion is an ever increasing problem as many urban bridges built in the 1960’s are now in need of remedial action. This should be considered, even if only approximately, in the total life cycle design of future bridges. Whilst this may increase the design cost the long term savings could be enormous.

The relative importance of congestion also requires designers to think carefully about the selection of durable materials and the most appropriate form of construction. As a consequence in the future it will be even more important to build bridges which require minimal maintenance and ensure that premature replacement is avoided.

2.3 Total Life Cycle “Cost” of Bridges

 Whilst the initial “costs” are useful it is the “cost”/”energy use” over their full life that is more significant. In this context the importance of adopting Integral Bridges \[2\] for relatively short spans is highlighted. Basically by designing a bridge without movement joints and which is integral from one abutment to the other the maximum resistance to chloride penetration is obtained. As a further step the timely and appropriate application of protective coatings which can be applied whilst it is in service, can delay the need for bridge repair. Thus, by using these methods and some of the innovative approaches detailed later in this paper the life of specific types of bridges can be greatly enhanced and the total life cycle “cost”/”energy use” reduced.

3 DEVELOPMENT OF NOVEL \textit{IN-SITU} TEST METHODS

3.1 Background

The single most important parameter that leads to premature deterioration is the ingress of moisture into the concrete\[3,4\]. Thus, the permeability of concrete to the macro-environment during its service life can be used as a measure of its durability.

In the development of a holistic model for concrete deterioration, Mehta \[4\] has considered the influence of environmental factors on the various deterioration mechanisms involved. In essence, the permeability influences the primary method of transport of moisture and aggressive ions into the concrete and subsequent increases in the permeation properties are responsible for the increased rate of damage. Thereafter, crack growth (which depends on the fracture strength) accelerates the penetration of aggressive substances into the concrete and the spiral of deterioration continues downwards. The interdependence of all these factors and the importance of permeability/transport properties and strength are clearly illustrated in the holistic model in reference\[3\].

3.2 Measurement of Durability Related Properties

Recognising the importance of these parameters researchers at Queens University Belfast have responded by developing the following three \textit{in-situ} test methods and the associated novel test equipment:

1. The “pull-off” test \[5\] for measuring TENSILE strength of concrete using the ‘LIMPET’;  
2. Permeation testing \[6\] utilising the ‘AUTOCLAM’; and  
3. Assessing the diffusion characteristics of concrete using the ‘PERMIT’ \[7\].
All the three in-situ tests have been used on site to assess the corrosion induced damage to the Dickson bridge in Montreal[8]. The tests indicated that strength did not correlate well with the levels of deterioration but permeability and diffusivity provided much useful information.

3.3 Conclusions on in-situ Test Methods

In the assessment of durability, the following potential uses for strength, permeability and diffusion testing have been identified:

1. Estimating the life of new structures: Here the equipment has been used to develop a “mix design for durability”[9] and important trends have been identified (Fig. 2) which could be extremely relevant to new construction.

2. Assessing the remaining life of existing structures: The good correlation between permeability indices and durability characteristics can allow remedial action to be taken before irreparable damage has occurred.

Thus, it is essential for practising engineers to work closely with those involved in relevant research. In this context the ‘LIMPET’, the ‘AUTOCLAM’ and the ‘PERMIT ION MIGRATION TEST’ (Fig. 3) could be invaluable tools for generating useful data.

Figure 2. Influence of mix proportion on Autoclaim air permeability index

Figure 3. Permit, Limpet and Autoclaim (from left to right)

4 TECHNOLOGICAL INNOVATIONS FOR ENHANCED SUSTAINABILITY

4.1 Background

Bridges with spans of up to 30m constitute the vast majority of road infrastructure bridges in service across the world. Within this category of bridges concrete deck slabs are widely used whether in combination with pre-cast pre-stressed concrete beams or steel girders. In addition, Arch bridges have been widely used in the past for shorter spans and even though their durability is unquestioned their labour intensive methods of construction have rendered these unpopular in recent decades. Technological advances to overcome some of these problems will now be briefly described.

4.2 Design of bridge deck slabs based on arching action

By taking the structural advantages of arching action into account in the design process[10] and[11] the following benefits can be achieved:

1. Reduction in reinforcement (from 1.7% to 0.5% or less);
2. Same slab depth for greater spacing of beams;
3. Lower overall cost of bridge superstructure as one larger beam at 2m centres is less expensive than two smaller beams at 1m centres.

Thus, substantial reductions in costs can be achieved whilst at the same time retaining comparable strength and durability (Fig. 4). Research has shown that significant enhancement to durability/sustainability can be achieved by utilising:

1. Concrete with fibres to reduce cracking or taking advantage of the fact that for a given degree of restraint the strength of slabs developing arching action significantly increases with concrete strength.
2. Conventional steel reinforcement located in a single layer at the centre of the slab (greatly increased cover).

These approaches have performed well in laboratory and field tests as anticipated, and it is clear that by using high strength concrete (with or without fibres) in conjunction with corrosion free reinforcement, bridge decks could be produced which should be virtually maintenance free (Fig. 4).

![Figure 4. Comparison of the total unit cost of beam and slab superstructure over their service life](image)

4.3 Development of a novel flexible concrete arch system

Brick or stone masonry arch bridges have been utilised for thousands of years and have proven durability. However, it is no longer economically viable to construct a masonry arch in the traditional way due to the cost of accurate centring and the preparation of the masonry blocks. In order to provide a viable alternative Queens University Belfast, in collaboration with Macrete Ireland Ltd, have developed a flexible concrete arch system made of un-reinforced pre-cast concrete voussoirs. The arch system is constructed and transported to site as a flat pack arch. A polymer grid reinforcement is used to carry the self weight during lifting to form a masonry arch. The preferred method of construction of the arch unit is as follows:

*The voussoirs can be pre-cast individually, laid contiguously in a horizontal line with a layer of polymer grid reinforcement placed on top. An in-situ layer concrete, is placed on top and allowed to harden to interconnect the voussoirs.*

The arch unit can be cast in convenient widths to suit the design requirement, site restrictions and available lifting capacity. When lifted, the wedge shaped gaps close, concrete hinges form in the top layer of concrete and the unit is supported by tension in the polymer grid. The arch
shaped units are then placed on precast footings and all self-weight is then transferred from tension in the polymer to compression in the “voussoir” elements of the arch.

The novel arch system has been demonstrated\(^{[12]}\), to be a viable alternative to long established methods of construction and the following advantages have been identified:

1. As the Arch system is cast horizontally it can conveniently be transported to site in a “flat pack” form.
2. As centring is not required during installation this greatly simplifies the process and enhances the speed of construction.
3. As there is no corroding reinforcement the long term durability is assured.
4. The system is cost competitive with less aesthetic RC box culverts.

5 CONCLUDING REMARKS

The sustainability of our infrastructure is now accepted as a key issue in many parts of the world and it is essential that the construction industry recognises the important role it has to play and responds positively to the associated challenges. Within our transportation network, crucial for the continued economic growth of our nation’s bridges form a critical part. Deficiencies in the durability/strength of bridges which necessitate repairs/replacement can lead to considerable disruption/congestion within the network and have a very negative impact on sustainability. Thus, bridge engineers will have to integrate aspects of sustainability, such as the relative merits of different forms of construction, maintainability and associated congestion, into the total life cycle cost design process.

Innovative research carried out over the past 30 years at Queen’s University Belfast has been aimed at increasing the durability of concrete structures and bridges in particular and has led to the following conclusions:

1. The availability of improved in-situ test methods paves the way for greatly enhanced durability by design for new and existing concrete structures.
2. Advances in structural design based on research on arching action in bridge deck slabs can lead to virtually maintenance free systems.
3. The flexible concrete arch system, which can be transported to the site in “flat pack” form and avoids the need for centring, has great potential.

6 ACKNOWLEDGEMENTS

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REFERENCES


Maintenance, reconstruction, repair, strengthening and rehabilitation of existing masonry buildings

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ABSTRACT: For the last decades, intensive activities on maintenance, reconstruction, repair, strengthening and rehabilitation of existing masonry buildings has been carried out. The reasons for such an extensive reconstruction is the increasing need of residential area, revitalization and repair of structures that are many years old as well as improvement of the quality of living of the occupants of those structures. Presented in the paper shall be the general aspects, proposed procedure for design and analysis of masonry building structures, traditional concept for repair and strengthening and some practical cases from Macedonia and Turkey.

1 INTRODUCTION

Masonry structures and masonry in general have been among principal construction materials for centuries. This is due to its good characteristics as is the thermal insulation, soundproofing, hygroscopy etc. However, the experience from occurred earthquakes points to unfavorable behaviour of masonry structures. Masonry structures have suffered mass failure and heavy structural damage.

Masonry structures are massive, with a high bearing capacity of walls under pressure, insufficient bearing capacity under tension, low ductility capacity and inadequate connection of structural elements into a whole, particularly inadequate interconnection of bearing walls in both orthogonal directions and inadequate connection of bearing walls with the floor structures. The buildings are mainly designed and constructed to sustain vertical - gravity loads.

Under horizontal - seismic loads, the bearing and deformability capacity is not satisfying considering that there is no integrity of horizontal and vertical bearing elements of the structure as well as the fact that the strength of bearing walls under tension and shear is considerably low.

Based on the performed synthesis of results from analytical and experimental investigations of elements of masonry systems in the world and in our countries, as well as the investigations carried out in IZIIS – Skopje and Engineering Faculty-Izmir, shown will be a procedure for design and analysis of new structures as well as repair and strengthening of damaged masonry systems exposed to static and dynamic effects.

The procedure consists of analysis of external effects, vertical and horizontal, static and dynamic, experimental tests of the characteristics of materials and behaviour of bearing elements under cyclic loads, proportioning of the constituent elements with controlled and dictated behaviour in all phases of behaviour up to failure and response of the system under real seismic - dynamic effects.

Developed are computer programmes for analysis and proportioning of elements of masonry systems with controlled behaviour and programme for nonlinear behaviour of the systems as a whole, under actual seismic effects, in which all the elements affecting structural response are included with their strength and deformability characteristics.

Presented in the paper shall be two practical cases, one from Macedonia and Turkey.
2. THE CRYSTAL PALACE IN BITOLA, MACEDONIA

2.1 Building features

The Crystal Palace – Bitola is located in the very centre of the city. With its extraordinary architecture, it attracts attention and is rightfully considered a show-piece among the army members, the Bitola citizens and beyond. The principal structural system of the building consists of bearing walls constructed of stone and brick in lime mortar in both orthogonal directions. The basement walls are constructed of stone in lime mortar in both orthogonal directions. Over the basement, all the walls, both interior and façade, are constructed of solid bricks in lime mortar. The foundation structure consists of strip foundation constructed of stone in lime mortar. The floor structures over the basement and the ground floor represent flat reinforced concrete slabs. Over the ground floor, i.e., the gallery, the floor structures represent flat Prussian vault and flat plate at the sanitary knots, while over the second storey, they partially represent flat plate and fine ribbed reinforced concrete structure. The roof structure is constructed of wood, with a roof cover constructed of interlocking pantiles (Fig. 1-4).

2.2 Historical background

The history of the Crystal Palace started in the distant 1911, when the construction of the building started upon the order of the then administrator of the Bitola district – Abdul Kerim – pasha. The architectural style of the building is mainly Islamic although there are also elements pertaining to the European architectonic styles. With the occupation of Vardar Macedonia by the State of Cerbs, Croats and Slovenians in 1918, the new authorities started to repair the damages and complete the interior of the building. The structure was completed several years after the end of the First World War. For its extraordinary beautiful architecture, the Crystal Palace represents a cultural monument.

Figure 1. General view
2.3 **Damage assessment**

During the earthquake of September 1, 1994, the building suffered considerable structural damage expressed via diagonal cracks in the bearing walls in both orthogonal directions, particularly in the longitudinal direction, that have contributed to a considerable decrease of the bearing capacity and certain disintegration of the bearing structural system under vertical and particularly horizontal loads.

2.4 **Description of past interventions**

No significant interventions in the past.
2.5 Design requirements

The structure of the building is characterized by considerable structural damage and certain disintegration of the bearing structural system in both orthogonal directions that contributes to a considerably decreased bearing capacity under vertical and particularly horizontal loads.

To make the structure functional again, it is necessary to repair and strengthen it in order to satisfy the requirements for the performance of its functions and the existing regulations.

Based on the performed analysis of the principal structural system, the following conclusions have been drawn:

The analysis of strength and deformability characteristics of the building has shown that the strength capacity at the base of the structure is 5.7% of the total weight of the structure in X-X direction and 11.5% in Y-Y direction, whereas the relative storey displacement capacity ranges between 1.03 to 1.82 cm.

The relative storey displacement capacity is relatively low. Relative storey displacements of such an order do not satisfy the requirements in case of occurrence of earthquakes with intensity and frequency content that can be expected in this area.

From the above stated, it is clear that it is necessary to improve the deformability characteristics of the bearing structural system in order to satisfy the main requirements set out in the existing technical regulations.

2.6 Rehabilitation options

Based on the required strength and deformability characteristics of the elements and the system as a whole, there have been proposed and analyzed a number of variant solutions for strengthening of the structure. From among a number of variant solutions, the most appropriate solution from economic aspect and from the aspect of satisfying the strength and deformability requirements from the valid technical regulations, has been selected (Fig. 5-9).

The solution for repair and strengthening of the principal structural system anticipates the following:

- Injection of the cracks in the walls and around the staircases.
- Connection of the longitudinal walls along the perimeter of the hall with reinforced-concrete belt course with a thickness of 40 cm and a width of min. 20 cm on the inner side of the external walls.
• Strengthening of the bearing walls with reinforced-concrete jackets on the inner side, with defined thickness and reinforcement, according to the enclosed details. The jackets at the level of the floor structure are to be connected with the horizontal belt courses, either existing or newly formed. The jacketed walls of the hall are to be connected by metal profiles according to the area available between the windows, in compliance with the details. The reinforcement concentrated in the jackets is to be pulled through the floor structures, while the uniformly distributed one is to run from storey to story and to be welded from place to place with the reinforcement of the floor structures or the hori-
zontal belt courses. The jackets are to be connected to the brick walls appropriately by cleaning of the joints, cramps with corresponding reinforcement and metal anchors.

- Rebuilding and partial closing of individual openings with walls of solid brick in cement lime mortar, with the same thickness as that of the existing bearing walls, framed with vertical and horizontal reinforced concrete belt courses.
- Foundation of jackets on bolsters with dimensions and reinforcement according to the details.
- Strengthening of the floor structure over the first storey that represents a Prussian vault, with a monolith reinforced concrete slab resting on the walls via an RC belt course, with proportions and reinforcement according to the details.
- Repair of the roof structure, particularly rearrangement of displaced tiles.
- Replacement of the installation for atmospheric water outlet from the roof and in the near surrounding of the structure.
- Replacement of the lighting arrester installation.
- Cleaning, repair and painting of the external façade.
- Plastering and painting of the interior walls.

Presented in the report are the minimal necessary elements for repair and strengthening of the principal structural system. The contractor may have own reasons and possibilities for performance of the works or equipment and material available to adopt different dimensions of elements or different reinforcements, however, the dimensions and the reinforcements must not be less than those defined in this report. The reinforced concrete elements of the structure are proportioned according to the theory of ultimate bearing capacity, i.e., according to PAB87, in accordance with the valid technical literature.

From the analysis of strength and deformability capacity of the repaired and strengthened structure, it has been confirmed that the strength and deformability requirements set out in the valid regulations have been satisfied.

2.7 Critical evaluation of proposed interventions

Analysis of the repaired and strengthened system

Analysis of strength and deformability of elements and the integral system up to ultimate states of strength and deformability has been performed for the strengthened structural system.

Based on the performed analysis of the repaired and strengthened system, the following has been concluded: The analysis of strength and deformability characteristics of the structure shows that the strength capacity at the base of the structure is 15.0% of the total weight of the structure in X-X direction and 15.4% in Y-Y direction, whereas the relative storey drift capacities range from 1.60 to 5.30 cm. These data are taken from the manually schematized force – displacement diagrams. From the diagrams, it is clear that the strength and deformability capacities are actually greater as is also the capacity for seismic energy dissipation.

![Figure 7. Storey P-∆ diagram, direction X-X, repaired state](image-url)
Based on the defined masses, stiffness and displacement of each storey and direction and the evaluated expected seismic effects, dynamic analysis of the structure has been carried out with consideration of actual seismic effects. Considering the fact that there are no defined seismic parameters of the site as well as corresponding time histories of earthquakes with different frequency content, there have been defined the maximal intensities of different earthquakes for which the required maximal relative storey drifts reach the characteristic points of the strength-deformability storey diagrams in both orthogonal directions.

**Analysis of roof structure**

Considering the fact that there is no damage to the bearing system of the roof structure and that there are elements with proportions that considerably exceed the necessary ones for the spans and the support, it has been concluded that the roof structure satisfies the requirements and that its modification is not necessary. During rearrangement of the displaced tiles, any observed damaged elements are to be replaced.

**Details**

Corresponding details are given for the characteristic new elements of the structure, while for all the new elements, details have been elaborated along with specification of material.

**2.8 Conclusions**

With its strength and deformability characteristics, the existing structural system does not satisfy the requirements according to the regulations and recent knowledge on the behaviour of masonry structures exposed to gravity and seismic effects.

The repair and strengthening of the bearing structural system has been carried out in such a way as to satisfy the requirements set out in the valid technical regulations and the requirements referring to controlled dynamic response of the structure.

The strengthening of the structure practically enables increase of stiffness, strength and deformability whereat these three characteristics are optimized in such a way that optimal quantities are obtained to provide the required seismic safety.

Presented in the report are the least necessary elements for repair and strengthening of the principal structural system through proportions and reinforcement.

The analysis of the strength and deformability characteristics of the structure shows that the strength capacity at the base of the structure is 15.0% of the total weight of the structure in X-X direction and 15.4% in Y-Y direction, whereas the relative storey displacement capacities range from 1.60 to 5.30 cm. The strength capacity of the structure in Y-Y direction is higher than that required with the regulations, amounting to 15% of the total weight of the structure, whereas the relative storey displacement capacities are satisfactory.
The maximal accelerations as percentage of ground acceleration for different earthquakes and for both characteristic points on the schematized working shear storey force – relative storey displacement diagram for the so called “Y” point range from 0.10 to 0.16 g, while for point “U”, these range from 0.25 to 0.32 g, which is within the limits of the expected earthquake intensities at the considered site.

The analysis of the strength and deformability capacity of the repaired and strengthened structure has proved that the requirements pertaining to strength and deformability according to the valid regulations and recent knowledge on behaviour of masonry structures exposed to static – gravity and dynamic – seismic loads, are satisfied.

3 REHABILITATION OF HISTORICAL MASONRY MILITARY BUILDING IN TURKEY

3.1 Introduction

Turkey is located on one of the most active earthquake areas on earth. Nearly 95% of Turkey is on very risky seismic zones. Therefore high-magnitude earthquakes commonly occur in Turkey. The structures suffer a very high amount of damage during these seismic activities and earthquakes cause widespread destruction. Major seismic events during the past decade, such as those occurring in Turkey: Erzincan, Turkey (1992); Kocaeli, Turkey (1999); Duzce, Turkey (1999); Bingol, Turkey (2004). Those earthquakes have continued to demonstrate the destructive power of earthquakes, with destruction of engineered buildings, bridges, industrial and port facilities as well as giving rise to great economic losses.

As a result, the need to improve seismic performance of the built environment through the development of performance-oriented procedures and guidelines has been recently highlighted.

3.2 Building features

The principal structural system of the building consists of bearing walls constructed of stone and brick in lime mortar in both orthogonal directions. The roof structure is constructed of wood, with a roof cover constructed of interlocking pantiles (Fig. 10-13).
3.3 Historical background

The building was used as a school building in early 1900s as seen in the photo. After 1950s, building was given to military services.

3.4 Performance Check of Structures

In order to define how the structure will perform when it is subjected to a given level of earthquake, we need to define structural performance, earthquake level and performance level.


Methods used for obtaining lateral load capacity of structures: linear static analysis, linear dynamic analysis, nonlinear static analysis (pushover analysis) and nonlinear dynamic analysis.

We perform pushover analysis because: design Earthquakes cause nonlinear behaviour; better understand building behaviour; identify weak elements with plastic hinge formation and order; realistic prediction of element demands and less conservative acceptance criteria can be used than linear analysis.

3.5 Performance Check Using Pushover

- Construct Pushover curve
- Select earthquake level(s) to check and construct their spectrum curves
- Decide the performance level(s) (i.e.: IO, LS, CP)
- Verify structural performance with guidelines
  - Capacity Spectrum Method (ATC-40)
  - Displacement Coefficient Method (FEMA 273)
  - TERDC – 2006 (Turkish Earthquake Resistant Design Code)

Shear capacity of each floor is not enough for resisting earthquake loads (Table 1).

The Building is going to be retrofitted. Shear capacity of repaired state for each floor is higher than required (Table 2).
Table 1. Shear capacity of each floor (existing state)

<table>
<thead>
<tr>
<th>Shear Stresses of Masonry Walls</th>
<th>τ_{max} (t/m²)</th>
<th>τ_{allowable} (t/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Floor</td>
<td>50.76</td>
<td>15.00*</td>
</tr>
<tr>
<td>1st Floor</td>
<td>55.31</td>
<td>15.00*</td>
</tr>
<tr>
<td>2nd Floor</td>
<td>39.41</td>
<td>15.00*</td>
</tr>
<tr>
<td>3rd Floor (Tower)</td>
<td>99.37</td>
<td>15.00*</td>
</tr>
<tr>
<td>4th Floor (Tower)</td>
<td>60.00</td>
<td>15.00*</td>
</tr>
</tbody>
</table>

Dynamic model of structure: lumped mass model of the building (Fig. 12). The Wall Weights are higher than Slab Weights and, they can not be neglected in the lumped mass model.
Figure 13. Details
Table 2. Shear capacity of each floor (repaired state)

<table>
<thead>
<tr>
<th>Shear Stresses of Masonry Walls</th>
<th>τ&lt;sub&gt;max&lt;/sub&gt; (t/m²)</th>
<th>τ&lt;sub&gt;allowable*&lt;/sub&gt; (t/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Floor</td>
<td>50.76</td>
<td>72.40</td>
</tr>
<tr>
<td>1st Floor</td>
<td>55.31</td>
<td>72.40</td>
</tr>
<tr>
<td>2nd Floor</td>
<td>39.41</td>
<td>72.40</td>
</tr>
<tr>
<td>3rd Floor (Tower)</td>
<td>99.37</td>
<td>154.00</td>
</tr>
<tr>
<td>4th Floor (Tower)</td>
<td>60.00</td>
<td>154.00</td>
</tr>
</tbody>
</table>

4 CONCLUSIONS

With its strength and deformability characteristics, the existing structural system does not satisfy the requirements according to the regulations and recent knowledge on the behaviour of masonry structures exposed to gravity and seismic effects.

To repair and strengthen the principal structural system, a number of variant solutions have been proposed and analyzed. From among a number of variant solutions, there has been adopted the most appropriate solution from economic aspect and from the aspect of satisfying the strength and deformability requirements pertaining to the valid technical regulations.

The repair and strengthening of the bearing structural system has been carried out in such a way as to satisfy the requirements set out in the valid technical regulations and the requirements referring to controlled dynamic response of the structure.

The strengthening of the structure practically enables increase of stiffness, strength and deformability whereas these three characteristics are optimized in such a way that optimal quantities are obtained to provide the required seismic safety.

Presented in the report are the least necessary elements for repair and strengthening of the principal structural system through proportions and reinforcement. The contractor may, due to own reasons and possibilities for performance of the works as well as available equipment and material, adopt different proportions of elements or different reinforcements, however the proportions and the reinforcements must not be lower than those defined in this report.

It is necessary that each change be reported to us in order that we might check whether the change affects the level of seismic protection and stability of the structure.

The analysis of the strength and deformability capacity of the repaired and strengthened structure has proved that the requirements pertaining to strength and deformability according to the valid regulations and recent knowledge on behaviour of masonry structures exposed to static – gravity and dynamic – seismic loads, are satisfied.

The report also contains the results from controlling the foundation of the existing and the repaired structure. It has been adopted that the foundation of the newly designed elements should not induce considerably higher stresses in soil than those induced in the foundation of the existing structure compliant to the results from the geomechanical investigations.

REFERENCES

Demolition and reconstruction of bridges

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**ABSTRACT:** The traffic density is growing during the last decades. As a consequence numerous new roads and railway lines were built or are planned to be realized in the near future. Along with that, existing bridges must carry the increased traffic. Most of these bridges were not originally designed for the high service loads and the amount of traffic of today. Many of the structures are aged and, depending on the maintenance and repair carried out, do not longer suit the purpose.

This paper discusses the potential for composite bridges for the reconstruction of old bridges with special focus on the specific requirements resulting from the existing environment and by severe constraints for site work. Via case studies structural systems, especially with the use of hot-rolled beams, and appropriate demolition and construction methods matching special site restrictions are presented and analysed.

1 INTRODUCTION

Road bridges are the most important carrier for the transport of people and goods. In the consequence of the stepwise enlargement of the European Union also the infrastructure has to be adapted. However these adjustments do not only affect the new members of the European Union. Also countries, e.g. Germany becoming a transit country, are facing new demands in the frame of the new European configuration.

As a consequence numerous new roads, and thus new bridges, have been built or are planned to be realised in the near future. Along with that existing bridges must carry the amplified traffic. Most of the existing bridges were not originally designed for the high service loads and the amount of traffic, which are applicable today. Many of the structures are aged and, depending on maintenance and repair carried out, do no longer suit the purpose. The increased traffic capacity requires often a deck widening for the carried traffic, or a longer span for the traffic to be bridged. These situations finally require the reconstruction of the bridge or replacement of the deck.

Over 220,000 railway bridges from 17 European railway administrations have been analysed in Sustainable Bridges (2003 – 2007) with the result, that the demand for reconstruction is significant. Similar information are available by the German administration which stated, that the share of the reconstruction of railway bridges will be larger than of building new bridges until the year 2015 [Schmitt et al. (2006)]. This is partly due to the changing demands on the clearance, the allowable loading and, mainly, the age distribution of the existing structures. For many aged bridges a refurbishment is not economic respectively realisable any more.

According to statistics short span bridges are the most frequent category for road as well as for railway bridges.
2 REFURBISHMENT

2.1 General

For the refurbishment of bridges intelligent solutions are requested. On one hand the interest of the public economy has to be satisfied; on the other hand the technical, economic and political boundaries have to be respected [Hechler et al. (2006)]. In this regard steel respectively composite constructions are providing an economical potential with the possibility to use cost-effective construction techniques and advanced construction procedures.

The final decision for a construction respectively refurbishment technique often purely depends on the construction costs. Although factors like user costs, costs for maintenance and repair as well as the possibility for strengthening should not be neglected. Further information can be found in Hechler & Girkes (2007).

Frequently there is mainly a need for deck replacement, whereas work on foundations, abutments and piers is limited to repair, strengthening or minor adjustments. Self-weight of the deck structure is then an essential parameter, as actual overall load capacity cannot be exceeded. It is particularly crucial if the new bridge should carry heavier traffic loads than those of the original design. Composite decks with steel girders supporting a reinforced concrete slab meet this requirement. The developed high strength steel grades for rolled beams (S460 with yield strength equal to 460 N/mm²) offer an additional possibility to reduce steel weight.

2.2 Case study: Refurbishment of a road bridge

A good example for refurbishment of a deck is the wooden bridge located in Buchfart (see Fig. 1), a small city of about 5km in the south of the Schloß Belvedere in Weimar. The origin of this crossing, called Ilmbrücke, goes back into the 16th century. This roofed bridge today is of the 18th century and represents a landmark in the national heritage.

In the frame of refurbishing the wooden roof, the deck has been adopted to the traffic demands of today. The old abutments could be sustained economically using hot-rolled sections.

Figure 1. Landmarked wooden bridge in Buchfart, Germany, after deck replacement

3 RECONSTRUCTION

3.1 General requirements

The requirements for the reconstruction of a bridge are quite different from those of building an entirely new construction. The bridge must geometrically fit the existing traffic ways. If the foundations are reused, loading limitations have to be dealt with. Especially construction has to take place with space and time restrictions. An appropriate erection method must be chosen in order to minimize disturbance to existing traffic. Therefore careful analysis of the situation and expert design are needed for successful realisation of the projects.

Steel and composite construction offers many advantages by its flexibility, lightness and cost effectiveness. Primary bearing elements should be hot rolled beams which are industrially produced, available in a full range of sizes and steel grades, including high strength steel grades. Their advantages are [Hauser (2005)]:

- Rolled beams are an industrial product with high quality and good availability;
- Economic due to minimal fabrication costs;
- Large delivery length avoiding field jointing;
- Production in the mill and consequently delivery of end product to site ready for placing.
In addition the use of steel and composite construction complies with the requirements for reconstruction as follows [Hauser (2005), PR/0113 (1998 – 2001)]:

- Industrial produced members with just-in-time-transport to the site;
- Corresponding smaller construction sites and construction site equipment;
- Short and hardly weather depending construction time;
- Quality control already in the shop;
- Fast erection due to standard connections;
- Minimal noise and dust disturbance in the area of the construction site;
- Optimal realization of the principles of sustainable development.

Consequently replacement decks for short and medium spans are most frequently based on steel-concrete composite structural systems.

Overall a short construction time and an easy erection are leading to a sustainable construction. Inspecting composite bridges is simple with a large reliability [Schmitt et al. (2006)]. Tenders including the life cycle costs proof the competitiveness of composite construction for bridges with small and medium spans.

However there is no specific method for refurbishment or reconstruction. Each problem requires an individual solution. In the following case studies should show the great variety of solutions on the market from which ideas can be taken from.

3.2 Case study: Reconstruction of road bridges

If sufficient construction space is available, the new bridge may be built at a site located near the old bridge. This option greatly simplifies construction and traffic on the old bridge may be maintained until the completion of the new bridge. However this does not mean that all constraints are eliminated. Construction over traffic flow asks for purpose-designed solutions. Available construction depth imposed by infrastructure is often problematic.

If the span is short, prefabrication may include the entire deck or a part of it, however transport and lifting devices must be designed to carry the element weight safely and efficient. The size of the crane is determined by the necessary boom height and the required crane range.

A good example for a very efficient construction of a composite bridge is the Horlofftal Bridge. This bridge has 8 spans with an overall length of 236.2m; the single spans vary between 23.7m up to 35.9m. 5 spans have been built with rolled beams HE 1000 B with the steel grade S460M. The cross section is consisting of 4 beams with prefabricated slab elements.

This large spanning bridge is crossing two German railway tracks, a former mining area and the river Horloff. Due to a strict environmental classification and to avoid any influence on protected areas scaffolding was not allowed.

The most economic solution has been the construction of a composite bridge using prefabricated elements. Fabrication, including the corrosion protection of steel elements, has been carried out at the workshop. The scaffolding for concreting the caps and the devices for the safety at work have also been prefabricated and fixed to edge beams before placing. Consequently the clearance has not been interfered at all. The placing of the prefabricated composite beams is shown in Fig. 2, the almost finished bridge in Fig. 3.

![Figure 2. Horlofftal Bridge: Placing of the prefabricated composite beams](image)

![Figure 3. Horlofftal Bridge: Almost finished bridge](image)

The most critical construction step has been the erection of the beams over the railway tracks, as railway traffic could only be interrupted during a few hours at night.
Rolled beams are produced with a maximum length of 32m; exceptionally up to 40m. Consequently very long pieces can be delivered to site (if access allows for) and the number of splices, if any, is kept to a minimum. Pre-assembling prior to erection speeds up lifting into final position. Added bracing gives lateral stability to the elements during handling and construction. Cross beams in span should be avoided in the final state. Low weight of steel elements allows mostly erection by crane, which is a fast and cost-efficient method [7].

If the new bridge is built at the same site as the old bridge, reduced construction time is essential in order to minimize traffic disturbance. As mentioned above steel and composite construction meets the requirements through lightness, prefabrication and fast erection.

Figure 4 shows an example of a short span composite bridge which has replaced an old single lane steel wood bridge. The whole structure has been assembled at the contractors area and afterwards the bridge has been transported to the construction site. The displacement took place after some small adaptions of the abutments. The steel girders and the concrete deck and even the elastomer bearings, already situated on the main girders, were applied at once. After the application of the water-proofing, the displacement of the edge beams and the pavement the bridge was ready to be used. With this method the time of road closure could be reduced to a minimum time.

The mentioned advantages in construction and costs of composite bridges using prefabricated slabs have pushed their acceptance on the last years. Especially the short construction time is of great significance for inner-city projects.

For composite decks, precast concrete planks are most frequently used as formwork. As an alternative to site-concreting, precast deck units may be used, see Fig. 5. By this method consists in the reduction of the number of site operations is reduced and substantial saving in construction time is achieved. With this method especial attention has to be paid on the construction of the joints between the single pieces.

Figure 4. Displacement of the whole composite bridge

Figure 5. Placing of precast deck units

3.3 Case studies: Reconstruction of railway bridges

In urban areas the replacement of existing railway bridges has got the following motivation linked to the listed requirements:
Motivation

- Replacement due to danger of impact for cast-iron supports,
- Increased clearance,
- Increased carrying capacity,
- Corrosion of the superstructure,
- Elimination of railway level crossings.

Requirements:

- Retaining of the elevation of the rails,
- Noise reduced construction,
- Short interruption of the traffic on and under the bridge,
- Minimized overlap of superstructure over the abutments (minimal horizontal movement of superstructure).

The reconstruction of railway bridges is generally a subject with even more severe constraints than for road bridges. Complete traffic disruption is acceptable only for a short time. With multiple track lines, traffic may be diverted, but with the result of substantial speed and volume reductions. Hence the reconstruction method of short span railway bridges consists typically in:
- first constructing the new deck next to the site,
- dismantling the old deck and
- moving the new deck in its final location.

The work is organized in several steps, each corresponding to a single-track deck portion.

Most frequently with old decks, rails are directly fastened to the steel structure. Nowadays continuity of ballasted track over bridge sections is generally preferred. Consequently the construction depth of the new deck is reduced, requiring a more slender design. Filler beam construction solves the problem with a slenderness ratio of 30 to 40 [ARCELOR (2005)]. The new deck is constructed on temporary supports, parallel to the bridge. The old deck is dismantled. If needed, the foundations and abutments are strengthened or reconstructed (during these stages temporary track support may be required to minimize traffic disruption). The new deck is moved into position by lateral rolling- or sliding-in. A schematic view of this erection method is shown in Fig. 6.

Figure 6. Filler beam replacement decks on temporary supports before sliding-in

If available depth for the construction of the deck below the track is particularly low, trough bridges are appropriate. Each single track is supported by a floor slab of minimum depth spanning between the main girders at lower flange level, transversely to the bridge longitudinal axis. The floor slab is of filler beam type with steel beams acting as multiple cross girders. For lateral stability of the main girders, some of the filler beams are moment-connected to form rigid U-frames.

Fig. 7 shows the section of a trough bridge in Differdange, Luxembourg. Main girders are 1m deep rolled sections with a span length of 13m. Construction depth under the track corresponds to the 34cm thick filler beam slab. Two separate units were needed for the replacement of the old double track deck.

Figure 7. Section of trough bridge with filler beam deck
Assembling of the steel elements and concreting of the floor were carried out on site, close to the existing bridge. A mobile crane was used to remove the old deck and to lift the new structures into final position.

Another example is the bridge EÜ Bahrenfelder Kirchenweg in Hamburg, Germany (see Fig. 8, 9) with a span of 15m. The old superstructure divided in a north and south part, with a single track on each, was not satisfying the demands of the present traffic anymore. In the consequence of the restricting situation for refurbishment there has been an extremely limited construction height.

Finally a trough bridge with two rolled beams HL1100 M as longitudinal main beams and a filler beam deck in transverse direction based on HE 140 M has been constructed. As steel grade S355M has been chosen.

Alternatively, a mobile gantry crane moving on the rails may be used to bring the new deck into position. However the dimensions and weight have to be within the capacity of the special equipment. The deck replacement of the double track bridge crossing a canal in Roux, France, is an example of this method. The new deck has a span length of 15.7m and is of composite type, with 8 main girders (HE 900 M rolled sections) supporting a reinforced concrete deck. It was completely prefabricated (steel structure and concrete slab) in two pieces, one for each track, and brought to site with a mobile lifting device (SNCF-type with a capacity of 100t [mobile] and 170t [static]). After positioning over the old structure, the old deck was dismantled and the new one lowered into final position (Fig. 9). The work was carried out at night and took only a few hours for each half-deck.

An innovative modification of this method has been used for the reconstruction of the Geultalviadukt in Moresnet, Belgium. The original bridge has been built from 1915 to 1916 to ensure the logistics to the German troops in France during the First World War. It has got a span of 1153m, which had been divided into 22 steel superstructures weighting 6000t each on 21 piles, 5 piles have been designed to bear the horizontal forces (breaking, acceleration, wind). The maximal clearance is up to 53m.
The viaduct is over 80 years old and deteriorated. The speed had to be limited to 20km/h although the viaduct is part of a very important logistic railway line nowadays. After the reconstruction a speed of 60km/h should be possible.

Three alternatives for the reconstruction have been discussed:
- Complete deconstruction of the existing bridges and rebuilt a new bridge: this alternative was too expensive and is not respecting the protection of the national heritage;
- Reconstruction with a total cut-off and therefore redirection of the traffic: this alternative was not possible due to missing capacities for redirection;
- Reconstruction under traffic: which was finally chosen as the most efficient and economic solution; however the reconstruction should be carried out as fast as possible, with a minimum of traffic interference.

The consortium “Galere-Aelterman” started the reconstruction in 2003 which can be divided into 5 main steps:
- Refurbishment of the piles, see Fig. 12: the concrete up to the old reinforcement and the old reinforcement itself has been removed, new reinforcement has been applied around the residual net pile section, formed and concreted. Consequently a new box section has been constructed around the old pile however the residual inner section is participating to carry the loads on the pile. The supports for the new segments have been prepared on the new section.
- Pre-fabrication of the 22 superstructure segments, see Fig. 13: all assembling, welding, concreting etc. required has been carried out in a plant 3km next to the site including the application of the ballast, ties and rails, see Fig. 14. Each segment is 6mx6mx48m with 700t weight. Always 2 segments have been prefabricated at once in an interval of 4 weeks.
- Transport of the elements to the site: first the elements are moved out of the plant on the rails via Teflon plates and hydraulic jacks (2 parallel rails needed for one element of 6m width), the transport scaffolding is applied on the elements, see Fig. 15, and finally they are transported with 2 engines to the site.
- Exchange of elements, see Fig. 16 and 17: each new segment is positioned over the existing segment, the transport scaffolding is lowered and fixed to the renewed pile; the old segment is fixed at 4 winches at the scaffolding, cutted by oxygen, and dropped with the winches to the ground; the supports for the new segment are placed and the new segment is lowered down on the new supports; immediately afterwards the railroad works have been started.
- Recycling of the deconstructed elements.
The transport of the elements and the exchange process lasted 52h for 2 segments in a cut-off time of the railway line between Saturday (15.00h) to Monday (16.00h) only. It was even possible for trains to pass the scaffolding during construction.

4 CONCLUSIONS

Reconstruction of bridges is characterized by specific requirements resulting from the existing environment and by severe constraints for site work. Composite decks with especially steel beams made of hot rolled sections meet these requirements through the variety of structural systems and dimensional flexibility, particularly if available construction depth is restricted. By using prefabrication and an appropriate erection method, traffic disturbances are kept to a minimum.

A number of case histories have confirmed that a good overall efficiency is achieved by using rolled beams in steel and composite construction, both for road and railway bridges.

For the final choice of a construction technique safety, robustness, sustainability and competitiveness should be the main governing factors.

REFERENCES

Innovative forms of construction for sustainable bridges

Queen’s University Belfast & Crane Environmental Ltd. UK

ABSTRACT: After a brief overview of sustainability issues details are given of recent research at Queen’s University Belfast on two innovative forms of construction, both of which have the potential to be highly sustainable. The first is on un-reinforced concrete bridge desk slabs and the second is the development of a flexible concrete arch system for short span bridges with no steel reinforcement.

1 INTRODUCTION

Within most regions in the world the built and natural environments are constantly interacting and they are inseparably linked. Energy, materials, water and land are all consumed in the construction and operation of buildings and infrastructure to such an extent that sustainable development can be said to depend on the built environment. The world’s cities have a major impact on emissions of ‘green house gases’ and global warming: they take up around 2% of the earth’s surface but account for nearly 80% of the carbon emissions from human activities. The urban environment influences our living conditions, social well-being and health. Thus, the performance characteristics and quality of our infrastructure are of fundamental importance to urban sustainability and the well-being of our environment. The significance of this should not be underestimated especially if it is borne in mind that our infrastructure accounts for at least 50% of our national wealth.

Sustainability issues in construction are characterised by their complexity, the diversity of those involved and the need for innovative and special solutions. As the largest and most fragmented industry, the construction sector faces huge challenges in the pursuit of sustainability. Sustainable construction is a way for the industry to move forward, taking into account environmental, socio-economic and cultural issues.

Enhanced sustainability can be achieved through an integrated approach, by adopting innovations in technologies and by taking it into account early in the design process. In this context more detailed information is provided in this paper of two technological innovations which could lead to much more durable and sustainable forms of construction. The development of maintenance free bridge deck slabs and a flexible concrete arch system for short span bridges is backed up by laboratory testing at Queen’s University Belfast and complementary field testing.

2 ENHANCED SUSTAINABILITY OF CONCRETE BRIDGE DECKS BY DESIGN

2.1 Background

Bridges with spans of up to 30m constitute the vast majority of road infrastructure bridges in service across the world – whether it is for overpasses/underpasses for motorways or for minor
river crossings. Within this category of bridges concrete deck slabs are widely used whether in combination with pre-cast pre-stressed concrete beams or steel girders. A similar type of deck can also be utilised for many medium span bridges hence the importance of designing a durable deck system cannot be overemphasised.

Over the past 20 years it has been found that many concrete bridges (concrete was selected in the 1960/70’s for its inherent durability) have exhibited problems, such as spalling, associated with reinforcement corrosion. Such problems are particularly prevalent in marine environments or where freezing/thawing conditions require the intensive use of salt to prevent the formation of ice. In the latter case the vulnerability of the reinforcement in the deck slab is exceptionally high and in many instances deck slabs have to be repaired/replaced at great cost within 20-30 years. This causes great disruption to traffic and the associated costs of congestion are high.

A further problem for bridge deck slabs is that they have to be assessed structurally to ensure that they can carry the heavier lorries now on our roads. These deck slabs would in many cases be found to be unsatisfactory were it not for an inherent strength which is not taken into account in normal flexural design approaches. In particular it is accepted that the capacity of the slab elements of beam and slab decks is greatly enhanced due to the restraint provided by the beams and diaphragms. This enhancement has been recognised by a number of bridge authorities worldwide by incorporating it into their national design codes. The recognition of arching action is most important as it can mean the difference between a bridge deck passing or failing the assessment requirements.

In this paper the greatly enhanced strength associated with arching action, which is clearly of benefit for increased loadings, when taken into account in the design process can be shown to produce concrete bridge decks which are more durable than current designs.

2.2 The concept of arching action in slabs

With the advent of Johansen’s [1962] yield line theory in the 1940s designers and researchers felt that at long last they had a prediction method for slabs which would provide realistic strength estimates. However, the tests carried out by Ockleston [1955] on interior panels of the Old Dental Hospital in Johannesburg revealed collapse loads of 3~4 times those predicted by the yield line method. This enhanced capacity was attributed to the development of an internal arching mechanism arising from the restraining effect of the surrounding panels.

Where a beam is restrained against longitudinal expansion, the concept of arching can best be understood by referring to Fig. 1. With the development of tension cracks at mid-span and at the supports the beam tries to expand longitudinally but as it is restrained, corresponding forces are induced which allow it to sustain a substantial load on the basis of the arching thrusts which develop as the deformation increases. Similar actions take place in two-way systems and this phenomenon is generally referred to as "Compressive Membrane Action" (CMA). The extent of the enhancement provided by CMA, over and above the flexural strength, depends on the degree of restraint provided by the surrounding structure. A typical load deflection curve with the notional contributions separately identified is given in Fig. 2.

2.3 Relevance to bridge deck slabs

Tests on model bridge deck slabs in the Civil Engineering Department, Queen's University, Kingston, Canada, in the late 1960s revealed considerable reserves of strength against punching failure [Tong & Batchelor, 1971]. The cause of this enhancement was correctly identified as CMA and its particular relevance to transient concentrated wheel loads was recognised. Bridge decks represent one of the first areas to be considered appropriate for the utilisation of these design concepts because the major localised loading is transient in nature and creep is not significant.

On the basis of small scale model tests a conservative design method was produced. Thus, in the Canadian design standards [2005] for beam and slab bridges, nominal transverse reinforcement, only 0.3% was required to resist concentrated wheel loadings as opposed to the 1.7% based on flexural design requirements. Similar design concepts are now accepted in various states in the USA and to date no adverse effects have been detected from these reductions in levels of reinforcement.
2.4 Research on arching action in the UK

2.4.1 Validation tests in Northern Ireland
In the knowledge of the research carried out in Canada on AASHTO girder based beam and slab bridge decks it was decided that parallel tests should be carried out on spaced M-beam (essentially a range of depths of prestressed I-beams with a narrow top flange and a broad bottom flange 1m wide) decks to determine whether similar reductions in transverse reinforcement were possible. This would allow a slightly larger M-beam to be used at a spacing of 1.5m or 2.0m with consequent savings relative to smaller M-beams at 1.0m spacing. In order to establish the strength of the slabs spanning between beams a one-third scale model bridge deck was constructed in the laboratory and tested at Queen's University Belfast, in the late 1970s.

The flexural design of the prototype slab for the two 112.5kN wheel loads indicated that steel reinforcement of the order of 1.7% was required. For test purposes areas of reinforcement equivalent to approximately 1.7%, 1.2%, 0.5% and 0.25% were provided in the model along with three panels equivalent to 2m spacing and two panels equivalent to 1.5m beam spacing providing a total of 20 panels for testing.

2.4.2 Model test results and prediction method
The ultimate load capacity of the 20 test panels was determined as the load which caused the loading shoe (simulating the wheel load) to punch through the slab in the characteristic manner. It was found that there was very little variation in the ultimate load capacity of all the panels even though the transverse reinforcement varied from approximately 0.25% to 1.7%. In comparison with design code predictions (Fig. 3) the results of the tests on the one-third scale model with the M-beams spaced at up to 2m apart showed considerable enhancement over the design capacity of the standard slab.

Figure 3 clearly shows that the codes do not give a satisfactory prediction of the punching shear capacity of typical bridge slabs and a more appropriate method which allows for in-plane restraint was therefore developed. This method makes use of an effective steel reinforcement ratio, and full details of the method and its derivation are given in Kirkpatrick et al, 1984. As can be seen from Fig. 3 the proposed method of predicting the punching shear strength of reinforced concrete bridge slabs gives good correlation with the results from the one-third scale model. This method has now been endorsed by the UK Highways Agency.

2.5 Serviceability of deck slabs
The ultimate load tests referred to above have indicated that strength is not critical in the design of deck slabs; however, designers also have to satisfy the serviceability limit state requirements. Thus, full-scale tests [Kirkpatrick et al, 1986] were subsequently carried out on a bridge built by the Northern Ireland Roads Service. This bridge incorporated beams at 1.5m and 2m spacing,
and the reinforcement varied from 0.25% to 1.7% in the standard 160mm thick deck slab. Initial cracking occurred at loads well in excess of the design service loads and even after cracks had been induced by severe overloading it was found that the slabs still satisfied the serviceability limit state requirements.

2.6 Review of the advantages arising from CMA

From a structural viewpoint the following benefits are evident:
1. Reduction in reinforcement (from 1.7% to 0.5% or less);
2. Same slab depth for greater spacing of beams; and
3. Lower overall cost of bridge superstructure as one larger beam at 2m centres is less expensive than two smaller beams at 1m centres.

Thus, substantial reductions in costs can be achieved whilst at the same time retaining comparable strength and durability. However, if the long-term durability of the bridge deck could be increased at a modest increase in cost then the whole life cost could be reduced as can be shown schematically in Fig. 4. Thus, the challenge to designers is to achieve the type of relative performance achieved by the CMA deck (enhanced durability). Significant progress of this front has been achieved in Canada [Mufti et al, 1993] and the UK in recent years.

![Figure 3: Test results of one-third scale model bridge deck](image1)

![Figure 4: Comparison of the total unit cost of beam and slab superstructure over their service life](image2)

2.7 Improved sustainability by design – developments in the UK

The system developed in Canada is not applicable to decks with pre-cast prestressed concrete beams which tend to be significantly more popular across the world. Thus, a number of alternative approaches have been the subject of ongoing research both in the laboratory at Queen's University Belfast and on site in conjunction with the Department of Regional Development-DRD (NI) Roads Service [Taylor et al, 2003]. This work focused on the following subjects:

1) Concrete - As well as considering the addition of fibres, advantage is being taken of the fact that for a given degree of restraint the strength of slabs developing CMA is significantly enhanced by increases in concrete strength.

2) Reinforcement - Apart from considering the lower percentages of top and bottom reinforcement (0.5% vs. 1.7%) site and laboratory tests have been carried out on:
   (i) Conventional steel reinforcement located in a single layer at the centre of the slab (greatly increased cover).
   (ii) Glass fire reinforced plastic reinforcing bars.

Both approaches have performed well, as anticipated, and it is clear that bridge decks could be produced which should be virtually maintenance free. Because of the lower percentages of
reinforcement these need not have a higher initial cost than conventionally decks hence it could be of enormous benefit to bridge owners.

2.8 Conclusions from CMA research
A sufficient understanding of the structural benefits of compressive membrane action for bridge deck slabs has now been achieved. This will allow:

(i) The enhanced strength and serviceability of laterally restrained slabs to be taken into account in the assessment of beam and slab bridge decks.
(ii) CMA concepts to be incorporated into relevant national design codes.
(iii) The development of durable deck slabs, which will be virtually maintenance free.

The net effect of all the above is more cost effective bridge decks which exhibit greatly enhanced sustainability relative to existing designs.

3 NOVEL FLEXIBLE CONCRETE ARCH FOR SUSTAINABLE BRIDGES

3.1 Background to the novel arch system
Masonry arch bridges are one of the oldest forms of bridge construction and have been in existence for thousands of years. Brick and stone arch bridges have proven to be highly durable as most of them have remained serviceable after hundreds of years. In contrast, many bridges built of modern materials have required extensive repair and strengthening after being in service for a relatively short part of their design life. This section describes the development of a novel flexible concrete arch system that has the potential to be highly sustainable due to the low or zero amount of steel reinforcement. It is no longer economically viable to construct a masonry arch in the traditional method due to the cost of skilled labour required to build the accurate centering and to cut the masonry blocks. Progress on this type of work is usually slow and can be weather dependent. In order to provide a viable alternative Queen’s University Belfast, in collaboration with Macrete Ireland Ltd, are developing a flexible concrete arch system made of un-reinforced pre-cast concrete voussoirs. The arch is constructed and transported in the form of a flat pack using a polymer grid reinforcement to carry the self weight during lifting but behaves as a masonry arch once in place.

Basically there are two options for the construction of the arch unit. The voussoirs can be pre-cast individually, laid contiguously horizontally with a layer of polymer grid material placed on top. An in-situ layer of concrete, approximately 40mm thick, is placed on top and allowed to harden to interconnect the voussoirs. The same unit can be made in a single casting operation by using a shutter with wedge formers spaced to simulate the tapered voussoirs. Both forms of construction are shown in Figs. 5 and 6. The arch unit can be cast in convenient widths to suit the design requirement, site restrictions and available lifting capacity. When lifted, the wedge shaped gaps close, concrete hinges form in the top layer of concrete and the unit is supported by tension in the polymer grid. The arch shaped units are then placed on precast footings and all self-weight is then transferred from tension in the polymer to compression in the arch.

3.2 Materials
Paragrid® polymeric reinforcement was utilized in conjunction with the concrete in the voussoirs which had a 28 day compressive strength of around 55MPa.

3.3 Manufacture of the arch unit
A prototype arch unit of 5m span, 2m rise and 2.5 m internal radius was constructed and lifted. This arch required twenty-three voussoirs which were 1m wide and 200mm deep with a 40mm slab interconnecting in-situ screed. The arch was lifted at approximately the quarter span points
with additional nominal support at the mid-span region. During lifting the arch drags at the each end and the mid span point tends to sag; hence the need for the additional support. When the end cantilevers are fully effective they produce a hogging moment in the mid-span region which assists in the formation of the arch. During this operation a critical case occurs when the arch is fully formed and suspended at the lifting points. A maximum bending moment occurs at the lifting points for the cantilever ends and to simulate this condition a series of short beam elements were tested to establish the capacity and to investigate the rate of creep in the low modulus polymer reinforcement. These were found to give an adequate factor of safety during the lifting procedure. The lifting sequence is shown in Fig. 7.

The arch unit complete with tapered seating is shown in Fig. 7c. Subsequently, an anchor block detail was designed for the seating of the arch ring. The anchor block caters for the slope of the last voussoir enabling the arch to form correctly. It also provided some lateral restraint to the arch ring both during construction, prior to completion of the arch system with spandrel walls and backfill, and in the long-term under live loading.

![Figure 5: Construction of arch unit using pre-cast individual voussoir concrete blocks](image1)

![Figure 6: Monolithic construction of the arch unit using a special form of pre-cast wedges](image2)

### 3.4 Stability test

#### 3.4.1 Test set-up

To assess the flexibility of this system, a stability test under backfilling operations was conducted and the arch unit was monitored for horizontal deflections, vertical deflections and strain at the voussoirs joints. It was originally intended to use granular backfill. However, after a preliminary cost estimate for this span, it was decided to trial the use of lean mix concrete as a backfill option.

#### 3.4.2 Test procedure and results

The backfilling operation was carried out by placing approximately 250mm deep layers of concrete to each side of the arch to minimise the effects of asymmetric load. The maximum movement at the crown was 0.8mm upwards for the full height of the concrete backfill. Overall the results of the stability tests showed very little movement in the arch ring and it was concluded that the arch was stable under the backfill operations.

### 3.5 Live load testing of the arch system

A simulated static wheel load was applied at the mid-span and the third span of the arch ring. The single wheel load (Fig. 8), for the intended category of bridge, is 5.75t. However, for both loading locations the arch system carried over 35t without showing signs of distress (that is, six times the single wheel load).
3.6 **Analysis of the arch unit**

An analysis of the arch unit was conducted using ARCHIE a numerical analysis package which allowed for interaction with the arch backfill. The predicted ultimate capacity was highly conservative when compared with the actual load which was safely carried by the prototype arch system.

![Figure 7a: “Flat-Pack”](image1)

![Figure 7b: Arch Unit during Lifting](image2)

![Figure 7c: Prototype arch on seating](image3)

![Figure 8: Test set-up for mid-span loading](image4)

3.7 **Conclusions for the novel arch system**

Experience has shown that arch bridges are highly durable structures requiring little maintenance in comparison with other bridge forms. Thus, the objective of the new Highway Agency Standard [2004] is welcomed especially if it encourages a renaissance in arch building using unreinforced masonry materials. The novel arch system has been demonstrated, Gupta et al. (2006), to be a viable alternative to long established methods of construction and the following advantages have been identified:

(i) As the Arch system is cast horizontally it can conveniently be transported to site in a “flat pack” form.

(ii) As centring is not required during installation this greatly simplifies the process and enhances the speed of construction.

(iii) As there is no corrodbile reinforcement the long term durability should be assured.

(iv) Initial estimates would indicate that the system is cost competitive with less aesthetic RC box culverts.

A complete 5m wide arch bridge with a 5m span and 2m rise complete with spandrels, fill and surfacing has been constructed, load tested and has performed exceptionally well. From all view points the system represents a very sustainable alternative for the future.
OVERALL CONCLUSIONS

Once designers and contractors have a better indication of what they are looking out for they will be better placed to take sustainability into account right from the inception of a project. In this way and by developing innovative technologies to overcome difficulties progress can be accelerated in this important field. The two examples of innovative approaches to bridges, i.e. unreinforced deck slabs and the flexible concrete arch, share the following positive sustainability features relative to conventional designs:

- Little or no maintenance throughout their life;
- Greatly extended lives.

Since these improvements can be achieved at little or no additional cost the problems associated with traffic disruption/congestion when a bridge is being repaired/replaced can be minimised. This recognition of the significance of full life cycle costing, as opposed to the minimum initial cost approach, is very important from the sustainability viewpoint.

ACKNOWLEDGEMENTS

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REFERENCES

ARCHIE-M: Masonry Arch Bridges and Viaduct Assessment Software, Version 2.0.8, OBVIS Ltd. UK.
Sustainable mixed building technologies applied to residential buildings: some Romanian examples

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ABSTRACT: Four examples of sustainable mixed building technologies, which combine steel and timber in the framing and different materials for cladding, roofing and flooring, in order to obtain highly performance thermo-energetic properties are presented. Some innovative design solutions have been used in these projects. Three examples present single family houses and one a block of flats, all of them built in Romania. All the buildings are located in medium and high seismic regions. The paper presents aspects related to design and detailing, as well as solutions for cladding and roofing, including structural features, thermo-energetic performance and cost efficiency analysis.

1 INTRODUCTION

Sustainability is one of the greatest challenges of the modern world. A very well known definition of this concept was given by World Commission on Environmental and Development in 1987: “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” Sustainability includes environmental, economic and social aspects which contribute to a durable development of the society.

Construction sector play 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 work 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 you, you 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.

The present paper focuses on the use of light gauge steel framing in housing, considering that sustainable construction technology is used. Steel-framed houses are usually built of light gauge steel framing having different solutions for interior and exterior cladding. This technology is popular and accounts for an important and increasing market share in the US, Japan, Australia and Europe.

Burstränd (2001) presents the reason why to choose light gauge steel framing from an environmental point of view:
• Light gauge steel framing is a dry construction system without organic materials. Dry construction significantly reduces the risk of moisture problems and sick building syndrome;
• Steel, gypsum and mineral wool are closed cycle materials;
• Every material used in light gauge steel framing (steel, gypsum and mineral wool) can be recycled to 100%;
• It is possible to disassemble the building components for re-use;
• Light gauge steel framing means less energy consumption during production than equivalent housing with a framework of concrete poured on-site;
• Light gauge steel framing only uses about a fourth of the amount of raw materials used for equivalent homes in concrete;
• Less waste means a cleaner work site and a low dead weight of building components ensures a good working environment;
• Low dead weight leads to reduced transport needs.

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 multifamily 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 labor 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 vapor barrier on studs. Currently, some directions of the research focus on finding alternatives, i.e. new or traditional materials which allow for vapor 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 fiber 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.

Paragraph 3.3 presents some ongoing analysis of a built example, which illustrates the need of adequate insulation of the envelope.

3 SOME REPRESENTATIVE ROMANIAN EXAMPLES OF SUSTAINABLE MIXED BUILDING TECHNOLOGY APPLICATIONS

In recent years, steel framed houses have become a choice for house construction in many European countries, including Romania. Compared with traditional solutions, the properties of the steel skeleton can be exploited to take both technical and economical advantages from lightness of structures, ease of prefabrication, speed of erection and enhanced quality.

On the following, four examples of sustainable mixed building technology, which combine steel and timber in the framing and different materials for cladding, roofing and flooring, in order to obtain highly performance thermo-energetic properties are presented. The first three examples present single family houses and one block of flats, all of them built in Romania. All the buildings are located in medium and high seismic regions. Traditionally, light gauge steel structures were considered non-effective for buildings in severe seismic zones. The examples presented here provide the evidence for the contrary – light gauge steel framed residential buildings really are very effective in seismic regions.

3.1 Bulzesc’s family house

The structure is a private single-family house built in 1999 in Timisoara, Romania (Dubina et al. 1999, 2000). The built area of the house is 117.5m², while the total area is 198.2 m². The structure combines steel shear “wall stud” made of C shaped cold-formed profiles placed at 600mm intervals with corresponding floor and a timber roof framing as Figure 1 shows.

The fastening technique is based on self-drilling self-tapping screws of 5.5mm diameter for most of the connections, but in a few special cases classic bolts are also used.

The thickness of the structural walls is 150mm. In order to provide load bearing capacity against horizontal loads bracing straps were used on both sides of the wall panels. The thickness of the straps had to be small in order to have a flat surface for the finishing.

Floors have been realized as dry floating-floors. The main joists were C profiles and the corresponding layers of the floor being: hard-wood parquet (2.2cm), phonic insulation (2.5cm), supporting wood decking (5cm) and gypsum board ceiling (1.25cm).

From the architectural point of view, there is great advantage due to light partition walls and high strength of the joists, leading to freedom in subdividing the internal space following functionality rather than structural requirements and allowing large free spans.
Adequate thermal and sound insulation was achieved by using high performance materials and by paying attention to the finishing details to ensure air tightness both to the exterior and between rooms. Against impact noise the floating floor solution adopted was found to be very effective. The following layers have been used for roofing and cladding (see Figure 2):

**Cladding (in/out):** gypsum board (12.5mm); vapor barrier (0.5mm); Lindab C150/1.5 joists; mineral wool (150mm); Heratecta wood particles and cement (50mm); plastering (20mm);

**Roofing (out/in):** asphaltic tiles, asphaltic bitumen membrane (3mm); OSB board (20mm); ventilation layer (50mm); SOLFLEX aluminum layer; basaltic mineral wool (200mm); timber rafter (250x50mm/600mm); vapor barrier (0.5mm); gypsum board (12.5mm).

For the external finishing there can be options for vernacular or modern appearances. In this case the owner’s option was for a traditional look which was obtained using traditional exterior and interior finishing materials (Figure 3).

Following a cost analysis, the steel structure is identified to represent around 20% of the total cost, the main costs being spent on finishing (see Figure 4).
3.2 Constantin’s family house

The structure for this private single-family house was built in 2003 in Ploiesti, Romania (Access Steel 2006). The two main characteristics of this two-storey building are the use of light steel framing for a private home, and an architectural solution shaped by a constrained site.

From the architectural point of view, the main challenge of the project was to fit this private home on an irregularly shaped lot of only 168m². The resulting cube-like building measured in the end 84m² of built area on each of the two floors (see Figure 5), going up to the maximum allowed by city regulations. Given the proximity of the buildings on the adjacent properties, the next difficulty consisted in finding the balance between the right amounts of views, natural light and privacy. Two skylights located above the stairwell and the hallway, were placed to provide a light shaft, in order to enhance the centre.

![Lower floor plan: 1. dining room; 2. kitchen; 3. family room; 4. den; 5. laundry; Upper floor plan: 6. master bedroom; 7. library; 8. bedroom; 9. dressing; 10. bathroom; 11. logia](image1)

The structure, presented in Figure 6, is a two-storey single family house. Because the building sits on the property limit, it was impossible to provide window openings on that side. This was also one of the reasons for the roof being made with a single slope, the high of the building going from 9m to 10.5m. Each floor has approximately 2.75m in high and the slope of the roof was 30°.

The structural skeleton is made of light-gauge C shaped profiles (C150/1.5) at 600mm intervals, with a thickness of 1.5mm, fixed with 4.8mm diameter self drilling screws. The height of the profiles is 150mm, which governed the thickness of the walls. In order to withstand horizontal actions and to provide stiffens and strength the walls were stiffened using 10 mm thick OSB plates provided on both sides of the structural walls (Figure 6b).

![Figure 6. a) Steel skeleton of the structure; b) Skeleton with structural OSB sheeting](image2)
The load bearing beams in the slab are C200/1.5 profiles at 600mm intervals, resulting from
the condition to control the vibrations of the floor rather than from strength conditions. Roof
purlins are Z150/1.5 profiles at 1200mm intervals. The floor diaphragms were originally de-
dsigned to be based on the same principle of covering with OSB, this solution being changed into
sheathing with trapezoidal steel sheaths both at the level of the slab and at the roof. No concrete
topping was used on the slab.

The following layers have been used for roofing and cladding (see Figure 7):
**Cladding (in/out):** gypsum board (12.5mm); vapor barrier (0.5mm); OSB board (15mm); Lind-
dab C150/1.5 joists; terwoolin mineral wool (150mm); OSB board (15mm); basaltic mineral
wool (40mm); mineral plastering BAUMIT (8mm);
**Roofing (out/in):** waterproofing membrane reinforced with mineral aggregates (3mm); water-
proofing membrane (3mm); OSB board (20mm); basaltic mineral wool (150mm); Lindab cor-
rugated sheet (LTP 45); Lindab C200/1.5 profiles; vapor barrier 0.5mm; gypsum board
(12.5mm).

Figure 7. Layers used for roofing and cladding

Figure 8 presents exterior and interior views of the completed house.

(a) General view
(b) Interior view – staircase

Figure 8. Constantin’s family house

### 3.3 Carmen’s family house

The structure is for a private single-family house built in 2006 in Timisoara, Romania. The main
structure is made of steel profiles, while the floor and roof is made of timber elements. The
building combines modern and traditional materials and techniques, in order to obtain a typical
Transylvanian village house (see Figure 9).

The following layers have been used for roofing (out/in): tiles of wood, battens (50x50mm);
boarding (20mm); SOLFLEX weather resistant barrier; OSB board (20mm); ventilation layer
(100mm); vapor barrier (0.5mm); basaltic mineral wool (200mm); timber rafter
(300x50mm/600mm); vapor barrier (0.5mm); gypsum board (12.5mm) as Figure 10 shown.
In Figure 11a are presented the actual layers for the cladding (in/out). Figure 11 illustrates the importance of adequate insulation both as thickness and position in the wall assembly. The following observation can be drawn:

(a) The adequate wall insulation (Figure 11a) presents a linear slope of temperature values through the layers of the wall assembly. No condensation conditions are present;

(b) The acceptable wall insulation (Figure 11b) presents a sharp decrease of temperature values through the layers of the wall assembly. Even though the model does not show any condensation, the middle section of the wall could be subjected to vapor migration (trapped moisture) and subsequently condensation;

(c) The unacceptable wall insulation (Figure 11c) includes only 10cm of mineral wool insulation and leads to condensation conditions on the interior surfaces of the wall. A similar situation can occur accidentally when the overall insulation is adequate, in areas where thermal bridging is not properly addressed, mineral wool are not properly positioned etc.
Figure 11: Importance of adequate insulation (source SINCRA Ltd.)

(a) adequate exterior wall insulation

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<tr>
<td>Vapor barrier - Polyethylene, low density</td>
<td>0.001</td>
</tr>
<tr>
<td>Oriented strand board - OSB</td>
<td>0.018</td>
</tr>
<tr>
<td>Mineral wool SCI60, SCO60, SPS60</td>
<td>0.07</td>
</tr>
<tr>
<td>Baumit syntethic stucco</td>
<td>0.02</td>
</tr>
</tbody>
</table>

| Interior Temperature: | 20°C |
| Interior Humidity: | 60% |
| Exterior Temperature: | -10°C |
| Exterior Humidity: | 90% |

(b) acceptable exterior wall insulation

<table>
<thead>
<tr>
<th>Element: exterior wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat transfer coefficient:</td>
</tr>
<tr>
<td>Direction:</td>
</tr>
<tr>
<td>Type of element:</td>
</tr>
<tr>
<td>Thermal resistance (ext.):</td>
</tr>
<tr>
<td>Thermal resistance (int.):</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Layers</th>
<th>d [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum board</td>
<td>0.013</td>
</tr>
<tr>
<td>Vapor barrier Polyethylene, low density</td>
<td>0.001</td>
</tr>
<tr>
<td>Mineral wool SCI60, SCO60, SPS60</td>
<td>0.06</td>
</tr>
<tr>
<td>Well ventilated air layer</td>
<td>0.01</td>
</tr>
<tr>
<td>Mineral wool SCI60, SCO60, SPS60</td>
<td>0.06</td>
</tr>
<tr>
<td>Vapor barrier - Polyethylene, low density</td>
<td>0.001</td>
</tr>
<tr>
<td>Oriented strand board - OSB</td>
<td>0.018</td>
</tr>
<tr>
<td>Mineral wool SCI60, SCO60, SPS60</td>
<td>0.07</td>
</tr>
<tr>
<td>Baumit syntethic stucco</td>
<td>0.02</td>
</tr>
</tbody>
</table>

| Interior Temperature: | 20°C |
| Interior Humidity: | 60% |
| Exterior Temperature: | -10°C |
| Exterior Humidity: | 90% |

(c) unacceptable exterior wall insulation

<table>
<thead>
<tr>
<th>Element: exterior wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat transfer coefficient:</td>
</tr>
<tr>
<td>Direction:</td>
</tr>
<tr>
<td>Type of element:</td>
</tr>
<tr>
<td>Thermal resistance (ext.):</td>
</tr>
<tr>
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</tbody>
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<table>
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<tr>
<th>Layers</th>
<th>d [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum board</td>
<td>0.013</td>
</tr>
<tr>
<td>Vapor barrier Polyethylene, low density</td>
<td>0.001</td>
</tr>
<tr>
<td>Well ventilated air layer</td>
<td>0.01</td>
</tr>
<tr>
<td>Mineral wool SCI60, SCO60, SPS60</td>
<td>0.1</td>
</tr>
<tr>
<td>Vapor barrier - Polyethylene, low density</td>
<td>0.001</td>
</tr>
<tr>
<td>Oriented strand board - OSB</td>
<td>0.018</td>
</tr>
<tr>
<td>Baumit syntethic stucco</td>
<td>0.02</td>
</tr>
</tbody>
</table>

| Interior Temperature: | 20°C |
| Interior Humidity: | 60% |
| Exterior Temperature: | -10°C |
| Exterior Humidity: | 90% |
3.4 **Block of flats**

The structure is a block of flats built in 2006 in Timisoara, Romania. Architectural views are presented in Figure 12. 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, uninterrupted floor plates are the optimum answer to allowing users to optimally reconfigure internal areas and this generally means long-span solutions (see Figure 13).

![Figure 12. 3D architectural views](image)

![Figure 13. Structure during erection](image)

The following layers have been used for roofing and cladding (see Figure 14):

**Cladding (in/out):** gypsum board (12.5mm); vapor barrier (0.5mm); basaltic mineral wool (80mm); gypsum board (10mm); ventilation layer (80mm); OSB board (15mm); basaltic mineral wool (100mm); C150/1.5…600mm joists; Al profiles; MEG plastic boards (8mm);

**Roofing (out/in):** gravel (50mm); rigid mineral wool (100mm); light concrete (50mm); corrugated sheet (45mm).

![Figure 14. Layers used for roofing and cladding](image)
4 CONCLUSIONS

The four examples presented in the present paper represent a complete sustainable technology of high performance thermo-energetic materials for cladding and finishing and use productive and qualitative technology both for fabrication and erection. It enables to obtain flexible partitions and allows for further up-grade, easy modifications and/or development.

All the buildings are located in medium and high seismic regions. Compared with traditional housing technologies, steel frame houses are, besides their technical advantages and enhanced quality of both structure and finishing, really cost effective, too.

REFERENCES

Data management, structural maintenance and life cycle performance for the CargoLifter airship hangar / Tropical Islands Dome

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Brandenburg Technological University Cottbus, Chair for Steel and Timber Structures, Germany

G. Mosler, O. Schemmel
Tropical Island Management GmbH, Brand, Germany

ABSTRACT: Base of all sustainable structural maintenance and the there from excepted Life Cycle Performance has to be a reasonable data management by the owner or user of a structure. Knowing this, decades ago the German Federal Highway Research Institute leaded the development of a computer based building data management system for bridges. By limiting the approach and of cause also the demands of the system to (e.g. 99%) of the bridges owned by public it will, of cause, not be suitable for other civil engineering structures. Some problems therefore may be named without the reasons: high variability of structural concepts / large amount of different structural components, concepts even within one single structure / multiple contractors at one building / high owner change rate / bad database / and so on. The structural failures during the winter 2005/06 demonstrated again the urgent need of a concept for Data Management and Controlled Structural Maintenance for other civil engineering structures than bridges. Responsible owners recognised it and are reacting to the fundamental demand of controlled maintenance for structures. A step towards a solution will be presented on a practical example, the Tropical Islands Dome south-east of Berlin (Germany), the largest free span Dome in Europe. Basic considerations herein are: practical use from today on for the owner / easy updating / long durability / low permanent costs / and some others. This may leaded in example to a concept of high Brain – low Tec, e.g. represented by the fact that just basic electronic formats were used to deal with a very complex structure. The result in this case is an, hopefully, easy to use database for the structure and controlled structural maintenance over the next decades of structural service time. It shall be serve as an example of treating the problem with the aim of keeping maintenance costs predictable and fulfilling the precondition of every structural design code: “Adequate Maintenance over the structure service time” to keep the calculated safety level.

1 INTRODUCTION

1.1 Problem

The collapse of a couple of wide-span structures during the last decades and the accumulated failures during the winter 2006 [after the structural collapse of a glulam roof of an ice hall in Bad Reichenhall (Germany), a steel roof of single-story exhibition in Katowice (Poland) and a reinforced concrete roof of a supermarket in Moscow (Russia) with a death toll of 120 persons, focused the officials to the problem of scheduled and controlled maintenance on high rise structures.

Basis of all proposals is the existing system for assessing and maintaining bridges. Here a staged schedule in intensity is given (DIN 1072). Attended a system and according software for structural and maintenance documentation was developed by the German Federal Highway Research Institute and prescribed (BMV, 1998).
As a reaction of these accumulated failures the fundamental structure of this, well working, system was intended to be transferred to building constructions with large failure consequence classes (ARGEBAU, 2006). This assignment is not so easy as it seems.

1.2 **Regulation by law**

By law the owner of a structure is responsible for obtaining sufficient safety, §3 MBO (ARGEBAU, 2002). This is also the fundamental demand of Eurocode 1 (EN 1990-1). Despise a couple of regulation on fire safety and the safety of other technical components (fume outlets, elevators etc., summarized list in (AIG, 2006)) until now there was in Germany nearly nothing that suggested the owner about this demands on structures. (An exception are some hints in DIN 32736). From the Swiss concept of a safety and utilization plan less ore nothing is known even by practical engineers (Schneider, 1994). The demand of a sufficient structural documentation is neglected as well by the owners as by the officials at the moment. One can proof this with a simple visit at a public archive.

1.3 **Applicability to building constructions?**

It is not really possible to transfer the system for bridges (BMV, 1998) unmodified to building constructions, even if the guideline by the ARGEBAU (ARGEBAU, 2006) suggests this. There are two main reasons therefore. These are the higher diversification as well as in the ownership as well in the structural details. Both is linked to significant higher reconstruction rates. These are some reasons which prevent the development of a special software. So the question arises if the simple aim of sufficient inspection system can be reached at the moment with less technological effort. This shall lead to a higher acceptance by the owner than just “it is prescribed by law”.

2 **SOLUTION APPROACH**

2.1 **Preparation of a Building Documentation**

Usually every structural work is completed with an “As Build” documentation. For building constructions this shall be done by architects and engineers in the “Service Rendering Phase 9” (HOAI 2002).

<table>
<thead>
<tr>
<th>standard activity</th>
<th>special activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Inspection for warranty covered defects</td>
<td>- As build drawings</td>
</tr>
<tr>
<td>- Inspection of rehabilitation of warranty covered defects</td>
<td>- Inspections</td>
</tr>
<tr>
<td></td>
<td>- Inspection and maintenance plans</td>
</tr>
<tr>
<td></td>
<td>- Generation of an object documentation</td>
</tr>
<tr>
<td></td>
<td>- ...</td>
</tr>
</tbody>
</table>

Table 1. Service Rendering Phase 9.

In times of budget control this position is sometimes not included in the according contracts. Even if this Service Rendering Phase is done during erection the documents were very seldom carried forward. So the first step is the preparation of a building documentation. Of course this documentation can be made in a scientific database as e. g. used by the Gemeinsamer Ausschuss Elektronik im Bauwesen (GAEB, 2007). But until now, these approaches are still under development and the main demands: sustainability and accessibility of the data are not fulfilled. So the best practice approach is, in the opinion of the authors, a simple text document, accompa-
nied by drawings in a *.pdf; *.dxf and *.dwg format. These documents shall contain all necessary information about the structural details according to (DIN 1072). Especially important are overviews as build drawings in a reasonable scale. From a practical point of view these blueprints shall not exceed the size DIN A1. These drawings are needed to document all future inspection results.

2.2 Inspection Schedule

The inspection schedule is proposed in the guideline by the ARGEBAU (ARGEBAU, 2006).

Table 2. Inspection Schedule.

<table>
<thead>
<tr>
<th>category</th>
<th>type of building</th>
<th>inspection</th>
<th>detailed inspection</th>
<th>extensive inspection</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Buildings with more than 5000 users</td>
<td>1-2</td>
<td>2-3</td>
<td>6-9</td>
</tr>
<tr>
<td>II</td>
<td>Structures with more than 50m height; 12m span; 6m cantilever beams and all other structures with high damage potential</td>
<td>2-3</td>
<td>4-5</td>
<td>12-15</td>
</tr>
</tbody>
</table>

This guideline rules the minimum qualification of the personal and the minimum inspection amount.

Table 3. Inspection Guideline.

<table>
<thead>
<tr>
<th>performed by whom</th>
<th>performed how</th>
<th>inspection</th>
<th>detailed inspection</th>
<th>extensive assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>owner</td>
<td>checking structural elements for: cracks, excessive deflection, corrosion,...</td>
<td>As before and e.g. additional check by structures: Concrete: carbonization / chlorides / concrete cover corrosion / ... Steel: loose screws / cracks in welds / corrosion / coating thickness / ... Timber: splits / decay / moisture contend / ... to be continued...</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If this guideline is sufficient, and if it is applicable to a structure with a large consequence class in practice will be presented at an example in the succeeding chapter.

2.3 Inspection and Maintenance Documentation

How the results have to be documented and an assessment of the condition of the structural components has to be done is not described. The existing grading system for bridges may be a solution. There grades were assigned for the load carrying capacity, the usability and the durability of components or the building. This assignment is done according to the influence of a damage. These grades provide a decision support to schedule maintenance and other actions.
3 EXAMPLE TROPICAL ISLANDS DOME

3.1 Introduction in the building Tropical Islands

At the end of the 20th century a new generation of airships has been developed by the CargoLifter AG. Therefore a new hangar for two airships has been built. With a span of 210 m, a height of 107 m and a length of 363 m it has been the largest single-story building in the world. The central part of the hangar is of a half-cylindrical shape consisting of five steel arches covered with a textile membrane. At both ends of the building are the doors which consist of two fixed and six moving elements. They form a semicircle in plan and a quarter-segment of a circle in elevation.

After the brake down of the Cargo-Lifter AG the real estate was bought by Tropical Island and converted to a leisure facility. Within the former hangar houses in native tropical style, a lagoon, a sauna and many other facility's were build in. To generate tropical climate, raise a rain forest and gain additional sunlight it was necessary to dismantle the membrane from the southern side. Transparent ETFE cushions, supported by a cable net, were installed. The capacity is 8000 visitors, so the building is category I (Tab. 2).

3.2 Building documentation / As build overview drawings

Not only the first owner, Cargo-Lifter AG, also some contractors went bankrupt during the last decade. Also the design responsible was changed. This caused a significant loss of information about structural details. So the first step was to write a summarizing building documentation. As build overview drawings including some standard details had to be made, too.

Figure 1. Tropical Islands Dome.

Figure 2. As build overview drawing: Detail cushion.
3.3 Inspection schedule

The inspection guideline (Tab. 3) had to be extended and changed in detail. A couple of reasons therefore can be named. Structural parts have a different potential of structural failure. So it will make sense to inspect the main arches more often or more in detail, than the infill of the gates. Also it makes sense to check innovative and new structures, as the cushions, more often to detect early failure. At least, some inspection is already covered by inspection contracts like fume outlets, cushion and membrane structures, or need more often inspection like guard rails. A part of the inspection plan, here for the cushions, including technical components, is given in the next table.

Table 4. Part of the inspection plan.

<table>
<thead>
<tr>
<th>every .... year</th>
<th>0.25</th>
<th>1</th>
<th>3</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Check Service Contract (DIN EN 13269)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Check of emergency kit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>simple visual inspection on water penetration / damages</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical Components</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Check trouble indicator, document errors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Check suction hole</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Open and close hatches</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Check sensors (Pressure / Temperature)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Check sensor (Snow)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Check sensor (Wind)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Service Compressor VDI 3801</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Service Dehumidifier VDI 3801</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A proper inspection plan contains also information about work preparation, inspection facilities.

3.4 Inspection results and documentation

In the next figure two usual maintenance problems are shown.

Figure 3. Some inspection results.

In the left picture of figure 3 the effect of the leakage in the facade is presented. Here it is linked to a basin like structural detail. The water was already removed by vacuum cleaner. The solution will be a fixing of the leakage. On the right picture beginning corrosion on the bracings is shown. It may be that the bracings have the thinnest paint cover. Here a new paint job is advisable during the next years.
It may be advantageous to document this inspection results (and the according maintenance) in a sufficient form. Here the grading system from the bridges may be adopted. The three categories may be adopted to safety, durability and usability. A grade of 0 means, similar to bridges, no effect. With a grade of 4 the component is not safe, durable and usable. An easy example for this case is the crane runway. It was not completed after the break down of Cargo-Lifter AG. So the cranes are not approved. Approved was just the static load carrying system by the check engineer. So it has no effect to safety, but using is prohibited.

Table 5. Documentation and assessment of inspection results.

<table>
<thead>
<tr>
<th>Date</th>
<th>Component</th>
<th>Subcomponent</th>
<th>Position</th>
<th>Who</th>
<th>Action</th>
<th>Result</th>
<th>Safety</th>
<th>Durability</th>
<th>Usability</th>
</tr>
</thead>
<tbody>
<tr>
<td>???</td>
<td>Crane</td>
<td>Runway</td>
<td>Check</td>
<td>Eng.</td>
<td>Prof.</td>
<td>Pasternak</td>
<td>Check</td>
<td>Eng. Report</td>
<td>Acc. To report, not finished, no loads allowed</td>
</tr>
<tr>
<td>???</td>
<td>Fixed Gate</td>
<td>Weather Strip</td>
<td>D/7-4</td>
<td>Trop.</td>
<td>Islands</td>
<td>Visual</td>
<td>Inspection</td>
<td>Weather strip, heavy leakage, water at framework knots</td>
<td>0</td>
</tr>
<tr>
<td>???</td>
<td>Bracings</td>
<td></td>
<td>G/H/4-7</td>
<td>Ceno-Tec</td>
<td>Check</td>
<td>Pretension</td>
<td>Pretension to small</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>???</td>
<td>Main Arches</td>
<td>Windows</td>
<td>All Arches</td>
<td>Check</td>
<td>Bracings</td>
<td>Ceno-Tec</td>
<td>Cracks at the covering bead</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>???</td>
<td>Pillows</td>
<td>Inside Membrane</td>
<td>Ceno-Tec</td>
<td>Check</td>
<td>Bracings</td>
<td>Cracks, where the ropes separate</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>???</td>
<td>Gate 2</td>
<td>Gate Rails</td>
<td>B-C 6-7</td>
<td>Check</td>
<td>Drainage defect, 10cm water</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

4 SUMMARY

It was possible to show, that even simple tools and limited efforts, can lead to a sufficient management of inspections and maintenance. So the public demand on safety is accomplished. From an owner’s point of view also immediately advantages are arising: structural maintenance can be scheduled more efficient, early failures are found during warranty, ... . This win-win situation shall be communicated more offensive to gain additional acceptance for the common aim: sustained and well maintained structures.

REFERENCES


ABSTRACT: The connections between inner and outer structures still seems to be one challenging question in the steel structures at the time of low-energy buildings and high claims of heat engineering standards. The construction of a bolted end-plate connection with a thermal-insulating layer which has not only the function of thermal insulation, but also the bearing function in respect to its compression and shear resistance is under progress. As a suitable material elastomers could be used. The research is focused on the new materials appearing in the market to study their suitability for this type of connections. The prediction of the connection mechanical behaviour is based on the component method. The component methods consist of decomposition of the joint into components, the description of the components' behaviour and assembling into connection behaviour. The design model is developed and needs to be checked by experiments and FE simulation.

1 INTRODUCTION TO THE THERMAL-INSULATING CONNECTIONS

The latest trend of heat-engineering, economical, technical and structural claims leads to a construction of new types of steel connections which should be heat-insulating and cost-effective as well as statically efficient. The steel connections with thermal barrier could be widely used in practical design such as connections of balconies, loggias, ramps, canopies, cold entry rooms, roofs, garages etc.

This work is focused on the bolting end-plate connection of two beams where the intermediate thermal-insulating layer is used as shown in Figure 1. The end-plate connection is under the effect of the combination of bending moment and normal force due to the application of the pre-stressed bolts and external forces. The possible shear stress is not concerned in this work and it can be easily transferred by using a shear bracket. Significant results from the shear tests performed on a similar joint with intermediate layer were presented by Lange & Göpfert (2005).

Figure 1. Model of the bolted end-plate connection with thermal separation
The component method is used to predict the behaviour of the joint and a couple of experiments are necessary to be made to check the propriety of this method. Furthermore the component method could be implemented to the standardized calculation process for this type of joints with thermal barrier.

2 APPLICATION OF COMPONENT METHOD

The goal this paper is to check the serviceability of the component method for a thermal-insulating steel joint. The component method is the analytical method describing the behaviour of the joint as the moment-rotation relation. Firstly the connection is disintegrated into separate parts and the characteristics of these so-called components are being investigated. The most important characteristics are the resistance and the stiffness of the component. Then the components are assembled with respect to their position in the structure and the general characteristics of the joint are calculated from the partial values. After determining the general stiffness of the joint, it can be easily classified as rigid, semi-rigid or hinged depending on its exact position in the structure (Jaspart, 1999).

First of all the thermal-insulating connection is disintegrated into components as shown in Figure 2. Then the partial components are being investigated.

![Figure 2. Components of the thermal-insulating joint](image)

2.1 Part in tension

The resistance of the tension part of the connection is the lowest value among the bearing resistances of the following components: ⑩ row of bolts in tension, ⑫ end-plate in tension, ⑭ beam web in tension.

The bearing resistances of the end-plate and the row of bolts in tension are both calculated by using the T-stub model. The failure of the component is caused by one of these three reasons:

a) the failure of the end-plate

\[ F_{1,Rd1} = \frac{4M_{pl,1,Rd}}{m} \]  

(1)

b) the failure of the end-plate and the bolts

\[ F_{1,Rd2} = \frac{2M_{pl,2,Rd} + 2nB_{1,Rd}}{m + n} \]  

(2)

c) the failure of the bolts

\[ F_{1,Rd3} = 2B_{1,Rd} \]  

(3)

where

\[ M_{pl,Rd} = 0.25L_{eff}r_{p}^{2}f_{y}/\gamma_{M0} \]  

(4)

\[ B_{1,Rd} = \min \{ 0.9A_{s,ref}f_{sy} / \gamma_{Mb} ; 0.6\pi d_{m}r_{p}f_{u} / \gamma_{Mb} \} \]  

(5)
The bearing resistance of the beam web in tension in a bolted end-plate connection is

\[ F_{k,t,Rd} = \frac{L_{nf} t_w f_y}{\gamma_{M0}} \]  

(6)

The stiffness of the end-plate in tension is calculated from

\[ k_5 = 0.85 \frac{L_{nf} t_p^3}{m^3} \]  

(7)

The stiffness of the bolts in tension is determined as

\[ k_{10} = 1.6 \frac{A_s}{L_p} \]  

(8)

The stiffness of the beam web in tension is supposed to be indefinite. The rotational stiffness of the tension part is then derived from

\[ \frac{1}{k_y} = \frac{1}{k_5} + \frac{1}{k_{10}} \]  

(9)

2.2 Part in compression

There are only two components in the part of the connection in compression - the beam flanges and (15) the thermal-insulating layer which is the crucial component of the joint.

The bearing resistance of the beam flanges in tension/compression is determined as

\[ F_{t,c,Rd} = \frac{W_{pl} f_y}{(h-t_f) \gamma_{M0}} \]  

(10)

The bearing resistance of the thermal-insulating layer is predicted to be given by a relation known from column-bases:

\[ F_{15,c,Rd} = \frac{A_{eff} f_{e,max}}{\gamma_{Me}} \]  

(11)

where \( A_{eff} \) is the compression area in the distance \( c \) from the beam flange under compression, see Figure 3, \( f_{e,max} \) is the resistance of the thermal insulation and \( \gamma_{Me} \) is the safety factor of the thermal-insulation material.

As the beam flanges are supposed to have an indefinite bending stiffness, the stiffness of the thermal-insulating layer is also the stiffness of the whole compression part and is supposed to be calculated from

\[ k_e = k_{15} = \frac{A_{eff}}{t_e} \]  

(12)

where \( t_e \) is the thickness of the intermediate layer. For detailed information see the work by Wald & Sokol (1999) and EN 1993-1-8:2005.

3 M-N INTERACTION

The simplified prediction model for the bending resistance and the rotational stiffness may take into account only the effective area at beam flanges. The effective area at the beam web is neglected, as shown in Figure 3. It is assumed the compression force acts at the centre of the flange in compression also in cases of limited size of outstand of the plate. The tension force is located in the bolt row in tension. In case of two or more bolt rows in tension part, the resistance
of the part in tension is obtained as the resulting force of the active bolt rows. The forces represent resistances of the components in tension $F_{t,Rd}$ and in compression $F_{c,t,Rd}, F_{c,b,Rd}$.

![Diagram of the joint](image)

**Figure 3.** Model with the effective area at the flanges only; a) one bolt row in tension; b) no bolts in tension.

For simplicity, the model will be derived for proportional loading only:

$$e = \frac{M_{sd}}{N_{sd}} = \frac{M_{rd}}{N_{rd}} = \text{const}$$

(13)

When the eccentricity

$$e = \frac{M_{sd}}{N_{sd}} \leq -z_e$$

(14)

see Figure 3a, there is tension force in the bolt row, and compression force in the lower flange. The bending resistance of the joint is derived as

$$M_{rd} = \min \left\{ \frac{F_{t} z}{e} \cdot \frac{F_{c} z}{1 - \frac{z_{c,t}}{e}} \right\}$$

(15)

When the eccentricity

$$e = \frac{M_{sd}}{N_{sd}} \geq -z_e$$

(16)

see Figure 3b, there is no tension force in the bolt row, but both parts of the connection are loaded in compression. In this case

$$M_{rd} = \min \left\{ \frac{-F_{c,t} z}{e} \cdot \frac{-F_{c,b} z}{\frac{z_{c,b}}{1 - \frac{z_{c,b}}{e}}} \right\}$$

(17)

The joint rotation is calculated using the elastic deformation of the components in tension and compression parts

$$\phi = \frac{\delta_t + \delta_c}{z} = \frac{1}{z^2} \left( \frac{M_{sd} + N_{sd} z_{c,t}}{E k_t} + \frac{M_{sd} - N_{sd} z_{c,b}}{E_e k_c} \right)$$

(18)

where $E$ is the elastic modulus of steel and $E_e$ of the separating layer.

The rotational stiffness of the joint depends on the bending moment which is induced by the normal force applied with constant eccentricity $e$. 

3.112
The stiffness is derived by substituting the rotation of the joint (18) into equation (19)

\[ S_{j,ini} = \frac{M_{sd}}{\phi} \]  

(19)

where the eccentricity \( e_0 \) is defined as follows

\[ e_0 = \frac{z_e k_e E_e - z_0 k_0 E}{k_0 E + k_i E} \]  

(20)

resp.

\[ e_0 = \frac{z_{c,b} k_{c,b} E_e - z_{c,j} k_{c,j} E_e}{k_{c,b} E_e + k_{c,j} E_e} = \frac{z_{c,b} k_{c,b} - z_{c,j} k_{c,j}}{k_{c,b} + k_{c,j}} \]  

(21)

The non-linear part of the moment-rotation curve may be modelled by introducing the shape factor \( \mu \), which depends on ratio \( \gamma \) of the acting forces and their capacities

\[ \mu = (1.5 \gamma)^{2.7} \geq 1 \]  

(22)

(23)

where

\[ \gamma = \frac{e + h}{2} \]  

(24)

Using the above described factor \( \mu \) allows modelling of the moment-rotation curve of the joint, which is loaded by proportional loading, in the form

\[ S_j = \frac{e}{e + e_0} \frac{z^2}{\mu \sum \frac{1}{E_k}} \]  

(25)

Detailed information can be obtained from the investigation made by Sokol & Wald & Chlouba (2006).

To verify the above presented predictions it is necessary to make a couple of experiments with a specific thermal-insulating material and its real behaviour in the connection. The influences of the geometry as well as the creep behaviour of the material have to be taken into account and included into the calculation. Then the relations can be put more exactly and forward-looking they could be used for practical standardized design.

4 HEAT-ENGINEERING

The new heat-engineering standard provides the obligatory values for heat conductivity of the structures as well as values for energy intensity of the building. The most efficient way to decrease the loss of energy is to prevent the thermal bridges in the external cladding of the building.

The Figure 4 shows a simple 2D simulation of heat conduction in a steel structure between inner and outer environment. There is a comparison between the joint without thermal separation and the joint with thermal separation of thickness 5, 10 and 20 mm. It is clearly shown how visible is the insulation effect of the intermediate layer in the joint.
The heat conductivity of elastomers or plastics usable for the intermediate layer is about 0.2 or 0.3 W/Km while the value of common thermal-insulating materials is 10 times lower. However, even the usable materials still have a great influence on the decreasing of the thermal bridges caused by steel connections.

5 CONCLUSIONS

The research is trying to develop standardized design rules for thermal-insulating joints and introduce this new type of connections into a common use. The tendency is to give opportunity for steel structures and show the way how to construct buildings with low energy intensity and minimized heat costs. The bolted end-plate connection with intermediate thermal-insulating layer could be easily designed using the component method which determines the bearing resistance as well as the rotational stiffness of the joint. The predicted method needs to be verified by a couple of experiments and FE simulation. The presented type of joint seems to be suitable for steel connections between inner and outer structures and minimizes the effect of thermal bridges in the external cladding.

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REFERENCES

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Sustainability of Constructions
Integrated Approach to Life-time Structural Engineering

L. Bragança, H. Koukkari, R. Blok, H. Gervásio, M. Veljkovic, Z. Plewako, R. Landolfo, V. Ungureanu, L.S. Silva

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