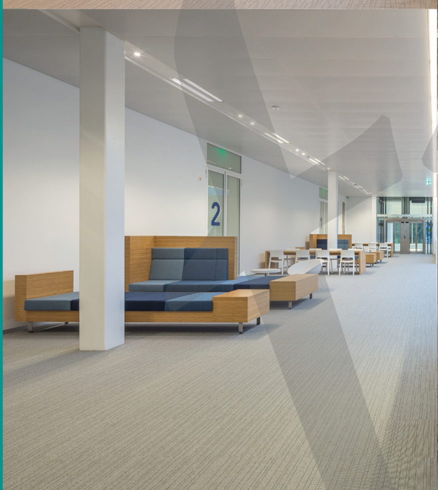
fib CEB-FIP

PCI Precast/Prestressed Concrete Institute

Bulletin 88



Sustainability of precast structures

State-of-the-art report

Bulletin 88

fib CEB-FIP

PCI Precast/Prestressed Concrete Institute

Sustainability of precast structures

State-of-the-art report

Task Group 6.3

December 2018

Approval for this bulletin

Subject to priorities defined by the Technical Council and the Presidium, the results of the *fib*'s work in commissions and task groups are published in a continuously numbered series of technical publications called *bulletins*. The following categories are used:

Category:	**Approval by**:
Technical report	Task group and chairpersons of the commission
State-of-the-art report	Commission
Manual / Guide to good practice / Recommendation	Technical Council
Model code	General Assembly

Any publication not having met the above requirements will be clearly identified as a preliminary draft.

fib Bulletin 88 was approved by Commission 6 "Prefabrication".

Cover images: Temporary Courthouse in Amsterdam. Photo credit: Jannes Linders (ext.) and Léon van Woerkom (int.)

ISSN 1562-3610
ISBN 978-2-88394-128-1
Proofreading by Gordon Clark. Layout by Marie Reymond (*fib*).
Printed by DCC Document Competence Center Siegmar Kästl e.K., Germany

Acknowledgements

The report "Sustainability of precast structures" was drafted by *fib* Task Group 6.3 "Sustainability of precast structures":

Authors:

David Fernández-Ordóñez (Editor/Convener)
fib, Switzerland

Iria Doniak
ABCIC, Brazil

Dean Frank
Dean Frank Associates LLC, USA

Albert de la Fuente
Universitat Politècnica de Catalunya, Spain

Antonio Gasperi
Consulting Engineer, Italy

Petr Hájek
CVUT, Czech Republic

Alejandro Lopez- Vidal
ANDECE, Spain

Emily Lorenz
PCI, USA

Stef Maas
FEBE, Belgium

Jyri Nieminen
Sweco Finland, Finland

Stefano Pampanin
University of Canterbury, New Zealand

Tomas Plauska
Consolis, The Netherlands

Alessandra Ronchetti
ASSOBETON, Italy

Koji Sakai
Japan Sustainability Institute, Japan

Bin Zhao
Tongji University, China

Additional Contributors

Antonio Aguado
Universitat Politècnica de Catalunya, Spain

Jaime Gálvez Ruiz
Universidad Politécnica de Madrid, Spain

Paulo Helene
PhD Engenharia Ltda, Brazil

Marco Menegotto
Consulting, Italy

Full address details of Task Group members may be found in the *fib* Directory or through the online services on *fib*'s website, www.fib-international.org.

Foreword

Sustainability is a crucial concept. Sustainability was first introduced in the *fib* by creating a Special Activity Group under the convenorship of Prof Sakai. This group encouraged and helped all *fib* commissions to create their own groups dealing with sustainability. The *fib* Commission 6 "Prefabrication" took up this challenge and created a Task Group called "Sustainability of Structures with Precast Elements" in 2012. The group was created as a joint group with PCI (Precast Concrete Institute of USA), with the then-active *fib* Commission 3 "Environmental aspects of design and construction", and the *fib*'s SAG8 on Sustainability. Therefore, this Bulletin 88 is a joint publication between PCI and *fib*.

The aim of the work was to gather and study the most recent work that has been developed regarding sustainability – and more particularly Life Cycle Assessment - of structures in which precast elements are used. The final aim of the group would be to provide recommendations for the study and assessment of structures built with precast elements. It will cover all aspects of this kind of structure, from planning, design, execution, use, maintenance and remedial activities to deconstruction, reuse, demolition and recycling.

The *fib* holds sustainability as a high priority, which triggered the creation of a new Commission 7 "Sustainability" during the 2015 *fib* commissions reorganisation. This commission has been chaired since then by Prof Hájek. Sustainability concepts were already introduced in the Model Code 2010 and are a key part in the elaboration of the Model Code 2020.

Experts from many parts of the world contributed to this *fib* Bulletin 88 which gives the document a broad overview of sustainability sensibilities across different continents.

Bulletin 88 starts with a description of the importance of environmental concepts and developments in the world today and the reason why sustainability is a crucial concept that will be even more important in the future. The document then focuses on the different advances of standards and regulations that have been developed or are in the process of being implemented. ISO, European regulations, North American regulations, Brazilian implementation in real precast companies and the developments of the *fib* Model Codes have been considered in this bulletin.

After that, the bulletin examines life cycle aspects of precast structures, taking former fib bulletins as a basis. Then, it moves on to an in-depth study of specific sustainability aspects of precast structures.

Then, the bulletin deals with the special methodologies and tools that are available around the world to handle sustainability in general and with precast structures in particular. A selection of tools is described in this chapter. The Task Group also developed proposals about how to deal with the sustainability of precast structures. Some of the proposals are described conceptually in the text.

The final chapter compiles several case studies or examples of sustainability applications of precast structures. The examples differ and are grouped by category: buildings, infrastructure and special works.

The task group continues to work on developing other documents that will focus on the detailed practical application of some of the sustainability models described in this document.

The Commission is grateful to all the Task Group members for this accomplishment, particularly to David Fernández-Ordóñez, who convened and led the Group successfully.

Stef Maas	Ned Cleland
Chair of the *fib* Commission 6: *Prefabrication*	Chair of the PCI *Technical Activities Council*

Contents

1. Scope

Sustainability is a main consideration for the future of construction, therefore it is also a significant consideration for the future of prefabrication. Since 2008, *fib* Commission 6 and PCI have established a close cooperation on issues of mutual interest, with the comparison of respective approaches and the development of common publications. PCI has produced various works dealing with sustainability of precast concrete structures and has recently completed a large research programme on this subject. The *fib* has also developed a large amount of work on sustainability. Both the former Commission 3 "Environmental aspects of design and construction" and Commission 6 "Prefabrication" have collaborated in the preparation of the Bulletin 21 "Environmental Issues in Prefabrication." Presently, the work regarding sustainability is being developed in the new Commission 7 "Sustainability" which incorporates the former Special Activity Group 8 (SAG 8).

The first part of this document presents an overview of the most recent work developed on sustainability; in particular, life-cycle assessment studies of structures where precast concrete elements are used. The developments by PCI and the *fib*, as well as by other organizations – such as Abcic quality control systems, ISO, and CEN –are included in the document.

The final objective of the task group is to draft recommendations regarding the study and assessment of precast concrete elements and structures with respect to sustainability. These recommendations cover all phases of the life cycle related to precast concrete structures, from planning, design, execution, use, and maintenance and remedial activities, up to the end of life, which may include dismantling, reuse, or recycling.

A framework has been developed and is proposed for the evaluation of precast concrete structures. The framework includes aspects regarding the whole life cycle of the structure and also includes environmental, economic, and social aspects to achieve a final sustainability index.

2. Introduction

Prefabrication has evolved in depth and breadth from its beginnings, bringing many of the advantages of industrialization to construction, while solving some of the problems that arose in the early years. Today prefabrication, compared to traditional construction methods, and concrete as a material, feature many beneficial characteristics. The inherent advantages in such industrialized construction are described in the following.

Precast concrete elements are factory-made products. The main way to industrialize the construction industry is to shift work from temporary construction sites to modern, permanent facilities. Factory production entails rational and efficient manufacturing processes, skilled workers, standardization of repetitive tasks, and lower labour costs per square metre of construction because of automated production. Products made in factories benefit from the deployment of lean-manufacturing principles. Automation is gradually being implemented in factories and is already used for the preparation of reinforcing steel, mould assembly, concrete casting, and surface finishing on architectural concrete.

Because prefabrication optimizes the use of materials, prefabricated products have a greater potential for savings than that of cast-in-situ construction. Structural performance and durability of prefabricated products are also enhanced through design, modern manufacturing equipment, and carefully planned working procedures.

Prestressing is commonly used in prefabrication. The technique not only delivers all the advantages of prestressed concrete from the construction standpoint, but also reduces manufacturing costs because fewer workers are needed and the absence of the expensive anchorage devices needed for post-tensioning.

Architectural freedom is needed to create new building designs. Architectural design is no longer subject to the inflexible concrete elements of yesteryear and almost any building can be adapted to the builder's or the architect's requirements. Architectural grace and variety need not to clash with increased efficiency. Gone are the days when industrialization meant large numbers of identical units. On the contrary, efficient production can be combined with skilled workers, allowing for modern architectural design at no extra cost. Today, building appearance and finishes may largely determine construction procedures. Precast concrete elements accommodate a wide variety of finishes, ranging from carefully moulded surfaces to high-quality architectural concrete. The use of beams and columns with special shapes and high-quality finishes can afford architects considerable creative freedom and range of expression.

Flexible building use may be another key aspect in design. Certain types of buildings, office buildings in particular, often need to be adaptable to user needs. The most suitable solution in such cases is open plan design.

The production of precast concrete elements normally takes place under controlled climatic conditions in enclosed factories. This makes control of waste, emissions, noise levels, among others, easy compared to the same process at a traditional building site. The factory work environment is also easily controlled and frequently safer.

Moreover, the use of new technologies like self-compacting concrete (SCC) can significantly reduce the noise and vibration in the production process. The use of high-performance concrete (HPC) enables design and production of more reliable and more durable structures with optimized shape. The potential for savings is evident in structural material consumption and consequently natural resources.[1]

The environmental impact of prefabrication is mainly the impact caused by the raw materials of concrete (especially production of cement and steel), which is similar to that of other concrete structures. Sometimes the environmental impact of precast concrete is less than that of other concrete construction because of the reduced use of materials in comparison with on-site construction[2,3]. The environmental impact caused by raw materials is approximately three times larger than that caused by the production process of the elements, as indicated by the examples of environmental product declarations[4].

The thermal inertia of heavy materials is well known both in warm and cold climates. Most people have experienced the comfort of coming into a comparatively cool stone building on a hot day in a warm climate. In precast concrete structures, several constructive systems have been developed using this characteristic.

2.1 Energy consumption

Although the world's fossil fuel reserves are unlikely to run out, the resulting greenhouse gases produced in using these fuels are having a significant effect on the world's climate. To limit temperature, rise to 2 degrees Celsius (3.6°F) as recommended by the Intergovernmental Panel on Climate Change (IPCC)[5] will require a significant move away from the use of fossil fuels. This is already occurring and sustainable renewable energy sources are providing significant percentages of energy in many countries. This combined with energy efficiency programmes has resulted in a disconnect between gross domestic product (GDP) and energy consumption. In many countries, energy consumption is falling despite increasing GDP (Fig. 2-1). There is also a worldwide move towards an agreement to limit the use of fossil fuels, and this will radically change how we view sustainability.

The growing importance of cities in the economy and resource consumption from the industrial revolution has been producing a very remarkable phenomenon of concentration of population in cities. This has been happening in both developed and developing countries. The United Nations (UN) forecast is that this concentration in the cities will continue throughout this century, meaning a global concentration slightly higher than 50% in 2010 and up to 70% in 2050, with very substantial increases in both groups of countries.

In Europe, the UN forecast is that the percentage would rise from 75% today to 85% in 2050. The main reasons for the accelerating concentration of the population in cities are the complexity of modern societies, which calls for greater interaction and interdependence between people, and the higher needs for practical management of certain services for the population, such as hospitals or specialised schools.

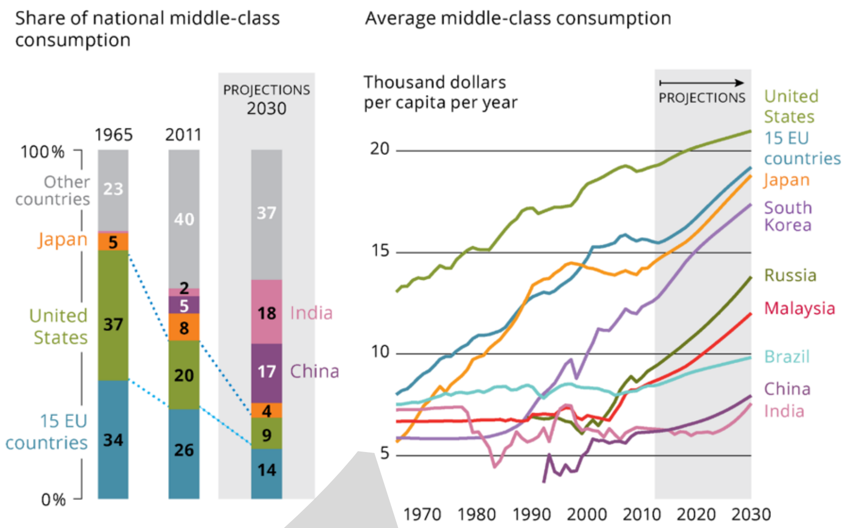


Fig. 2-1 In many countries, the share of energy consumption is falling despite increasing gross domestic product. http://www.eea.europa.eu/data-and-maps/figures/urban-trends-by-world-regions

The pace of growth in emerging countries is considerably higher than that produced in today's industrialized countries. This is due, undoubtedly, to the greater mobility of capital and technology. For example, the UK needed 154 years to double its per capita GDP since its pace of growth is considerably higher, the U.S. required 53 years and Germany 65 years. The rhythms of South Korea, China, and India to double its per capita GDP were 10, 12, and 16 years, respectively, having all produced this doubling in the last 50 years. There has to be taken into account that these are very fast growing systems and maybe not very stable.

In another way of looking at this, the energy consumed and emissions from human settlements have three origins:

1. Those that come from buildings;
2. Those that come from communication infrastructures and services;
3. Those that come from urban mobility.

In the case of buildings and urbanization the entire life cycle, that is, energy and emissions from the production of materials, transport to work site, demolition and, if applicable, recycling should be considered.

Currently, quality data related to energy consumed and emissions are only available for buildings[6]. There are no conclusive comparative data for urban mobility between transport modes and for specific cities. Current data for urban mobility have a large scatter in the results. Also, there are no systematic studies on energy and life-cycle emissions of communications infrastructure and urban services, but it seems clear that there would be a large dispersion in the data depending on the city.

There are several studies where the energy consumption and emissions from buildings are estimated[6]. The most comprehensive and rigorous studies have the following characteristics. They refer to:

1. the entire life cycle of the building, and
2. the entire building stock. This means not just residential use, but also commercial buildings, offices, hotels, warehouses, and other uses.

The main conclusions of these studies are:

1. According to the European Directive on Energy Efficiency in Buildings, buildings in the European Union consume 40% of the energy and create 36% of the greenhouse gas emissions .

2. According to the U.S. Green Building Council, buildings in the U.S. account for 39% of the energy consumption and 36% of greenhouse gas emissions.

3. According to a study conducted in 2005 by the Royal Institute of Chartered Surveyors (RICS) in the UK, buildings account for about one third (1/3) of total emissions of greenhouse gases in the world.

For developed countries, the combined energy and emissions from buildings, urban mobility (including transportation), and communications infrastructure and urban services represent between 50% and 60% of a country's total energy consumption. For developing countries, the combined energy and emissions from these sectors are between 40% and 50% of a country's total energy consumption.

To reduce energy consumption and emissions of greenhouse gases, a good first step is to optimize energy use (and related emissions) from buildings and urban planning, which impacts energy and emissions related to mobility and urban infrastructure.

2.2 The Green Package 2009 (EU)

The EU Council adopted on April 6, 2009, the Green Package 7, which consists of a set of guidelines and standards with binding commitments to ambitious climate policies. The three main objectives, commonly known as 20-20-20 for 2020, are:

- Reduce by 20% the emissions of greenhouse gases over those in 1990, contemplating the possibility of increasing this reduction to 30% following a satisfactory international agreement on climate change.
- Reach a binding target of 20% renewable energy in the final energy demand. This commitment includes the goal of renewable energy, not just biofuels, that will be at least 10% of transport fuels.
- Achieve energy efficiency improvement of 20% compared to the basic scenario.

The Green Package consists of six directives that allow creation of the necessary tools to achieve the desired objectives:

- Promotion of renewable energy (Directive 2009/28/EC).
- Emission allowances commerce (Directive 2009/29/EC).
- Emissions from fuels (Directive 2009/30/EC).
- CO_2 geological storage (Directive 2009/31/EC).
- Shared effort to reduce emissions (Decision 406/2009 of the European Parliament and the Council).
- Emissions from new automobiles (Regulation 443/2009 of the European Parliament and the Council).

The significance of these measures is that they attempt to reconcile the objectives of energy policy and the fight against climate change by setting powerful targets on climate and energy. (Fig 2.2)

The objective to obtain a 20% share of renewables in the final energy demand is included in national targets is based on the baseline of renewable energy use starting in 2005 and on the "per capita" GDP.

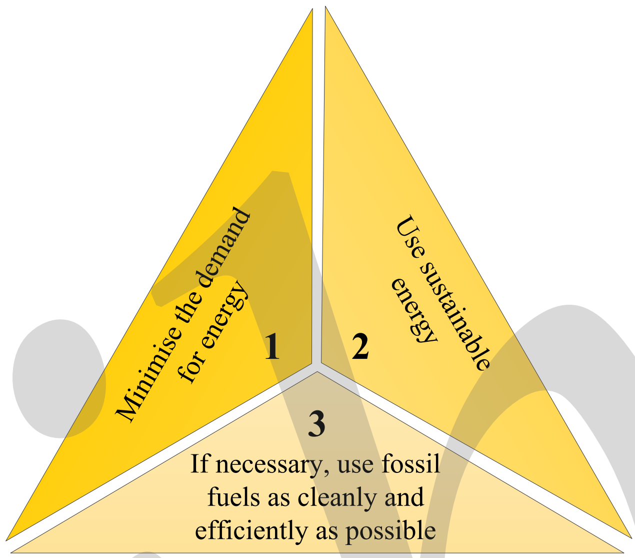


Fig. 2-2 Principles of Design for Sustainable Energy

Of all the directives, the one related to emission allowance trading is of particular interest. It has indirect influence on the achievement of all the objectives because it is most dependent on regulation of emissions. It also will encourage the use of renewable energy, the development of new technologies, and energy saving and energy efficiency.

2.3 The European Directive on Energy Efficiency in Buildings

In the context of energy and climate policies contained in the Third Package and the Green Package, as set out previously, the European Parliament and the Council of the European Union approved May 19, 2010, Directive 2010/31/EU on energy efficiency of buildings, which had considerably strengthened the provisions in the previous Directive 2002/91/UE on the same subject. All this is done to meet the EU target of 20-20-20 in 2020, and due to the facts that 40% of total energy consumption in the EU and 36% of their emissions correspond to buildings. These percentages only include energy due to the use and operation of the building, not the energy derived from the manufacture, transportation, and installation of building materials.

The most relevant elements included in this directive are:

- All new buildings must be nearly zero energy consumption from December 31, 2020. This date was brought forward to December 31, 2018, for new buildings occupied and owned by public authorities.
- Member states should set intermediate targets for new buildings by 2015.

- In terms of minimum energy requirements, member states shall meet the following requirements:
    - be able to distinguish among new and existing buildings,
    - will not involve minimum requirements that make losses for considering the life cycle of the building, and
    - be reviewed at regular intervals not exceeding five years.
- Member states shall calculate cost-optimal levels of minimum energy performance requirements using the methodological framework that provides the directive.
- It is compulsory to issue a certificate of energy efficiency in the building:
    - for buildings that are constructed, sold, or rented to a new tenant, and
    - for buildings in which a public authority occupies a total useful floor or higher of 500 m^2 (5'382 ft^2) and are frequently visited by the public, in addition, by July 9, 2015, this starting point will be reduced from 500 m^2 (5'382 ft^2) to 250 m^2 (2'691 ft^2).

The expected impacts of the implementation of this directive are:

- Savings of 5% to 6% of total energy consumption in the EU by 2020,
- Reduction of 5% of EU emissions in 2020,
- Creating 280,000 to 450,000 jobs, and
- CO_2 abatement costs reduced or eliminated.

The European Commission approved on January 16, 2012 a regulation establishing the comparative methodology framework for calculating cost-optimal levels of minimum energy requirements of the buildings and their components. That regulation provides that:

- The methodology of cost optimization is neutral from a technological point of view and does not help, therefore, one technological solution over others, not being confined to only those already tried and tested;
- The minimum national energy efficiency should not be lower, by more than 15%, than the result of cost optimization calculations taken as a national reference. The cost-optimal level should be within the range of levels efficiency at which the cost-benefit analysis offers a positive result over the building life cycle, and
- Calculations and cost estimates involved in the large number of assumptions and uncertainties should be accompanied by a sensitivity analysis to assess the robustness of the main parameters used in the calculation, for the calculation of cost optimization. This analysis must cover at least the future evolution of energy prices and the evolution rate and, where appropriate, the future price development of the proposed technology. There are some systems like MIVES[8] in Spain, which take into account this aspect (Fig. 2.3).

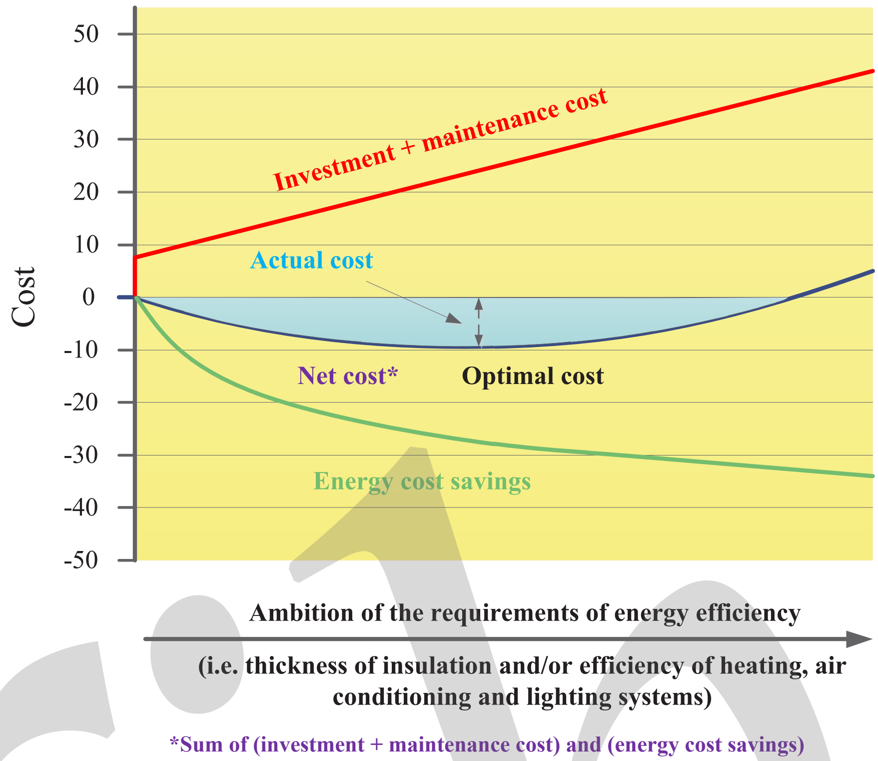


Fig 2.3. Costs of energy savings

2.4 Energy efficiency in buildings

The energy consumed and emissions of greenhouse gases from buildings occur in all phases of the building life cycle:

- Manufacture of building materials.
- Transport of raw materials to factories, semi-finished products between factories, building materials to the construction and demolition materials to landfill or factory for recycling.
- Construction of the building.
- Use and operation of the building.
- Maintenance, which in turn incorporates new materials to the building.
- Demolition and recycling.

Of these, the only one known precisely is the energy consumed and produced for the use and operation of the building, which may come from heating and cooling loads, or electricity from a network, renewables, cogeneration, or geothermal sources.

Regarding the embodied energy in construction materials, to accurately calculate these values, studies must account for different construction techniques, manufacturing technologies and materials, and country regulations. These variables can all lead to very different results and therefore values proposed and measured within some specific situations cannot be extrapolated.

Furthermore there are no available reliable statistics on the transportation aspects which can be attributed to the building during its life cycle. For example, the energy used in the process of construction of the building or its demolition, although we consider it negligible with respect to the energy consumed in the life cycle of the building, is frequently not known.

Finally, when calculating the energy related to the maintenance phase of a building, a study should take into account the addition of new materials to the building. In this case, not only the maximum amount of energy attributable to the production of the corresponding materials should be taken into account, but also the energy consumption associated to the transportation, assembly, demolition, and transportation of the replaced items.

In order to provide a rough estimation of the percentage of total emissions in Spain represented by the construction sector, a study by the Ministry of Housing (now Ministry of Development) entitled "On a strategy to address the building sector towards efficiency in the emission of greenhouse gases," in October 2007, estimated that emissions from the manufacture of materials and the use and operation of the buildings had increased from 24% of total national emissions in 1990 to 33% in 2005.

Moreover, the study estimated that the sole emissions from the use and operation of buildings (that is, excluding those relating to the manufacturing of materials) was between 16% and 21% of the total emissions in the country. Also, the quantified emissions from manufacturing construction materials of buildings were 49% of those associated with the use and operation of buildings in 1990, a figure that reached 56% in 2005.

It should be noted that the previous data related to the emissions do not include those related to transport of construction materials because of the difficulty in obtaining this data. The consequence is that if we want to reduce the global emissions of developed countries by 80 to 90% by 2050, it will be necessary to considerably reduce emissions in the manufacture of materials and in the use and operation of all buildings. Specifically, the European roadmap for a low carbon economy by 2050 targets a reduction in emissions from the use and operation of the building by 90% by 2050. (Fig. 2-4)

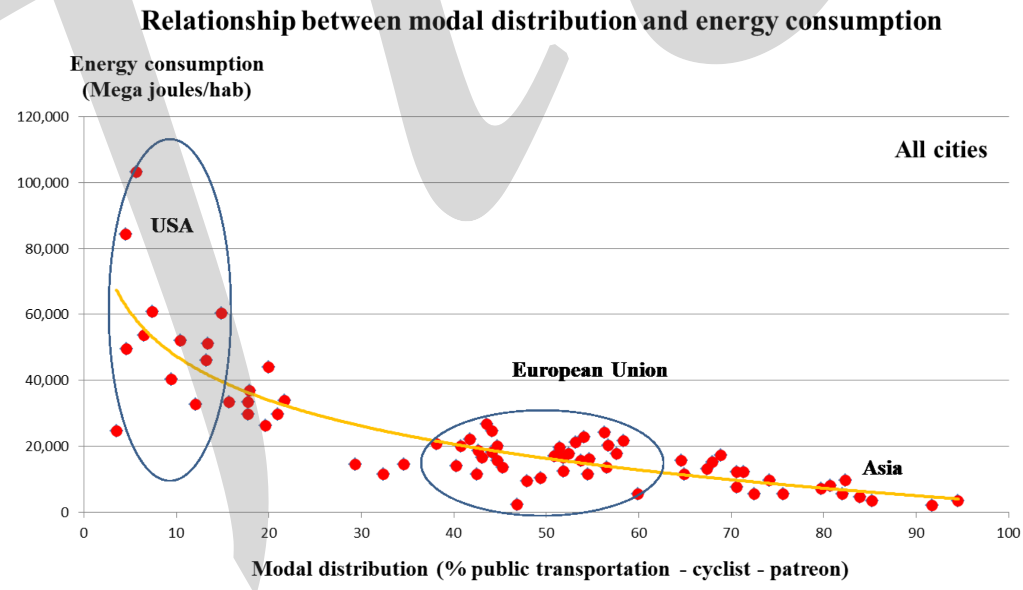


Fig. 2-4 Energy consumption and modal transportation in the cities. Note: 1 MJ/ha = 384 btu/acre.

2.5 The energy and emissions of greenhouse gases in the manufacture of building materials

As previously mentioned, the energy and greenhouse gas (GHG) emissions in the manufacture of building materials are significantly influenced by the construction technology of each country.

For example, ceramics and structural concrete are widely used in Spain, while in the United Kingdom uses steel and concrete blocks more commonly. Also, the transmittance values for façades and windows suggested in the respective building codes are very different, largely reflecting climatic differences. This makes the energy and emissions per square metre vary by country.

In Spain, there are four relatively recent studies that address the quantification of energy consumption and/or GHG emissions produced in the manufacture of building materials, although none of them allocated the energy and transport emissions of the raw materials, the intermediate, or finished products to the manufacturing process[6].

One can determine from the results of these studies that the multifamily housing sector:

- has a lower consumption in energy
- has lower CO_2 emissions

2.6 The energy and GHG emissions from the use and operation of the building

Many studies have confirmed that the largest proportion of energy use and GHG emissions result from the use phase of the building over its life cycle. In the EU 28, the final energy consumption for the use and operation of buildings accounted for 40% of the total energy consumed in 2009, with 27% of that associated to households and 13% to commercial buildings (Sources: Buildings Performance Institute Europe, Europe's Buildings Under the Microscope, in October 2011, and the Directive European energy efficiency the building)[9].

Moreover, the final energy consumption for the use and operation of the entire residential and commercial buildings represented 29% of the total energy consumed in 2010[10].

For the whole building sector, 64% corresponded to residential (18.5% of total final energy consumption) and 36% to tertiary sector (10.5% of total final energy). Both data come from the EU reports, and do not include the energy corresponding to the manufacturing of building materials.

From the point of view of emissions of GHG, the use and operation of buildings accounts for 36% of total emissions in the EU 28[11].

The European roadmap for a low carbon economy by 2050 sets a target of reducing GHG emissions in 2050 by 80% compared to those in 1990, targeting a 90% reduction of the use and operation of building by that date.

One can conclude that there is a need for a profound transformation in the design and construction of buildings to meet such ambitious goals. Never before has there been the need for such a deep transformation within the building sector, nor within such a short time frame. The need to rapidly transform the energy performance of buildings is motivated by the long life of the same and by the difficulty and costs of improvements through rehabilitation.

2.7 The current situation of building energy efficiency in Europe

The net area built in the EU 28, Norway, and Switzerland is about 25,000 km^2 (9'653 mi^2) and is growing at an annual rate of about 1% (BPIE, 2011)[12]. The gross surface area is equivalent to the surface of a country like Belgium. (30,528 km^2) (11,787 mi^2).

Of the total floor area of 25 Mm^2 (9.7 million mi^2) in EU 28, Norway, and Switzerland, 75% corresponds to residential use while 25% corresponds to non-residential use. These percentages in Spain are of 86% residential and 14% non-residential. Regarding the type of building, 64% of the number of buildings of all the countries are individual houses and 36% collective.

Energy consumption in buildings has had two very distinct trends since 1990: an increase of 50% in gas and electricity consumption, and a reduction in the use of solid or fuel oil between 25% and 75%.

As for emissions, buildings are responsible for 36% of them in Europe. The average emission in the use and operation of the building is 54 kg $CO2/m^2$ (11 lb CO_2/ft^2) net surface, with values ranging in different countries from 5 to 120 kg $CO2/m^2$ (1 to 25 lb CO_2/ft^2).

In 2009, the final energy consumption of buildings in Europe was distributed into 68% for residential and 32% for non-residential buildings. Since the floor area in Europe is divided by 75% for housing and 25% for other uses, it indicates that the energy intensity of residential buildings is somewhat lower, on average, than for other uses.

The energy consumption in homes is used for heating, cooling, hot water, lighting, cooking, and appliances. There was an increase in electricity consumption by 38% over the past 20 years, while fuel consumption has remained reasonably constant.

The percentage of final energy consumption dedicated to heating is 55% in the countries of the south, 66% in central and east, and 67% in the north and west. As for the final energy consumption of non-residential buildings in Europe, electricity consumption has grown by 70% since 1990 while it has remained fairly constant for fuel.

In the U.S., the largest users of energy are the electricity, transportation, and industrial sectors, using 40, 28, and 21% of the total energy of the U.S., respectively (Fig. 2-5).

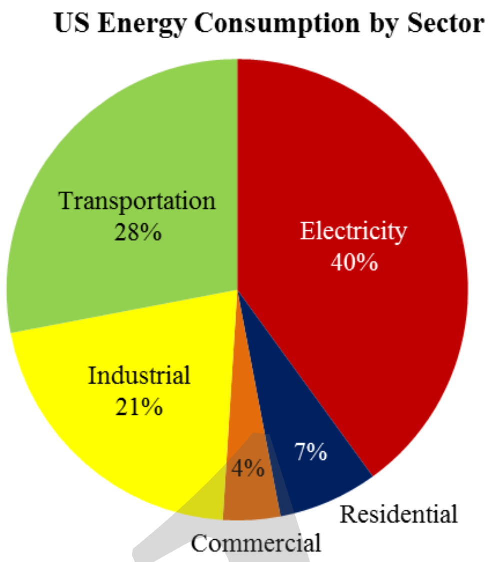


Fig. 2-5 Energy consumption by activity. Source: US Energy Information Agency

3. Current Guidelines and Standards

The recent proliferation of standards related to sustainability makes it difficult to make meaningful comparisons among programmes, or even between environmentally-conscious construction and traditional construction. As a reaction to such numerous tools and methods for measuring the environmental (sustainable) performance of products[1], the main standardizations organizations worldwide – CEN, ISO and ASTM – have been considering voluntary or mandatory policies based on life cycle assessment. In addition, private initiatives were coming up with multi-criteria methods for measuring the life cycle environmental performance of products, which will be explained later.

3.1 ISO information

According to ISO, a standard is a document that provides requirements, specifications, guidelines or characteristics that can be used consistently to ensure that materials, products, processes and services are fit for their purpose. ISO published over 19,500 international standards, covering almost all aspects of technology and business, which have been developed by over 250 technical committees (TCs). Each TC has its subcommittees (SC).

At present, there are three TCs which deal with sustainability aspects in ISO: ISO TC207; ISO TC59 SC17; and ISO TC71SC8.

3.1.1 ISO TC207

TC207, Environmental Management, was created in 1993. Its scope is the standardization in the field of environmental management systems and tools in support of sustainable development. However, TC207 excludes test methods of pollutants, setting limit values and levels of environmental performance, and standardization of products. Currently, TC207 has the following subcommittees:

SC1: Environmental management systems

SC2: Environmental auditing and related environmental investigation

SC3: Environmental labelling

SC4: Environmental performance evaluation

SC5: Life cycle assessment

SC7: Greenhouse gas management and related activities

TC207 has published 32 ISO standards as ISO 14000 series as of 2014. In ISO 14040, LCA (Life Cycle Assessment) is defined as the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle, which includes extraction of resources, production of materials, manufacture of products, use, end of life phase, and disposal.

The environmental impacts cover global climate change, natural resources use, stratospheric ozone level, land use and habitat alteration, eutrophication, acidification, air pollution, water pollution, soil contamination, pollution due to radioactive substances, and impacts due to waste generation, noise/vibration, and others. TC207 has played an important role to raise awareness of the importance of environmental aspects from more than 20 years ago. Recently, TC207 focuses on the standardizations related to greenhouse gas emissions.

3.1.2 ISO TC59/TC50/SC17

TC59, focusing on buildings and civil engineering works, was created in 1947. At present TC59 consists of 8 subcommittees, including:

- SC2 (Terminology and harmonization of languages),
- SC3 (Functional/user requirements and performance in building construction),
- SC8 (Sealants),
- SC13 (Organization of information about construction works), SC14 (Design life),
- SC15 (Performance description of houses),
- SC16 (Accessibility and usability of the built environment), and SC17 (Sustainability in buildings and civil engineering works). The standard ISO 15686-6:2004 by TC59
- SC14 (Buildings and constructed assets – service life planning – Part 6: procedures for considering environmental impacts) was withdrawn.

This standard showed how to assess, at the design stage, the potential environmental impacts of alternative designs of a constructed asset considering technical, economic, and environmental assessments (that is, sustainability). The reason for its withdrawal is not available. TC59 SC17 was created in 2002. SC17 currently has five WGs, including WG1 (General principle and terminologies), WG2 (Sustainable indicators), WG3 (Environmental declaration of products), WG4 (Environmental performance of buildings), and WG5 (Civil engineering works). SC17 has published the following standards so far:

- Sustainability in buildings and civil engineering works – Guidelines on the application of the general principles in ISO 15392
- ISO 15392:2008: Sustainability in building construction – General principles
- ISO 21929-1:2011: Sustainability in building construction – Sustainability indicators – Part 1: Framework for the development of indicators and a core set of indicators for buildings
- ISO 21930:2007: Sustainability in building construction – Environmental declaration of building products
- ISO 21931-1:2010: Sustainability in building construction – Framework for methods of assessment of the environmental performance of construction works – Part 1: Buildings
- ISO/TR 21932:2013: Sustainability in buildings and civil engineering works – A review of terminology

SC17 WG5 has published recently ISO/TS 21929-2 (Sustainability indicators – Part 2: Framework for the development of indicators for civil engineering works).

3.1.3 ISO TC71/SC8

ISO TC71, Concrete, reinforced concrete and prestressed concrete, was created in 1949. At present, TC71 consists of 7 subcommittees, including

- SC1 (Test methods of concrete),
- SC3 (Concrete production and execution of concrete structures),
- SC4 (Performance requirements for structural concrete), SC5 (Simplified design standard for concrete structures),
- SC6 (non-traditional reinforcing materials for concrete structures),
- SC7 (Maintenance and repair of concrete structures), and
- SC8 (Environmental management for concrete and concrete structures). TC71
- SC8 was created in 2007. Until today, the following two standards were published:
  - ISO 13315-1:2012 Environmental management for concrete and concrete structures – Part 1: General principles
  - ISO 13315-2:2014:Environmental management for concrete and concrete structures – Part 2: System boundary and inventory data

The scope of ISO 13315-1:2012 is to provide a framework and basic rules on environmental management related to concrete and concrete structures. This includes the assessment of the environmental impacts and methods of implementing environmental improvement based on the assessment. The scope of ISO 13315-2: 2014 is to provide a general framework, principles, and requirements related to the determination of system boundaries and the acquisition of inventory data necessary for conducting a life cycle assessment (LCA) of concrete, precast concrete and concrete structures. For example, the system boundary of cement production is shown in Fig. 3-1.

The remaining standards of ISO 13315 series to be developed are:

- Part 3: Constituents and concrete production
- Part 4: Environmental design of concrete structures
- Part 5: Execution of concrete structures
- Part 6: Use of concrete structures
- Part 7: End of life phase including recycling of concrete structures
- Part 8: Label and declaration

There are three benefits in the ISO 13315 standards as follows:

- Inventory data can be calculated with transparent common rules.
- Environmental impact can be quantitatively evaluated.
- Therefore, the development of innovative concrete technologies is promoted.

ISO standards have significant influence on society because they are internationally developed using a consensus process. Environmental aspects of sustainability are becoming more and more important worldwide. If we continue to utilise natural resources and energy on the earth, we will have a serious problem which includes natural resources depletion and global warming due to greenhouse gas emission. We need to know the current situation by calculating the impacts and to find ways to reduce the consumption of natural resources and energy. ISO standards guide the procedures on how to do this.

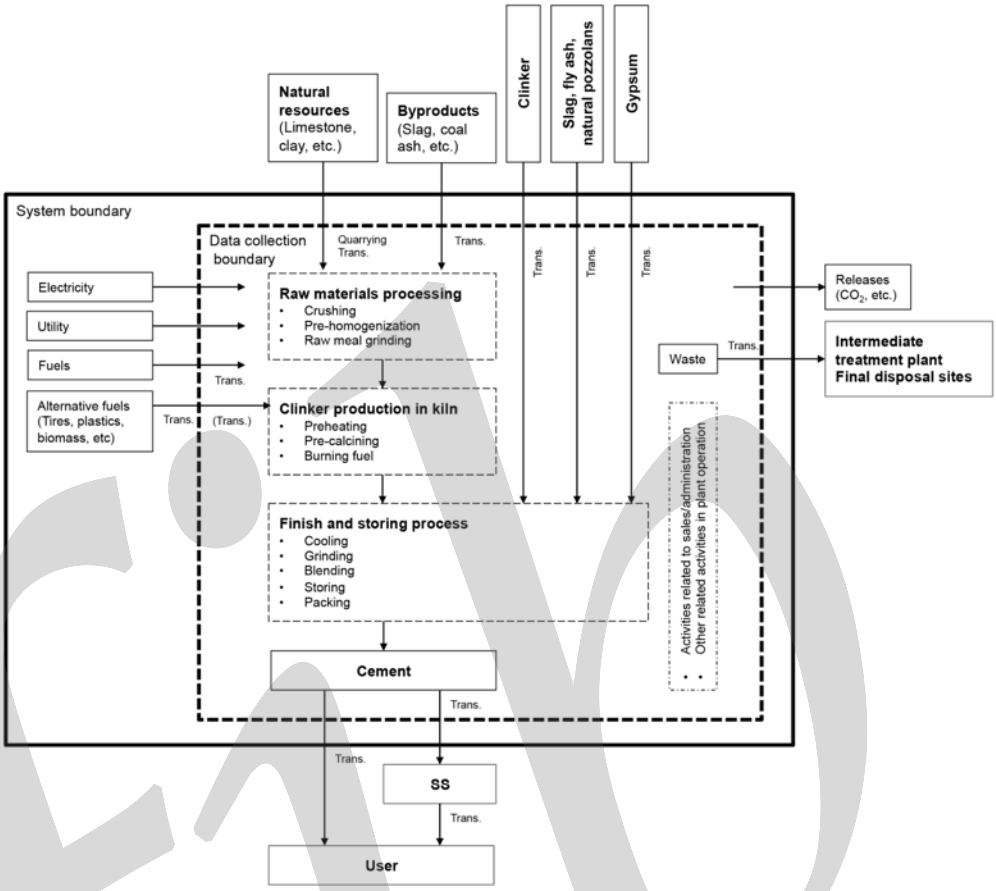


Fig. 3-1 System boundary of cement production[2]

3.2 CEN information

3.2.1 Information on CEN/TC 350 activity

CEN Technical Committee TC350, Sustainability of construction works, is preparing a set of European Standards that provide a system for the sustainability assessment of buildings using a life cycle approach and quantitative indicators for the environmental performance, social performance and economic performance of buildings.

CEN/TC 350 is 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 its life cycle. The standards will describe a harmonised 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.

The purposes of the suite of these standards are:

- to provide a framework with principles, requirements and guidelines for the sustainability assessment of construction works,
- to enable comparability of the results of assessments,
- to allow the sustainability assessment; that is, the assessment of environmental, social and economic performance.

Although the evaluation of technical and functional performance is beyond the scope of this set of standards, the technical performance and functional performance are considered within this framework by reference to the functional.

The Technical Committees to carry out the CEN 350 work began to be set up in 2005 with the work divided into seven work groups:

- CEN/TC 350: TG Framework
- CEN/TC 350/WG1: Environmental performance of buildings
- CEN/TC 350/WG2: Building life cycle description
- CEN/TC 350/WG3: Product Level (EPDs , communication formats)
- CEN/TC 350/WG4: Economic Performance Assessment of Buildings
- CEN/TC 350/WG5: Social Performance Assessment of Buildings
- CEN/TC 350/WG6: Civil Engineering works (new)

CEN/TC 350 focuses on sustainability of construction works, both on frameworks and at the building and building product level. While the framework standards are very general, the standards for building and product level are more specific and applicable in building practice.

Nowadays, the most significant standard that relates to sustainability assessment of all building products, including concrete structures, is EN 15804 Sustainability of construction works: Environmental product declarations, which includes core rules for the product category of construction products. This standard is in accordance with ISO 14025 *Environmental labels and declarations: Type III environmental declarations*, and Principles and procedures, which was the first in this area.

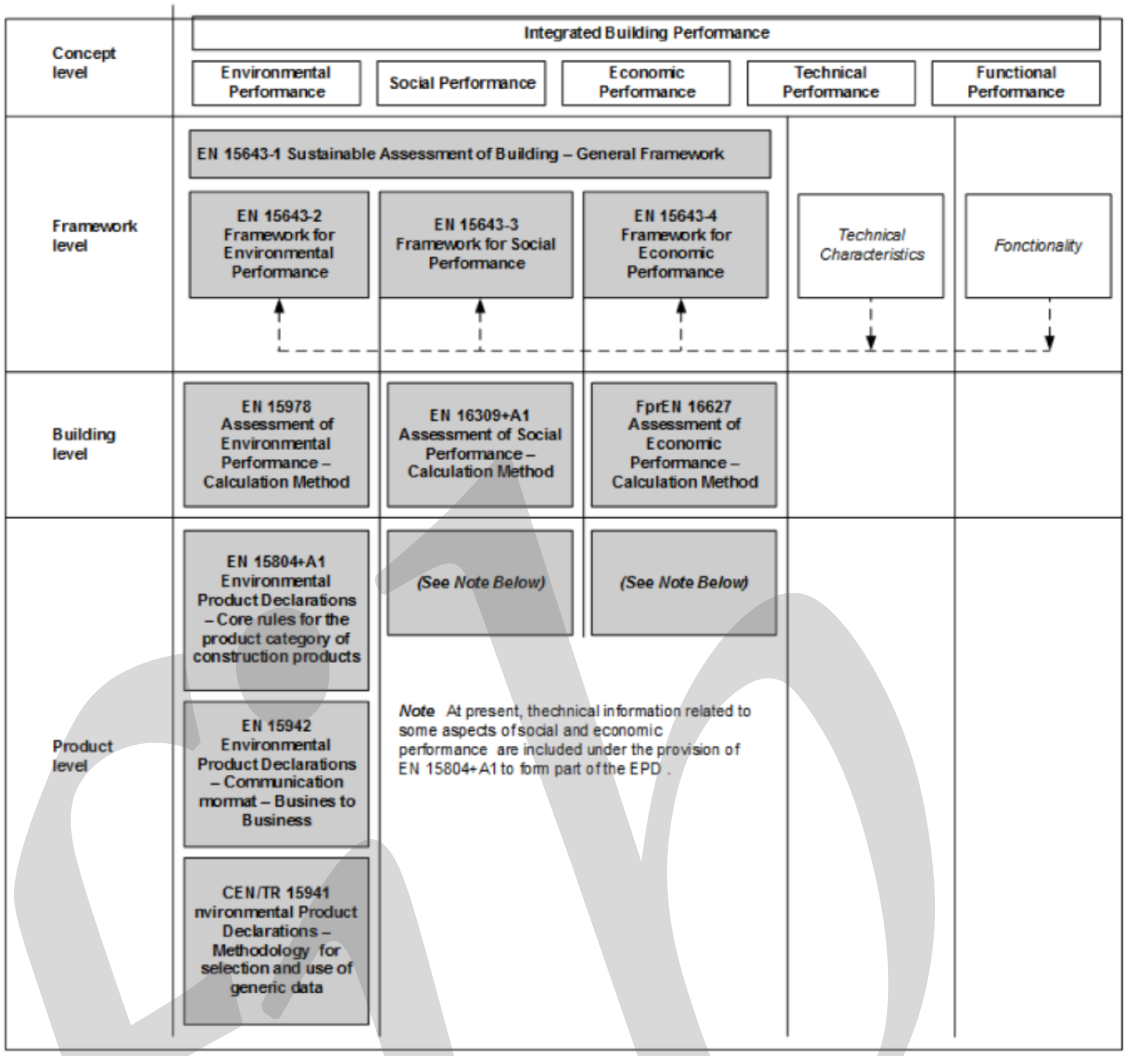


Fig. 3-2 Work programme of CEN/TC 350[3]

3.2.1.1 Framework level

There are four standards (Parts) already approved that relate to the series of EN 15643:

Part 1 provides the general principles and requirements, expressed through a series of standards, for the assessment of buildings in terms of environmental, social, and economic performance while taking into account the technical characteristics and functionality of a building.

The assessment will quantify the contribution of the assessed construction works to sustainable construction and sustainable development. The framework applies to all types of buildings and it is relevant for the assessment of the environmental, social, and economic performance of new buildings over their entire life cycle, and of existing buildings over their remaining service life and end of life stage. The standards developed under this framework do not set the rules for how the different assessment methodologies may provide valuation methods. Nor do they prescribe levels, classes, or benchmarks for measuring performance.

Part 2 provides the specific principles and requirements for the assessment of environmental performance of buildings, taking into account the technical characteristics and functionality of a building. In this series of standards, the environmental aspects of sustainability are limited to the assessment of environmental impacts of a building on the local, regional, and global environment.

The environmental assessment is based on LCA and additional quantifiable environmental information expressed with quantified indicators. It excludes the assessment of a building's influence on the environmental aspects and impacts of the local infrastructure beyond the area of the building site, and environmental aspects and impacts resulting from transportation of the users of the building. It also excludes environmental risk assessment.

Part 3 has the same principles of the Part 2 but it is intended for the social dimension.

Finally, Part 4 is intended for the economic dimension.

3.2.1.2 Building level

Hereafter some information about the 3 standards published by TC 350 concerning the building level are given.

EN 15978 specifies the calculation method, based on LCA and other quantified environmental information, to assess the environmental performance of a building, and gives the means for the reporting and communication of the outcome of the assessment. The standard is applicable to new and existing buildings and refurbishment projects and provides:

- the description of the object of assessment; – the system boundary that applies at the building level;
- the procedure to be used for the inventory analysis;
- the list of indicators and procedures for the calculations of these indicators;
- the requirements for presentation of the results in reporting and communication; and
- the requirements for the data necessary for the calculation.

The approach to the assessment covers all stages of the building life cycle and is based on data obtained from environmental product declarations (EPD), their "information modules" (EN 15804), and other information necessary and relevant for carrying out the assessment. The assessment includes all building related construction products, processes and services, used over the life cycle of the building.

Only the LCA of a building can provide estimates of the full range of environmental impacts, such as embodied energy use and related fossil fuel depletion; other resource use; greenhouse gas emissions; and toxic releases to air, water, and land.

When applied to buildings, an LCA includes:

- resource extraction;
- manufacturing and transportation of materials and prefabricated components;
- on-site construction;
- building operations, including energy consumption and maintenance;
- end-of-life reuse, recycling, or disposal.

EN 16309 provides the specific methods and requirements for the assessment of social performance of a building, while taking into account the building's functionality and technical characteristics. This European Standard applies to all types of buildings, both new and existing. In this first version of the standard, the social dimension of sustainability concentrates on the assessment of aspects and impacts for the use stage of a building expressed using the following social performance categories (from EN 15643-3): accessibility; adaptability; health and comfort; impacts on the neighborhood; maintenance; safety and security.

EN 16627 specifies the calculation methods, based on life cycle costing (LCC) and other quantified economic information, to assess the economic performance of a building, and gives the means for the reporting and communication of the outcome of the assessment. This European Standard is applicable to new and existing buildings and refurbishment projects.

This European Standard provides:

- the description of the objective of assessment;
- the system boundary that applies at the building level;
- the scope and procedure to be used for the analysis;
- the list of indicators and procedures for the calculations of these indicators;
- the requirements for presentation of the results in reporting and communication;
- and the requirements for the data necessary for the calculation.

The approach to the assessment covers all stages of the building life cycle and includes all building related construction products, processes and services, used over the life cycle of the building.

3.2.1.3 Product level

The changes in the building sector towards more sustainability lead to new information requirements for buildings and therefore building products. Since sustainability is assessed on a building level, not on a product level, relevant product related data is required in a harmonised format for building assessments.

EN 15804 provides core Product Category Rules (PCR) for Type III environmental declarations for any construction product and construction service. The core PCR:

- defines the parameters to be declared and the way in which they are collated and reported,
- describes which stages of a product's life cycle are considered in the EPD and which processes are to be included in the life cycle stages,
- defines rules for the development of scenarios,
- includes the rules for calculating the life cycle inventory and the life cycle impact assessment underlying the EPD, including the specification of the data quality to be applied,
- includes the rules for reporting predetermined, environmental and health information, that is not covered by LCA for a product, construction process and construction service where necessary,
- defines the conditions under which construction products can be compared based on the information provided by EPD.

For the EPD of construction services the same rules and requirements apply as for the EPD of construction products.

This standard provides rules to ensure that all EPDs of construction products, services, and processes are derived, verified, and presented in a harmonised way. The overall goal of an EPD is to provide relevant, verified, and comparable information about the environmental impact from construction product (for example, concrete component like precast floor panel or precast column) and services.

The information in a EPD is based on LCA, covering different life cycle stages based on different system boundaries, according to EN 15804 (Fig. 3-3):

- "Cradle to gate" LCA concept includes: Product stage – raw material supply (stone, gravel, sand, water…), transport, manufacturing and other associated processes influenced by the producer.
- "Cradle to gate with options" LCA concept includes: Product stage and selected further life cycle stages, for example, end-of-life stage, recycling, or other stages.
- "Cradle to grave" LCA concept includes: All stages, from Product stage to End of life stage (deconstruction, demolition, transport, waste processing, disposal). Reuse, recovery and recycling potential may also be included in this concept.

In order to enable the assessment of the environmental performance of construction works during their life cycle, it is recommended to provide an EPD based on a cradle to grave assessment.

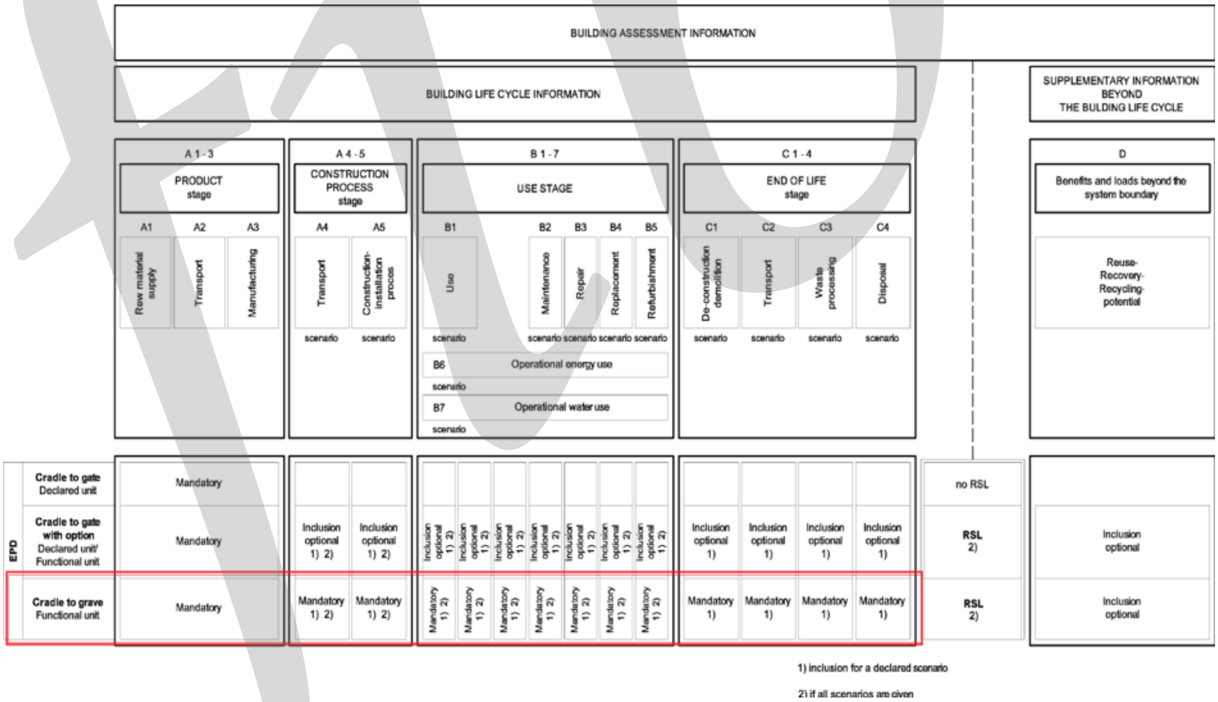


Fig. 3-3 Types of Environmental Product Declaration (EPD) with respect to life cycle stages covered and life cycle stages and modules for the building assessment (see EN 15804)

This standard sets up the basis to estimate the values corresponding up to 24 parameters[4], typically referred to as environmental indicators that can be gathered into three main groups in Table 3-1:

Table 3-1 Environmental Indicators used in TC 350 standards

1. Environmental Impact Indicators
- Global Warming Potential (GWP) - Ozone Depletion Potential (ODP) - Acidification potential (AP) - Eutrophication potential (EP) - Formation potential of tropospheric ozone (POCP) - Abiotic depletion potential for non-fossil resources (ADP-elements) - Abiotic depletion potential for fossil resources (ADP-fossil fuels)
2. Resource Use Indicators
- Use of renewable primary energy excluding renewable primary energy resources used as raw materials - Use of renewable primary energy resources used as raw materials - Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials) - Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials - Use of non-renewable primary energy resources used as raw materials - Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials) - Use of secondary material - Use of renewable secondary fuels - Use of non-renewable secondary fuels - Use of net fresh water
3.Waste Category Indicators
- Hazardous waste disposed - Non-hazardous waste disposed - Radioactive waste disposed

The assessment of social and economic performances at product level is not yet covered by European standards, at least on a European scale.

3.2.2 PCR for precast concrete

CEN Technical Committees in charge of building materials and products are now developing, on the basis of the general rules given in EN 15804, specific standards for their products adding the characterizations factors missing in EN 15804.

Such standards will be approved as a result of the entry into force of the Construction Product Regulation (EU 305/2011), the general European framework for most of the construction products traded in the continent. PCR has added a new essential requirement called "sustainable use of natural resources" that should notably take into account the recyclability of construction works, their materials and parts after demolition, the durability of construction works, and the use of environmentally compatible raw and secondary materials in construction works.

EN 16757 "Sustainability of construction works - Environmental product declarations - Product Category Rules for concrete and concrete elements" is the European Standard that complements the core rules for the product category of construction products as defined in EN 15804. This European Standard applies to concrete and concrete elements for building and civil engineering, excluded autoclaved aerated concrete. It was developed jointly by the CEN product committees for concrete: CEN/TC 104 Concrete and CEN/TC 229 Precast concrete products].

This document defines the parameters to be reported, the EPD types (and life cycle stages) to be covered, what rules must be followed to generate life cycle inventories (LCI) and conduct life cycle impact assessment (LCIA), and the data quality to be used in the development of EPDs.

In addition to the common parts of EN 15804, this European standard for concrete and concrete elements:

- defines the system boundaries;
- defines the modelling and assessment of material-specific characteristics;
- defines allocation procedures for multi-output processes along the production chain;
- defines allocation procedures for reuse and recycling;
- includes the rules for calculating the LCI and the LCIA underlying the EPD;
- provides guidance/specific rules for the determination of the reference service life (RSL);
- gives guidance on the establishment of default scenarios;
- gives guidance on default functional units for concrete elements.

This document is intended to be used either for cradle to gate, cradle to gate with options, or cradle to grave assessment, provided the intentions are properly stated in the system boundary description.

Within the construction works context, a cradle to grave declaration delivers a more comprehensive understanding of the environmental impact associated with concrete and concrete elements.

It is necessary to clarify that such standards are related to the building itself (or at the most specific case to some building units such as facades, roofs or structures) and not to the components or elements are composed from. For instance, a precast concrete beam could not be considered a sustainable element everywhere and/or every time if the whole structure is not assessed. Nevertheless, some sustainable (environmental) characteristics may be remarked about precast concrete solutions are really competitive, as in Table 3-2:

Table 3-2 Precast concrete contribution to Sustainability

Precast concrete contributions	**ENVIRONMENTAL**	**SOCIAL**	**ECONOMIC**
Thermal inertia	Savings in energy consumption CO_2 emissions avoided	Higher comfort	Fewer operational costs: heating and cooling
Fire protection	Lower toxic emissions	Better protection to persons (and firefighters) Better protection to heritage	Lower insurance Higher possibility of reconstruction
Acoustic insulation	Less additional materials	Higher comfort Higher privacy level	
Industrialization	Lean construction: nearly no waste Dry construction: precast concrete arrives on site ready for installation	Increased safety: fewer labour accidents	Faster loans/mortgage repayment
Resource efficiency	Reduction of the consumption of natural resources by using waste materials in products (ex. recycled aggregates from concrete wastes)	Partial elimination of a global problem	Increased use of better materials (high-resistance/performance concrete, prestressed steel) means an optimized ratio materials/cost
Resilience (robustness) Fire		Better performance against natural disasters	Fewer expenses in recovery the original construction
Durability	Longer period of environmental impacts amortization	Better safety against hazards	Less maintenance

Source: Towards sustainable civil engineering works using precast concrete solutions[5]

Even though an EPD is a powerful tool to increase the environmental quality of building products and buildings, it is not yet mandatory for the producers to have it. However, in several countries, the local and also national authorities are very supportive. For instance in France and Germany, the EPD programme operators are highly supported by the national governments. In Germany, public buildings supported by the governmental funds must be built of products with EPDs. In Switzerland, the similar principle is used in Zurich. The Italian Green Public Procurement asks for minimum environmental requirements to be respected by means of EPDs.

The new Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC may have some positive effect on EPDs processing in larger scale.

3.2.3 Environmental product declarations of precast concrete

Environmental product declarations (EPDs) have been created by industry groups and individual manufacturers in several countries. In this section, we will highlight the scope and results of several of these EPDs.

When performing an LCA, the assessment period is subdivided into life-cycle stages, and those stages are then subdivided again into information modules. The four life-cycles stages are product stage, construction stage, use stage, and end-of-life stage. Information modules A1-A3 comprise the product stage, and are the minimum assessment period required to perform an LCA. An LCA that covers modules A1-A3 is considered a cradle-to-gate assessment.

Information module A1 includes extraction and processing of raw materials, including fuels used in product production and transport within the manufacturing process. All average or specific transportation of raw materials (including recycled materials) from extraction site, manufacturing source or distribution terminal (as appropriate for each material) to manufacturing site (including any recovered materials from source to be recycled in the process), and including empty backhauls and transportation to interim distribution centers or terminals are included in information module A2. Finally, information module A3 includes manufacturing of the product including all energy and materials required and all emissions and wastes produced.

In Annex 1 of EN 16757, several detailed examples of EPDs from distinct countries, for example, North America, Norway and United Kingdom are shown.

In applying EN 15804 to precast concrete, the following specific definitions of the modules as they relate to precast concrete are provided:

UPSTREAM MODULE

A1) Raw Materials. Supply of raw materials, ancillary materials and primary packaging, and the generation of electricity used in the manufacturing carried out at the plant;

CORE MODULE

A2) Transport to the manufacturing plant and internal transport;

A3) Manufacturing of the finished product (Fig. 3-4) which includes the production phases reported below:

- Mix of raw materials in the mixing tower;
- Curing of the concrete in prestressing beds and insertion of steel tendons;
- Cutting and packaging of the product;
- Finishing process (painting of the products);
- Storage;
- Treatment of the wastewater from the mixing tower and other phases of the manufacturing.

Beyond the energy and materials consumption of the different production phases, the treatment of waste generated during manufacturing and the consumption related to company management have been accounted for in the core module.

DOWNSTREAM MODULE

A4) Transport. Delivery of the final product and its primary packaging using an average distance representative of the reference year.

A5) Construction

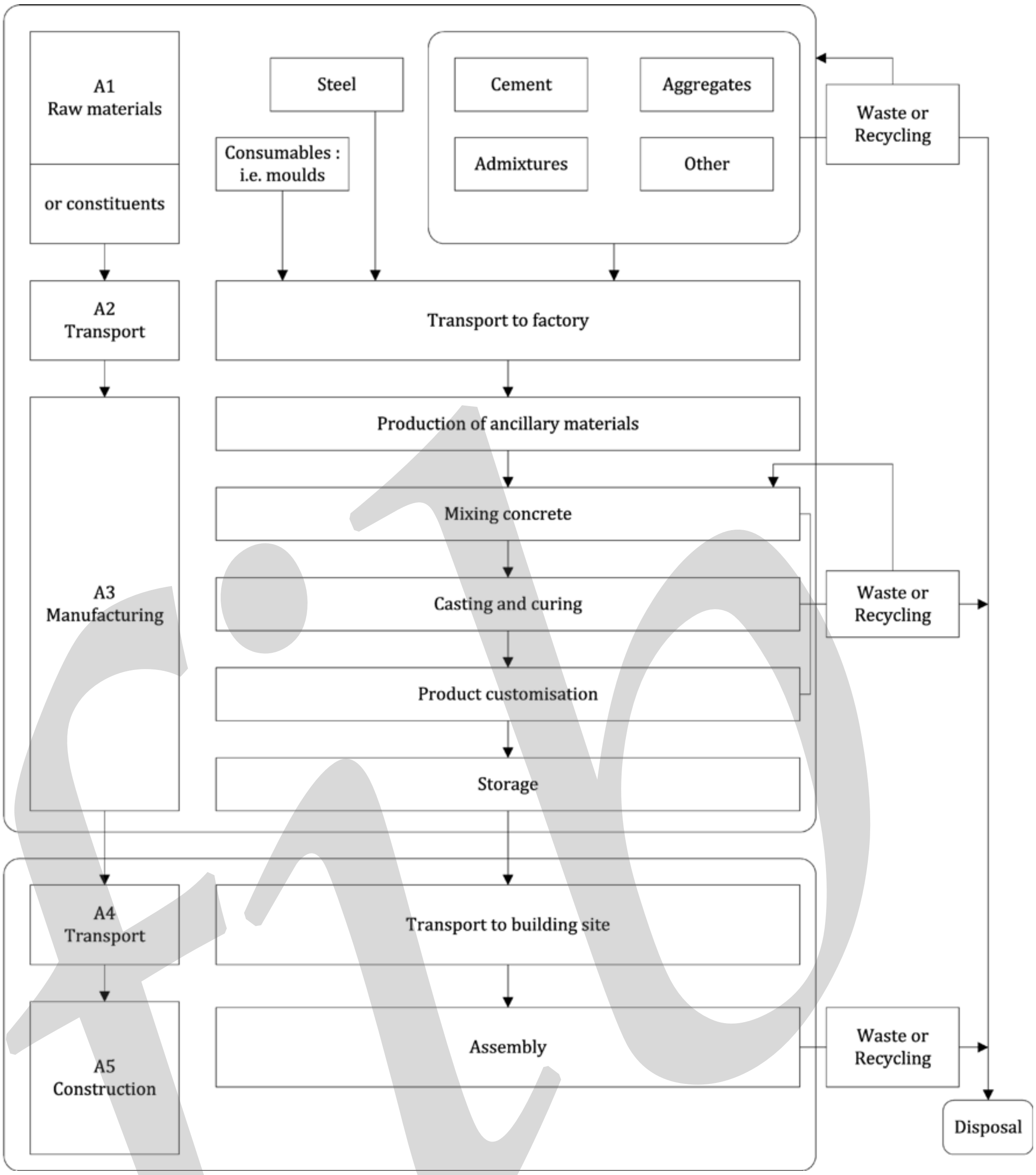


Fig. 3-4 Manufacturing example of precast concrete element.

3.3 *fib* Model Code

3.3.1 *fib* Model Code 2010

The *fib* Model Code 2010 was published in 2013. The characteristics of this code are its performance-based design incorporating probability theory as a design framework, while its performance requirements are based on three categories; safety, serviceability, and sustainability. It is made clear that durability is to be treated within serviceability, suggesting for the first time that durability is only a prerequisite to secure serviceability and should not be treated on the same level as safety or serviceability.

The *fib* Model Code 2010 incorporated sustainability for the first time in the history of design criteria formulation for structures. As for the factors of sustainability, the code structure takes account of environmental and social aspects, but not the economic aspect. The performance requirements concerning sustainability are determined by laws, specific intention of the owner, specifier, and other stakeholders or decision makers.

Environmental performance requirements can include: the pollution of air, water and soil, hazardous substances, ozone depletion, global warming, eutrophication, photochemical smog, land use, waste discharge, and resource consumption, on the basis of impact on human health, social asset, biodiversity, and primary productivity. The environmental performance requirements should be set considering material selection, structural design, construction method, usage, method of maintenance management, demolition, disposal and recycling, consumption of energy and resources, and required limits with regard to pollution of water, soil and air, and pollution by CO_2, noise, vibration, chemical substances, and others.

Social performance requirements are diverse; in this code, landscape is taken as an example, in which the aesthetics of a structure and harmony with its surrounding environment are possible requirements, while appropriate form, various structural elements, color, texture and materials shall be selected to meet such requirements.

Based on these performance requirements, various matters are assumed and examined as to whether the actual performances satisfy the requirements or not. The verification structure for performance requirements and retained performance are identical regardless of whether the problem is mechanical or environmental.

The *fib* Model Code 2010 considers sustainability as one of the performance requirements, but has no comprehensive treatment concerning its three aspects (society, economy and environment). It is undeniable that the most important task in the design of structures is to secure safety, which is one of the key elements of the social aspect in sustainability design. In other words, safety is an element to be considered within the social aspects in sustainability design.

3.3.2 A preliminary proposal for the *fib* Model Code 2020[7]

The following is a proposal made by Prof Sakai for the *fib* Model Code 2020. It will be discussed by the relevant *fib* working group after the publication of this bulletin.

"Sustainability design" in which social aspects, economic aspects, and environmental aspects are appropriately considered, is the most reasonable option. Satisfying the performance requirements for safety and serviceability is a prerequisite for the design of concrete structures. Giving too much consideration to environmental performance without ensuring safety is not an option. It is paramount to achieve the construction of a structure by adding economic and environmental elements to conventional design considerations with a good balance among them.

Sustainability design does not rule out options to increase the safety margin based on comprehensive judgment, even if doing so may reduce environmental performance. There is no absolute solution to the relationship between safety, economics, and environmental performance. A new design framework should be formulated in this context.

The current design procedure comprises verifying whether the designed cross sections and structures meet the performance requirements based on the set performance requirements regarding safety and serviceability. The validity of the design of section capacity and deformation, for instance, is assessed respectively by the following verification equations:

$$\gamma i \cdot S_d \leq R_d$$

where S_d denotes the design section force or design limit value; R_d the design section capacity or design response value; and γ_i the structure factor.

$$\gamma_i \cdot \delta_d \leq \delta_a$$

where δ_d denotes the deformation design response value; δ_a the deformation design limit value; and γ_i the structure factor.

The structure factor, which has traditionally been used in the Standard Specifications for Concrete Structures of the Japan Society of Civil Engineers (JSCE)[8],is generally assumed to be 1.0. Values above 1.0 have scarcely been discussed.

Though durability, resilience, and robustness may in addition be named as matters to be examined, durability is related to safety and serviceability, while resilience and robustness are related to the safety margin and the mechanism of mechanical fracture.

Durability can be dealt with in sub-design to obtain the safety and serviceability necessary for structural members. The above-mentioned structure factor γ_i is introduced in order to consider at the verification stage the uncertainty of design limit and design response values, but the meaning of this factor is in essence unclear. Essentially, all one has to do is to consider all uncertainties during the stage of calculating the design limit values and design response values.

Considerations regarding safety and serviceability for the design of structures seem to have been carried out under certain conditions in a considerably rational manner. The design cross-section force and deformation can usually be obtained by estimating the applied external force, but solutions are only based on assumed actions. Obtained design cross-sectional strength and response values are also nothing more than results obtained on an assumption based on inconsistent materials and dimensions of a cross section. If such applied external force is underestimated, the structure will be destroyed or collapse. Therefore, we have repeatedly taken measures to enhance safety by reviewing the assumed applied external force and details of structural elements every time structures have suffered seismic damage. In the case of the Great East Japan Earthquake, the magnitude was 9.0. Such scale demonstrates that there are limitations in correctly estimating movements of the inner Earth, because to estimate an unlimitedly large external force is not realistic from the standpoints of both financial and environmental burden.

The safety of structures is categorized under the social aspect in sustainability and its margin has been decided based on experience, however, its relation with other sustainability aspects, that is, economy and environment has hardly been considered. Enhancing the safety of structures generally increases cost and environmental impact, unless innovative technologies are developed and introduced. As the owner places most importance on cost, the safety margin tends to be set as small as possible. However, when considering the true efficiency of economy and environment against unpredictable external forces, one begins to see a totally different "landscape" from that of the past.

The sustainability design of structures is systemised to consider in a comprehensive manner: safety and serviceability under the social aspect, cost under the economic aspect, and resources and energy under the environmental aspect. The system must be so developed to allow proper selection of evaluation indices which enable prediction of a good balance between social, economic, and environmental aspects, in order to place the utmost priority on the sustainability of humankind, the region, and the earth.

The construction cost and environmental impact cannot be considered unless decisions are made regarding structural style, construction materials and other details. Therefore, the design procedure begins with rationally setting performance requirements based on various information, assuming necessary mechanical and environmental actions, and selecting structural style, materials, and construction methods.

The procedure of sustainability design is described as follows and presented in Fig. 3-5:

1. Collect and organize basic information for implementing a construction project

   - Social aspect: Safety, serviceability, access, adaptability, health, comfort, loads on the surrounding environment (such as, noise, vibration), maintenance, procurement of materials and services, involvement of stakeholders, job creation, population changes, cultural assets, legal restrictions, and the like.

   - Economic aspect: Costs, property values, direct benefits, indirect economic effects, external costs, and the like.

   - Environmental aspect: Energy and resource consumption (including renewable energy and byproduct utilization), contamination, noise, vibration, water control, waste control, land use, landscape, ecosystem, legal restrictions, and the like.

   - Combined aspects: It is possible to introduce indices to deal with the social, economic, and environmental aspects in combination, for example, increases in energy and resource consumption, and cost per increment in safety, and CO_2 emission per unit concrete strength.

2. Set the loading and environmental action
3. Set the margin, γ_i, to ensure safety and serviceability under the social aspect

   - γ_i is hereafter referred to as "sustainability factor", as this is related to the overall evaluation of sustainability.

   - Durability performance is examined as a prerequisite for safety and serviceability performances.

4. Set the performance requirements concerning economy and environment

   - Economic aspect: Though performance requirements are set based on the standard costs, these should be eventually judged in relation to safety and environmental performance.

   - Environmental aspect: As to environmental performance requirements, reduction targets based on the standard energy and resource consumption and CO_2 emissions are set. However, these should be eventually judged in relation to safety and costs, as well as lifecycle performance. In principle, the same applies to the noise and vibration loads under legal restrictions. As to environmental impacts, not only requirements for load reduction but requirements for environmental enhancement should also be appropriately considered.

- Combined evaluation: Numerical targets of the adopted assessment indices are set.

5. Select the structural style, section size of members, reinforcement arrangement and its materials, concrete mixture proportions, and construction methods based on the performance requirements set in Steps (3) and (4) above.

6. Calculate the section forces, section capacities, and deformations.

7. Verify safety and serviceability.

8. Calculate and verify the economic performance.

   - If the economic performance requirements are satisfied, then proceed to calculation of the environmental performance
   - If the economic performance requirements are not satisfied, then determine if the conditions should be changed.
   - If failure to satisfy the economic performance requirements is accepted, then proceed to calculation of the environmental performance.
   - If the conditions are to be changed, then there are options to go back to Step (5), (4), or (3).

9. Calculate and verify the environmental performance.

   - If the environmental performance requirements are satisfied, then the procedure is complete.
   - If the environmental performance requirements are not satisfied, then determine if the conditions should be changed.
   - If failure to satisfy the environmental performance requirements is accepted, then complete.
   - If the conditions are to be changed, then there are options to go back to Step (5), (4), or (3).

10. Make a comprehensive judgment and, if necessary, repeat the whole procedure from the beginning by changing gi to optimize the design.

11. Report the following data obtained from the above procedure:

   - Sustainability factor
   - Standard costs and final costs (such as, reductions, increases, reasons to allow cost increases)
   - Environmental impact values (such as, energy and resource consumption; reductions in the environmental loads, for example, CO_2 emissions; reasons to allow increases in the environmental loads)

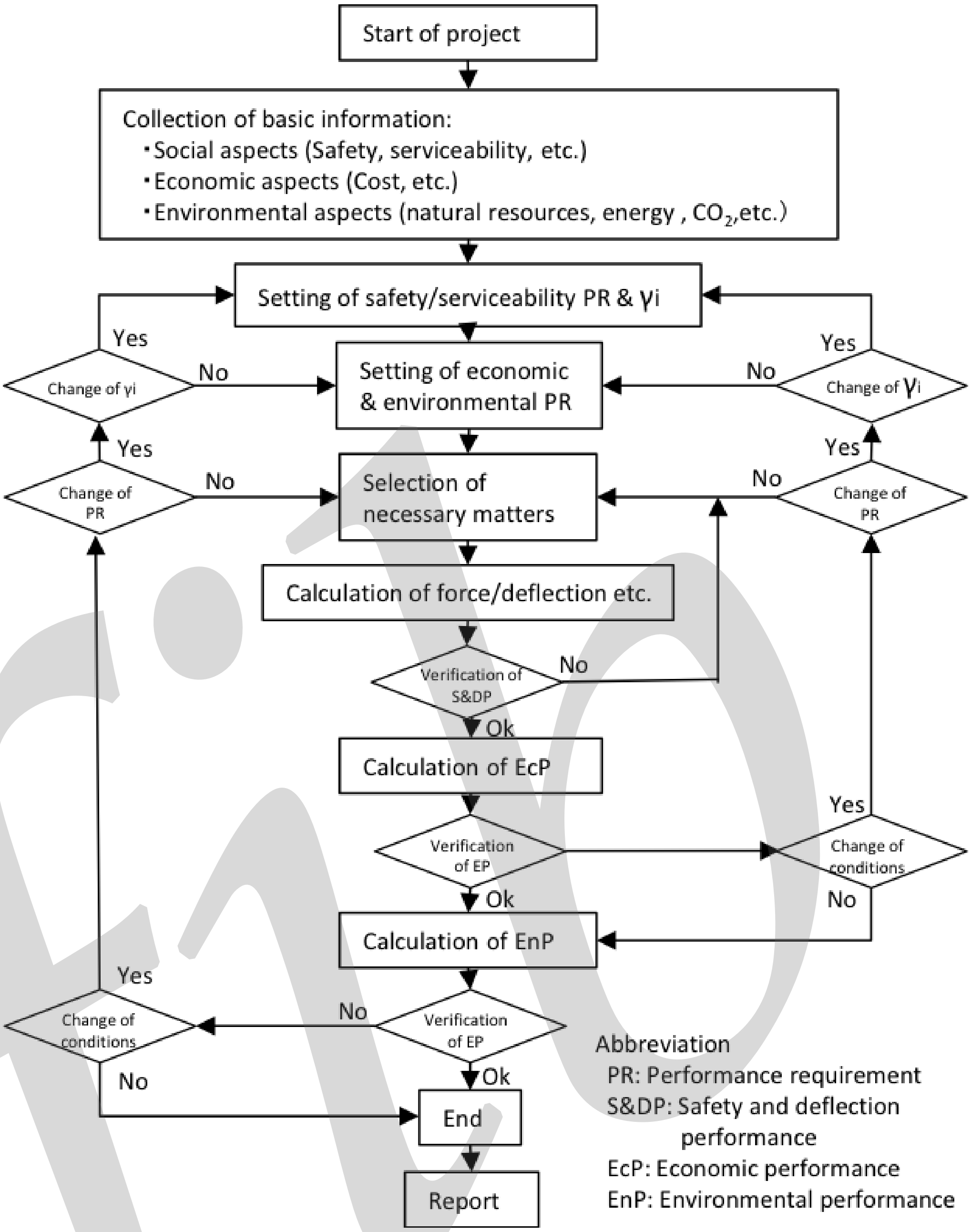


Fig. 3-5 Flowchart of proposed MC sustainability assessment[9]

The framework of sustainability design is comparable to giving consideration to regional and global sustainability from the act of construction. The terms "resilience" and "robustness" which are recently highlighted as notable keywords should be defined in relation to the safety margin and destruction mechanism, and are a major subject for future study.

3.4 U.S. information

There are only few resources that have been developed in the United States as normative codes or standards related to sustainability and that are related to precast concrete structures.

3.4.1 ACI Building Code Requirements for Structural Concrete[10]

Among a large number of documents published by the American Concrete Institute (ACI), the ACI 318 is one of the most important. Under ACI 318-14: Chapter 4, it introduced sustainability for the first time as a structural system requirement in addition to strength, serviceability, and durability, in other words it has approved establishing sustainability as one of the performance requirements. However it sets two preconditions for this: one limits the setting of sustainability for performance requirements to licensed design professionals, and the other prioritises strength, serviceability, and durability requirements over sustainability. While it was not necessary to mention the condition in the latter, it was perhaps included to avoid any misunderstanding.

With respect to the licensed professionals mentioned in the former, it probably envisages those with LEED certification and the like, but there is no specific reference to this. None of the concrete evaluation indices regarding sustainability are stated either. As LEED has wide ranging evaluation indices, they can be applied, however very few concern concrete. It is of great significance that the ACI revised the key criteria for the design of concrete structures, in order to at least consider sustainability, although not detailed, by expanding the conventional design framework. However it also has similar problems with the framework of sustainability as in the *fib* Model Code 2010.

3.4.2 The need for a new design system

In order to appropriately cope with the problems the industry faces, it is necessary to reconstruct the current design concept's basic framework, by recognizing that there is a limit to thinking by extending the "traditional" engineering of the past. The basic philosophy for reconstruction is "what is most important for humankind is to maintain the Earth's environment, which is the basis of human survival, in good condition".

It is of the utmost importance to construct a socioeconomic system that allows sustainable use into the future of the natural capital provided by the earth. In other words, the industry will be required to rethink everything based on the sustainability of humankind and the earth.

The industry must acknowledge that the traditional engineering thinking and systems were accumulated during an era when one did not have to consider issues such as depletion of resources and energy nor global warming, and that these are now about to collapse. What is now essential is to promote the innovation of technology and systems through establishment of a new design system.

Sustainability acts as a comprehensive indicator for assessment and realization of the sustainability of mankind and the earth. It is vital to expressly incorporate this indicator into the design of structures, and its system shall be called "sustainability design".

3.4.3 ASHRAE Standard 189.1

Developed jointly by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), the U.S. Green Building Council (USGBC), and the Illuminating Engineering Society of North America (IES), the first edition of the ANSI/ASHRAE/USGBC/IESNA Standard 189.1 Standard for the Design of High-Performance

Green Buildings Except Low-Rise Residential Buildings was published in 2009[11]. At that time, it was the first U.S. standard written in code-intended language on the topic of green construction. The goal of the committee was to create a standard that could be adopted by state and local jurisdictions to reduce the environmental impact of buildings. Because Standard 189.1 is written in code-intended language, it contains minimum performance requirements to ensure a high-performance green building. ASHRAE 189.1 was updated in 2011, and again in 2014, and the 2014 version of the standard will be explained here.

3.4.3.1 Scope

ASHRAE 189.1 contains requirements in five broad areas: Site Sustainability; Water Use Efficiency; Energy Efficiency; Indoor Environmental Quality (IEQ); and The Building's Impact on the Atmosphere, Materials, and Resources. It also includes a section on Construction and Plans for Operation. Each of these topics is a separate chapter, and each includes the following sections: general, compliance paths, mandatory provisions, prescriptive options, and performance options (Fig. 3-6).

Mandatory provisions in each chapter contain those requirements that must be met on all projects. Each chapter then contains prescriptive and performance options (the two compliance paths), and the project must meet requirements in one or the other of these sections. In general, the prescriptive option allows for simpler showing of compliance, and the performance option is more involved.

Fig. 3-6 ASHRAE 2009 Standard for the design of High-Performance Green Buildings cover

3.4.3.2 The Building's Impact on the Atmosphere, Materials, and Resources

Table 3-4 lists the mandatory provisions related to the section on the building's impact on the atmosphere, materials, and resources.

Table 3-4 Mandatory provisions related to atmosphere, materials, and resources

9.3	Mandatory Provisions	
9.3.1	Construction waste management	
9.3.1.1	Diversion	At least 50% of nonhazardous waste must be recycled or reused, thus diverting it from landfills and incinerators.
9.3.1.2	Total waste	A maximum of 42 yd^3 or 12,000 lb of waste, per 10,000 ft^2 of new floor area, is allowed (35 m^3 or 6'000 kg of waste per 1'000 m^2).
9.3.2	Extracting, harvesting, and/or manufacturing	Extracting, harvesting, or manufacturing of materials, products, or assemblies must conform to the "laws and regulations of the country of origin"[12].
9.3.3	Refrigerants	Heating, ventilating, air conditioning, and refrigerating systems shall not use chlorofluorocarbon (CFC)-based refrigerants.
9.3.4	Storage and collection of recyclables and discarded goods	
9.3.4.1	Recyclables	There must be a dedicated recycling area that accepts metal, glass, corrugate cardboard, plastic, and paper
9.3.4.2	Reusable goods	If the building has residential space, it must have a designated area to store donation items for charitable organizations.
9.3.4.3	Fluorescent and HID lamps and ballasts	There must be a dedicated collection area for fluorescent and HID lamps and ballasts.

3.4.3.3 Prescriptive option

Table 3.5. Prescriptive option related to atmosphere, materials, and resources

9.4	Prescriptive Option	
9.4.1	Reduced impact materials	Materials used in the building must comply with 9.4.1.1, 9.4.1.2, or* 9.4.1.3. Like with many green guidelines, mechanical, plumbing, electrical, and elevator equipment are exempt from these requirements, as are any materials that are not permanently installed. Also, the cost of materials is allowed to be assumed as 45% of total construction cost.
9.4.1.1	Recycled content	Total cost of post-consumer recycled content and one-half pre-consumer recycled content must be 10% of total building-material cost." Constituent materials in concrete…are allowed to be treated as separate components and calculated separately"[13].
9.4.1.2	Regional materials	Based on cost, 15% of materials need to be manufactured, extracted, harvested, or* recovered within 500 mi of the project site. Percentages are allowed if only a portion of a material meets the 500 mi criterion. There is a notable exception to this requirement that is different from many green guidelines. Longer distances are allowed (up to 2'000 mi) when products are shipped by rail or water.
9.4.1.3	Biobased products	"A minimum of 5% of building materials used, based on cost, shall be biobased products"[14].

*Note that this requirement is "or" not "and."

3.4.3.4 Performance option

The performance option for the materials section requires performance of a life-cycle assessment (LCA) conforming to ISO 14044[15]. To meet the conditions of this section, an LCA is conducted on two building alternatives (minimum) that meet the owner's project requirements. Building alternatives must meet all requirements of the authority having jurisdiction, and also meet the requirements of ASHRAE 189.1 sections 6, 7, and 8. Table 10.2.3.2 in ASHRAE 189.1 includes service lives used for modelling[16]. Buildings must be modelled using a full LCA for the full life of the building. Energy consumption during operation does not need to be included as part of the LCA model, but it is allowed to be included as an option.

To meet the performance path, a 5% improvement has to be made in a minimum of two impact categories. Accepted impact categories include: acidification, climate change, ecotoxicity, human health effects, land use (habitat alteration), ozone layer depletion, resource use, and smog.

Another requirement of the performance path is to conduct the LCA with minimum steps listed in section 9.5.1.2, Procedure. The three mandatory steps include:

1. Perform an LCI
2. Prepare a report (according to ISO 14044 requirements for third-party reporting) that compares the alternatives "using a published third-party impact indicator method that includes, at a minimum, the impact categories listed in section 9.5.1.1"[17].
3. Have the LCA report reviewed by an external expert.

Once completed, the project team must submit the LCA report and proof of third-party critical review to the authority having jurisdiction.

3.4.4 International Green Construction Code

Development of the International Green Construction Code (IgCC) began in 2009 led by the International Code Council (ICC) and with the following co-sponsors: USGBC; IES; ASHRAE; ASTM International; and the American Institute of Architects (AIA). According to the IgCC, it is "a model code that provides minimum requirements to safeguard the environment, public health, safety and general welfare through the establishment of requirements that are intended to reduce the negative impacts and increase the positive impacts of the built environment on the natural environment and building occupants".

Because the IgCC is one of the ICC's I-codes, it was developed through the same process (two sets of public hearings) and it has similar attributes to other codes. The initial IgCC was released in 2012[18],and the second edition was released in 2015. The 2015 edition of the IgCC will be discussed here.

3.4.4.1 Scope

Chapters 1 and 2 address administration and definitions, and all text is written in code-mandatory language. Remaining chapters focus on topics such as:

- Jurisdictional requirements and life cycle assessment
- Site development and land use

- Material resource conservation and efficiency
- Energy conservation, efficiency and CO_2 emission reduction
- Water resource conservation, quality and efficiency
- Indoor environmental quality and comfort
- Commissioning, operation and maintenance

The prescriptive requirements are related to Material Resource, Conservation and Efficiency, and contained in Chapter 5 of the IgCC. If the project team choses to perform an LCA according to Chapter 3 (Section 303) of the IgCC, however, it does not have to comply with Section 505 of the IgCC. Chapter 5 and Section 303 of the IgCC will be explained in more detail in the following sections.

3.4.4.2 Whole Building Life Cycle Assessment

Section 303 of the IgCC lists the requirements for performing a whole building LCA according to the IgCC. If a whole building LCA is performed, "compliance with Section 505 shall not be required"[19]. The performance option for the materials section requires performance of a life-cycle assessment (LCA) conforming to ISO 14044[20]. To meet the conditions of this section, an LCA is conducted on two building alternatives (minimum) that have the same reference design. Building alternatives must meet all minimum energy requirements of the IgCC, and also meet the structural requirements of the International Building Code. The default reference service life used for modeling is contained in ASTM E2921-13 and is set at 75 years[21]. Buildings must be modelled using a full LCA for the full life of the building.

To meet the requirements of this section, a 20% improvement has to be made in the global warming potential and a minimum of two of the following impact measures: acidification potential, eutrophication potential, ozone depletion potential, smog potential, and primary energy use.

Other requirements are to conduct the LCA including:

- Operational energy use, and optionally including building process loads,
- Maintenance and replacement schedules for components, and
- The complete building envelope, structural elements, and interior walls, floors, and ceilings, including interior and exterior finishes.

The assessment for both buildings must be conducted with the same LCA tool, and that tool must be approved by the code official.

3.4.4.3 IgCC Chapter 5

Table 3-6 Material Resource Conservation and Efficiency

502	Construction Material Management	
502.1.1	Storage and handling of materials	Materials must be handled and stored according to manufacturer's instructions.
502.1.2	Construction phase moisture control	Materials subject to moisture damage must be protected during construction.
503	Construction Waste Management	
503.1	Construction Waste Management Plan	At least 50% of nonhazardous waste must be diverted from disposal.
504	Waste Management and Recycling	
504.1	Recycling areas for waste generated post certificate of occupancy	Must provide areas for the collection of recyclables.
504.2	Storage of lamps, batteries and electronics	Must provide areas for the collection of lamps, batteries, electronics, and other special-disposal items.
505	Material Selection	
505.1	Material selection and properties	Building materials must comply with 505.2 or 505.3
505.2	Material selection	55% or more of total building materials must be used materials and components; recycled content building materials; recyclable building materials and building components; bio-based materials; or indigenous materials.
505.3	Multi-attribute material declaration and certification	55% or more of total building materials must have a Type III environmental product declaration or be verified to a multi-attribute standard.
506	Lamps	
506.1	Low mercury lamps	Mercury content must comply with 506.2 or 506.3
506.2	Straight fluorescent lamps	Mercury content must be less than 5 mg
506.3	Compact fluorescent lamps	Mercury content must be less than 5 mg and lamps must be listed and labeled according to UL 1993
507	Building Envelope Moisture Control	
507.1	Moisture control prevention measures	Inspect moisture preventative measures for foundation sub-soil drainage systems, waterproofing, and damp-proofing; under-slab water vapour protection; flashings; exterior wall coverings; and roof coverings, drainage, and flashings.

To supplement information in ASHRAE Standard 189.1 and the IgCC, ASTM published a standard practice in late 2013 on Minimum Criteria for Comparting Whole Building Life Cycle Assessments for Use with Building Codes and Rating Systems (ASTM E2921-13). The purpose of ASTM E2921-13 is "to support the use of whole building life cycle assessment (LCA) in building codes and building rating systems by ensuring that comparative assessments of final whole building designs relative to reference building designs take account of the relevant building features, life cycle stages, and related activities in similar fashion for both the reference and final building designs of the same building".

3.5 Brazil

Modular Life Cycle Evaluation

The CBCS's (Brazilian Council of Sustainability Construction), proposes the Modular Life Cycle Evaluation (ACV-m). It is an initiative to create an information platform with materials, products, and components sustainability indicators to help professionals and consumers alike in their decision making process.

The materials, products, and components selection—supported by environmental, social, and economic criteria – is of fundamental importance for the sustainability management in the construction industry.

The ACV-m project involves the manufacturers' production data collection and their consolidation in a consultation platform, to allow the easy and proper comparison among products and suppliers. To this end, CBCS's goal is to involve the construction industry to survey the main products, based on a common methodology, with manuals and guidelines to be applied by the participating companies and areas, for compatible data measurement and standardization.

The idea is to have a modular, realistic, and effective system to measure the data that is collected during the development of the construction process. The system will allow greater control at the job sites or in the plants, and will allow for the effective collection of continuously measured and monitored data.

What is measured in the ACV-m? The initiative proposes the identification of five minimum aspects that are identifiable in any process:

- Energy consumption,
- Water consumption,
- Raw-materials consumption,
- Waste generation,
- CO_2 emission.

Properties information can also be included, such as durability, resistance, reflectance, among others, as well as data of social character of formality, legality, socio-environmental initiatives, among other parameters.

The system will allow for the evaluation of sustainability at the product level, as well as at the project and business level. The current market is already demanding this type of information; industries that can offer their data transparently meet these customer requests while giving their products a competitive advantage. CBCS wants to involve the whole construction industry chain in this initiative.

The CBCS proposal, which is essentially to make the process more effective, meets the boundaries established by the "Selo de Excelência" ABCIC (Brazilian Association of Industrialized Concrete), which represents the precast concrete industry in Brazil. The programme was called "Excellence Seal" because not only a quality programme, but also integrates quality, safety (personal insurance), and environmental aspects. This programme is based on PCI Plant Certification (Precast Concrete Institute USA), where the plant and job site are assessed. The Brazilian Programme has three levels and the requirements references are: ISO 9001, ISO 14001, and also the Brazilian Standards on Precast Concrete ABNT NBR 9062 – *Design and Production of Precast Concrete*. The plants are submitted for a third party accredited organization, every six months. Related to the environmental requirements are defined in level III and listed below:

1. Environmental impacts diagnosis

A production plant should identify in its internal activities or production areas, the environmental impact referring to the following aspects:

- Water and energy consumption in precast elements production
- Generation and destination of liquid wastes that are produced in the production plant
- Production plant generated noises
- CO_2 emissions
- Circulation in the transportation of elements from the plant to the jobsite

The impacts should be established in an internal or external document which also identifies the areas and/or activities where they will be critical.

2. Impacts control

The production plant should determine systematic policies to control the impacts that are mentioned in 1, for the activities and/or areas that are considered as critical ones. The control systematics should avoid or minimize the impacts that are relative to the following aspects:

3. Environmental legislation analysis

The production plant should make an assessment about the applicable legislation to the environmental aspects, as described in 1 and 2, identifying possible items that perhaps are not met by the production plant. If any item is so identified, the plant should submit a plan for its remediation.

4. Environmental management training

The company should provide a specific training programme for those employees who are accountable to carry out the environmental plans or programmes in the company.

Record should be made about the training in environmental plans or programmes established by the company and accomplished in the production plant.

4. Life Cycle of Precast Structures

4.1 General Aspects of LCA

4.1.1 Introduction. Service Life

In the First International Conference on Sustainable Construction in 1994, sustainable construction was defined as the creation and the responsible maintenance of a healthy constructed environment, based on ecological principles and with an efficient use of resources[1].

This definition resumes most of the essential functional characteristics, as the use of energy, internal ambient conditions, and flexibility. A very important aspect for sustainability, and for the LCA for the construction of a building or a structure, consists of taking into account a design life for different structures and systems that are in the building following the principles life cycle analysis, and this means as follows:

Primary System = External façades and structural design > 80 years[2]

Secondary System = main interior load bearing partitions > 30 years

Tertiary System = interior non load bearing partitions > 10 years

Therefore, both durability and recycling possibilities are both relevant aspects of life cycle design, as can be observed in Figure 4-1.

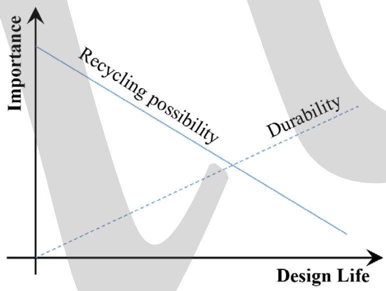


Fig. 4-1 Principles for optimization in service life[3]

In a recent *fib* Bulletin on Integrated life-cycle assessment of concrete structures, Bull 71[4], the methodology of Integrated LCA (ILCA) has been developed.

The methodology for an ILCA represents a multi-parametric assessment of the structure within the whole life cycle. The integrated assessment covers all essential aspects of sustainability (environmental, economic, and social).

Complex integrated approach is based on simultaneous and interactive consideration of different aspects:

- sustainability requirements (environmental criteria, economic criteria, and social criteria)
- technical and functional requirements (technical performance, functional performance, durability)

- life cycle phases throughout the entire life of the structure
- various functional units (material, component, entire structure – building, bridge, road)

It is necessary to identify essential issues relevant and significant to particular life cycle phases, also called environmental hot spots, with respect to specifics in operation and maintenance, and corresponding behavior of the concrete structure in different life cycle phases (Fig. 4-2).

Due to the different types of concrete structures (such as, building structures, bridges, roads), it is also important to determine specific information to be gathered in assessment tools for evaluation of corresponding types of structures.

Finally, regional conditions due to different material basis, different energy supply (energy mix), various climatic conditions, and distinct technology and cultural traditions, must also be evaluated.

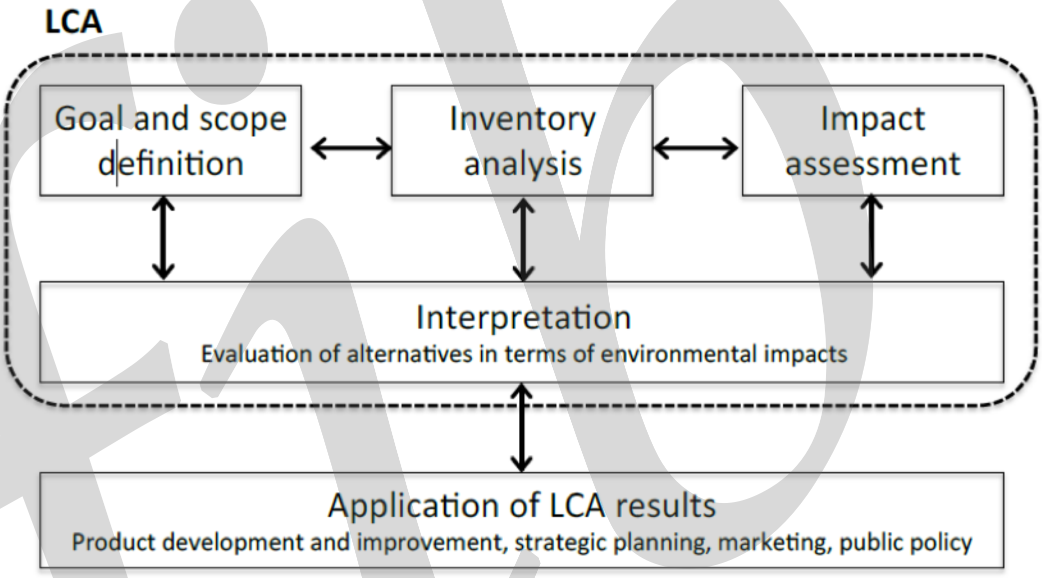


Fig. 4-2 Relationships and interactions of the steps in a LCA[4]

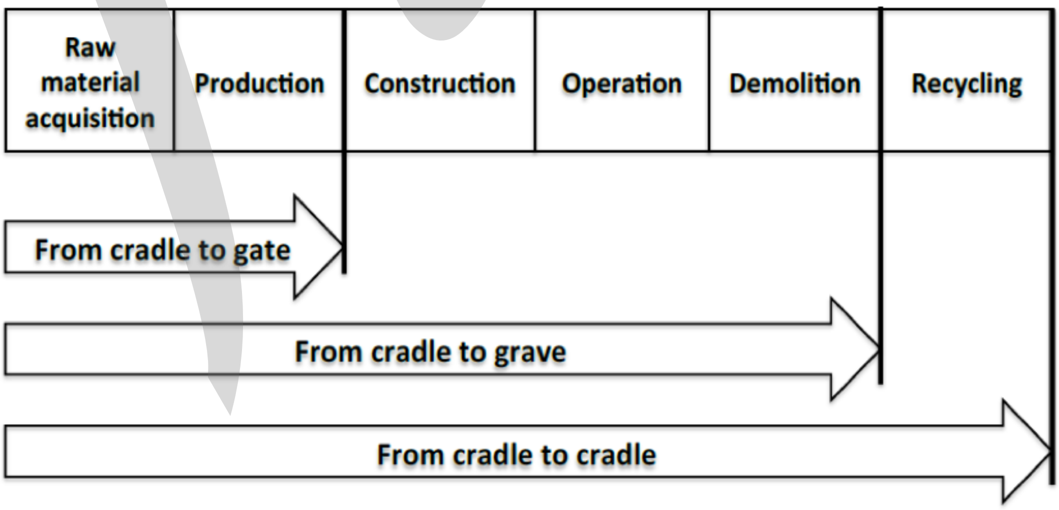


Fig. 4-3 Different LCA concepts[4]

The goal and scope of an LCA study must be clearly defined and consistent with its intended application. The scope must consider all relevant aspects and criteria and should be sufficiently well defined to ensure that the definition of the evaluation model and specification of the assessment data sets are compatible and sufficient to address the stated goal (Fig. 4-3).

The inventory analysis (LCI or life cycle inventory analysis) involves data collection and calculation procedures to quantify relevant material and energy inputs and outputs of a product system – for example, a concrete element, concrete structure, whole building or other civil engineering works – through the whole life cycle.

The target of the impact assessment phase (LCIA or life cycle impact assessment) is to examine the product system from an environmental point of view using impact categories and category indicators connected with the inventory analysis results.

The final phase of LCA is interpretation in which the findings of either the inventory analysis or the impact assessment, or both, are combined (consistent with the defined goal and scope) in order to reach conclusions and recommendations (Fig. 4-4).

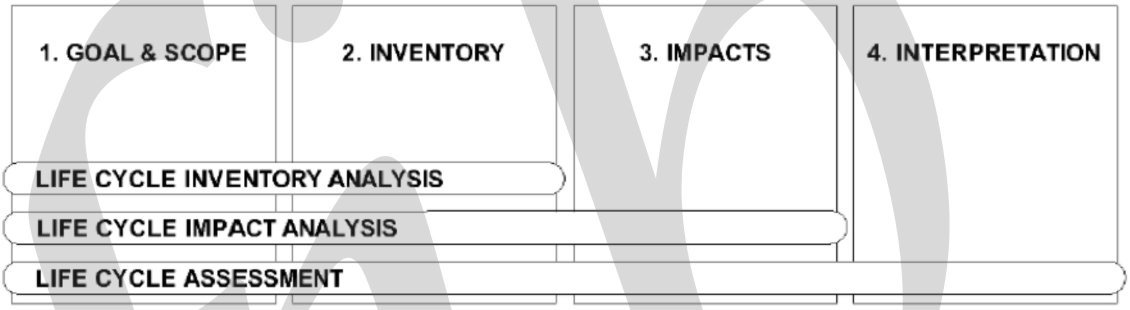


Fig. 4-4 The LCA process flow and inherent subprocesses[4]

4.2 Buildings

The design of a building must address a number of aspects. These are implicitly included in the scope of the ILCA. The aspects should also be stated more or less explicitly in the goal of the ILCA. One way of thinking of these aspects has been suggested by Sarja[5], who classified the requirements on buildings in four groups. In this expression, human and cultural requirements are included in the social pillar of sustainability.

Important positive sustainability aspects of the use of concrete in building structures and in particular in precast concrete buildings are:

1 Human requirements	2 Economic requirements
• functionality in use • safety • health • comfort	• investment economy • construction economy • lifetime economy including operation and end of lifecycle
3 Cultural requirements	**4 Ecological requirements**
• building traditions • life style • business culture • aesthetics • architectural styles and trends • image	• raw material economy • energy economy • environmental burdens economy • waste economy • biodiversity and geodiversity

Fig. 4-5 Generic requirements on buildings according to Sarja[5]

To optimize components and systems with regard to durability over the total life cycle of the structure, and to facilitate changes, a modular design approach is envisioned.

Sarja[5] discusses the classification of building modules into target life classes so that the components and systems can be optimized with regard to life cycle costs and environmental impact.

Important positive sustainability aspects of the use of concrete in building structures and in particular in precast concrete buildings are:

- High thermal mass of concrete – Concrete elements can serve, due to their density, as thermal energy storage. It means that they are able to absorb and release heat or cold at a rate that roughly corresponds to a building's daily heating and cooling cycle. This can result in savings in energy use for heating and cooling. Precast concrete elements can use thermal mass to drastically reduce the use of energy in heating and cooling of buildings. Also precast concrete sandwich panels can have all necessary insulation incorporated in the construction of the element.

- Acoustic parameters (airborne sound insulation properties) of concrete plane elements – Concrete walls and floors – provide the mass that is required for effective reduction of sound transmission, particularly low frequency sounds.

- High resistance of concrete structures against climatic effects (in environmental exposition) – High mechanical resistance of concrete structures; high durability of concrete surface (advantage for bridges, roads and other civil structures); resistance against floods, winds, frost, sun radiation, abrasion. Durability and water tightness of HPC and UHPC. Normally in precast concrete structures and panels HPC and SCC is used and therefore good properties of these concretes are incorporated in precast buildings.

- High fire resistance of concrete structures – In comparison to most steel or timber structures, concrete structures provide significantly greater fire resistance.

- High durability, low maintenance requirements – especially in an inside building environment, where concrete is protected against direct climatic impacts.

- Demountability and Reuse of materials – Precast concrete structures can be designed to be easily demountable and the possibility to recycle precast concrete is high compared to other materials.
- Industrialization – Lean construction: nearly no waste. Dry construction: precast concrete arrives on site ready for installation.
- Resource efficiency – Reduction of the consumption of natural resources by using waste materials in products (ex. recycled aggregates from concrete wastes).

4.3 Infrastructure

The designs of civil structures made of concrete are carried out according to local or regional codes and standards. Codes and standards are intended to serve all normal types of construction, thus representing the societal demands for quality.

Therefore these documents represent the minimum quality acceptable for such structures. For most national or regional codes and standards a service life of about 50 years is assumed to be achievable by following the codes although no factual or quantifiable requirements in means of determining the service life are generally presented in these documents.

General principles and framework of service life planning are defined in ISO 15686-1:2011 (32) and in the corresponding set of ISO 15686 standards (focused to service life prediction procedure, performance audits and life cycle costing).

From experience, the structures built according to these standards have shown to have a service life of 50 to 70 years before repairs are to be conducted. Service life, however, must be defined both in length (years) and limit state (depassivation of reinforcement, spalling, safely limit state…). More information could be found in Guidelines for green concrete structures[6].

This process should lead to selection of two or three alternative durability strategies where the construction costs and the operation and maintenance costs over the anticipated service life can be looked at.

All these costs for the different strategies are then compared based on net present values. The net present value is based on the selected interest rate.

In infrastructure, it is especially important to consider resilience. Resilience, defined as the capability of the structure to resist future extraordinary events, is becoming a very important aspect to be considered in any evaluation of sustainability. Resilience will have an impact on the economic part of the evaluation and on the social part of the evaluation. To evaluate resilience, the risks are associated with the event and with the structure. These have to be taken into account. This risks will bring economic costs and also social impacts that have to be adequately considered in the evaluation.

5. Sustainability Aspects of Precast Structures

5.1 Introduction

5.1.1 What is a SWOT Analysis?

A SWOT analysis is a structured strategic planning method used to evaluate the Strengths, Weaknesses, Opportunities, and Threats involved in a proposed project or objective. The analysis may be carried out for a product, place, industry or person and involves identifying the internal and external factors that are favorable and unfavorable to achieving that objective. In this case, it is being performed for the precast concrete industry. The resulting analysis may reveal positive forces that work together and potential problems that need to be addressed or recognised, at a minimum, in the planning process.

5.1.2 Strengths (Internal)

The following are strengths of the precast industry with regard to sustainability:

- The precast concrete products, as a result of an industrial process, have a high degree of inherent quality, which reduces defects (waste) and increases durability and service life.
- The precast concrete industry is highly adaptable and capable of adopting new technologies (such as supplementary cementitious materials) quickly. This was clearly demonstrated with the quick adoption of self-compacting concrete by the precast concrete industry.
- Precast-prestressed structures provide long spans for initial design flexibility and later reuse.
- The precast concrete industry uses local skilled labour, under much more safe and healthy working conditions, increasing manufacturing efficiency, as opposed to jobsite labour that is often transient.
- There is substantial potential for the precast concrete industry to continue improving their operations and decrease the environmental impact of its products. Whereas, other competing industries may not have the same potential for improvement.
- By completing a life cycle assessment project, PCI and other related organizations have identified several aspects of the manufacturing operations that can be modified to improve the environmental impact of precast concrete components.
- Precast concrete plants provide permanent employment to the local community, which contributes to better quality of life, wealth and progress to those employees and the community as a whole.

5.1.3 Weaknesses (Internal)

The following are weaknesses of the precast industry with regard to sustainability:

- In order to increase plant efficiency, heat curing is often required, which increases energy demand and associated emissions; however, heat curing also shortens the delivery cycle, increases the plant's capacity and improves the end product's quality.
- Although fly ash is often pointed to as a partial solution to decreasing the carbon footprint of concrete products, it extends the required curing time, which reduces plant production efficiency. Fly ash also affects the aesthetics of the concrete, which reduces its effectiveness for architectural uses.
- Precast concrete components are heavy and must be shipped to the jobsite, often one or two pieces at a time.
- Shipping of large precast concrete components often requires careful coordination with local authorities and route-planning to ensure that bridges along the route are not over-loaded. Precast loads can use permits to ship heavier loads.
- Some designers may mistakenly view precast concrete as a rigid system that is not customizable.
- Some designers may not be comfortable designing with modular designs. Modular designs when used, greatly increase manufacturing efficiency and reduces the carbon footprint from formwork.
- Initial investment and infrastructure required to build a plant must be recovered over the life of the plant.
- Concrete manufacturers cannot change the input values for environmental impacts for upstream materials.

5.1.4 Opportunities (External)

The following are opportunities for the precast industry driven by the marketplace:

- PCI's recent Life Cycle Assessment project confirms that precast concrete products contribute the same amount of environmental impacts as other structural materials (particularly steel), which contradicts the common misconception that all concrete products are bad because of their reliance on Portland cement.
- Concrete's thermal mass can save energy, reducing related emissions and increase occupant comfort.
- Concrete is fire and disaster resistant.
- Prefabrication reduces jobsite waste and speeds construction, reducing jobsite impacts.
- Most precast concrete plants are within 200 miles (300 km) of a building site. Using local materials reduces the transportation required to ship heavy building materials, and the associated energy and emissions.
- Indoor environmental quality is not affected because concrete contains low to negligible volatile organic compounds. Exposed concrete walls do not require finishing materials, eliminating particulates from sanding drywall taping seams.

- Concrete provides reflective surfaces that minimize the urban heat-island effect.
- Concrete walls provide a buffer between outdoor noise and the indoor environment, improving indoor environmental quality.
- Precast-prestressed parking structures preserves land for other uses.
- Precast concrete manufacturing operations generate a low amount of waste with negligible toxicity, with much of it capable of being recycled.
- Safety can be improved compared to on-site construction activities due to the fact that most of the labour tasks are carried out in factories.
- Prefabricated construction allows for deconstruction and reuse of the elements in another structure at some time in the future.
- Concrete is a highly durable and resilient material.
- Precast concrete wall panels can be manufactured with integrated insulation, improving the energy performance and speeding up the construction work at site.

5.1.5 Threats (External)

The following are threats to the precast industry driven by the marketplace or competing industries:

- Concrete's reliance on Portland cement as a binder negatively affects the industry's image and directly influences the environmental impact of concrete products.
- The concrete industry is very fragmented, especially when compared to other structural materials, making coordinated efforts to address sustainability more difficult.
- Attempts to regulate fly ash as a hazardous material (in the U.S.) threatens the increased utilization of fly ash as a supplemental cementitious material.
- As energy sources slowly move away from coal-fired plants, fly ash may become more difficult to obtain.
- Environmental groups have specifically targeted industries that rely on mining in order to increase regulation and generally make doing business more difficult as a means of reducing the amount of mining.
- Concrete construction is often mistakenly perceived as old technology, incapable of adopting new technology and meeting the changing needs of the building design professionals, owners and the general public.

5.2 Environmental Aspects

5.2.1 Production of Precast elements. Raw materials

The types and amounts of raw materials used do not differ between cast-in-place concrete or precast concrete elements. However, the losses of raw materials in the production of prefabricated elements are much less in comparison with the cast-in-situ structures.

5.2.2 Formwork and demoulding agents

Typically, forms are made of steel or plywood. With steel forms, usually a large number of production cycles of the formwork are possible for the production of precast concrete elements in fixed installations. This number is significantly higher than the ones used on site, and therefore there are savings in raw materials of manufacture of the forms. Steel forms are common in prefabrication allowing for manufacturing of practically unlimited number of elements, whereas with plywood formwork life cycle is limited to 20 to 50 uses or concrete cycles depending on the complexity of the form.

Furthermore, with all industrialization to standardise their products, the precaster makes an attempt to save costs. The costs are bound to get the maximum number of elements made from each mould.

Nowadays in the Nordic countries steel formwork represent about 65% of the forms used in the production of facade panels, and 70% in the production of units of structures (beams and columns). The average consumption of plywood in these items is 5 kg/m^3 (8 lb/yd^3), and 12 kg/m^3 (20 lb/yd^3), in wooden forms. Wooden materials are reused in other formwork when they have completed their life as material form.

5.2.3 Fresh concrete

Most of the excess concrete is coming from fresh concrete of washing equipment, saws, prestressing steel from the end of prestressing steel cut-offs, among others, and contains a lot of water. Sand and gravel are removed from the fresh concrete and reused in the production immediately.

The remaining cement slurry after removal of the sand and gravel is normally left in the containers for evaporation and reuse of water, and the residue is re-used in the mixture as fine or sent to deposits. The remains of concrete production are also often left to harden, and then go through the recycling process for hardened concrete.

The remaining sludge is the product obtained of the separation of the sand and gravel from fresh concrete, but also sludge generated with water used for cooling when hardened concrete is cut.

Fines in the slurry have a high specific surface area and as such are not usually used in the production of new concrete since it can influence the quality of concrete. The use of the residue from the production of concrete may result in higher consumption of cement, and as such is not a good solution to the environment, both from economic and technical point of view. The residue may also be contaminated by oil release agent.

5.2.4 Hardened Concrete

The crushed waste concrete is made into fragments to be used as aggregates in concrete again, or to be used as recycled material in the surface layers. The precasters have the advantage that they know well the quality of material to be crushed, and therefore hardened concrete can be used with confidence as an aggregate in the production of recycled concrete with fairly equal costs to that using new natural or crushed aggregates.

Recycled aggregates can be used in reinforced and prestressed concrete in many countries. In Spain, the use is only allowed in reinforced concrete (up to 20%, $f_{ck} \leq 40$ N/mm^2 [5'800 psi]) and with quality equal to or less than the original concrete.

Many codes accept that up to 20% of the aggregate can be replaced with recycled concrete aggregates with no loss of performance in concrete. In fact, in certain areas in the Netherlands at least 20% of the total aggregates for concrete production must be recycled. Tests have been performed with 100% recycled crushed concrete aggregates in the production of hollow-core slabs, with no detrimental effect on the new hollow core. However there remain some rather restrictive regulations when it comes to the use of crushed concrete aggregate in new concrete.

Removal of the steel is easily performed during the crushing operation. Crushing machinery generally is mobile and transported to the prefabrication plant. The disadvantage is that to justify the expense of bringing mobile crushing equipment, concrete waste must be stored for fairly long periods, and thus become small mountains of debris.

5.2.5 Activities in the plant

Among the activities regarding sustainability in the plant (made in closed factories), are labour, energy efficiency, water use and internal transport.

There are several options for efficient production; one is the repetitive use of formwork and the ability to standardise as many components as possible. Therefore, the use of labour hours per m^3 of concrete in a precast plant is dramatically lower than on site. This is added to the fact that concrete for precast solutions usually requires less volume than that of onsite solutions, and therefore there are substantial savings

Energy efficiency of the manufacturing is improved, for example, by utilizing the heat used to accelerate the development of strength of concrete for heating the building. In the mass production of items exothermic reactions (hydration) of the cement may contribute to the heating of plants.

In a precast plant, energy is a necessary element for machinery, for accelerating the development of strength of products and for heating of buildings. These aspects play an important role in the colder climates, such as in the Nordic countries where energy consumption in precast plants during winter is about 40% higher than the annual average. Energy consumption in the production process depends on the type of production.

5.2.6 Recycling

The excess material generated during the production of prefabricated elements mainly consists of:

- Hardened concrete with or without steel reinforcement
- Reinforced or prestressed steel and structural steel parts
- Plywood and other wood materials (if used)
- Fresh concrete (in production and washing equipment)
- Waste water and sludge from concrete cutting saws
- Insulating materials (mineral wool and polystyrene)
- Oil, from machines, lubricants.
- Paper and other packing materials.

The volume of surplus material varies among distinct plants and also between different types of production. Several studies in the Nordic countries have shown that the order of magnitude is about 100 kg of excess concrete material developed per cubic metre. About 40% of excess material is fresh and hardened concrete and 45% of waste is related to washing equipment and saws, which are residues from the cutting saws for slabs during the production of hollow-core slabs.

In prefabrication plants, it is easy to collect and classify different types of residual material. In most places, there are laws that require excess materials to be returned to producers for the following materials:

- Steel
- Insulation Materials
- Oil
- Paper and other packing materials
- Wood materials are sorted, cut and used as firewood industry, or alternately given to private builders for construction purposes.

5.2.7 Waste

There is little waste to be disposed at the site when the structure is prefabricated. In a study carried out in Sweden, the construction of 400 apartments in 10 separate buildings was reviewed. Of these, five buildings were prefabricated and five were built in situ. An independent project maintained accurate energy consumption, time consumption, material consumption, productivity, construction time, the workplace, sickness, accidents, quality, quality control, facilities, generating waste and of course cost.

The unique aspect of this research referred to here is the generation of waste at the site. The end result was that the amount of waste in the prefabricated solution was 35% less than the in situ solution as seen in Figure 5-1.

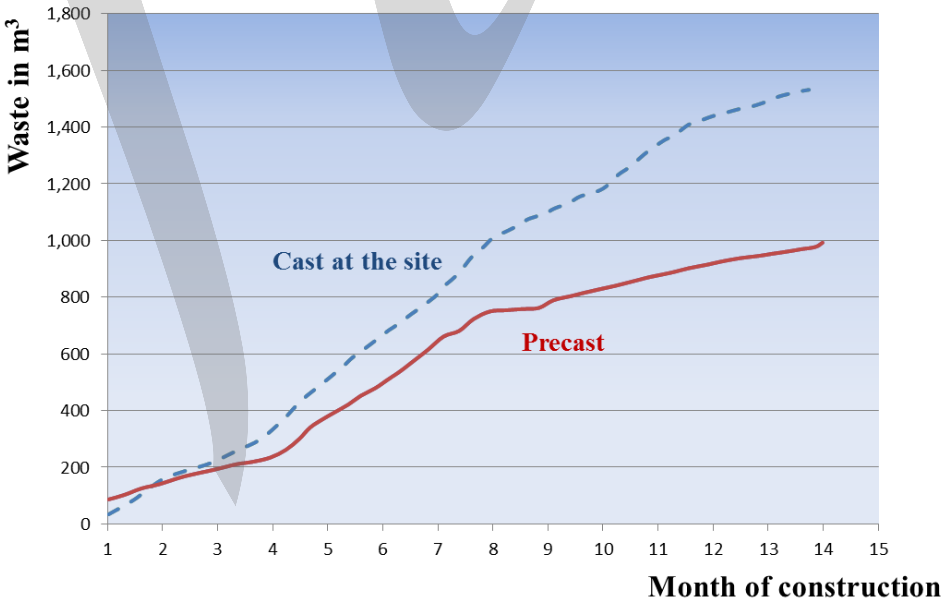


Fig. 5-1 Generation of waste on site and precast plant[1] Note: 1 m^3 = 1.3 yd^3.

Recently a comprehensive analysis paid attention to the generation of waste in a large project in Oslo, Norway. The buildings are all around 150,000 m^2 (1.6 million ft^2). The basic structure is steel columns and beams with precast hollow-core floor slabs. The manufacture and installation of the auxiliary steel structure and assembly of the slabs were in the precast producer's contract. Excess material generated on site by the construction of these components was about only 1 kg per m^2 (0.2 lb/ft^2) of hollow-core. Excess material consisted mainly of wood, concrete and steel reinforcement, and the remains of grout joints on site.

5.2.8 Carbonation

The major part of the CO_2 emission from the production of concrete is related to the production of the cement and such aspect is considered as the main weakness of any concrete element analyzed from a sustainable point of view. Nevertheless concrete has an inherent chemical capacity to reabsorb or uptake CO_2 from the atmosphere, a phenomena known as carbonation.

Carbonation of concrete is a natural process by which CO_2 in the ambient air penetrates the concrete and reacts with $Ca(OH)_2$ to form $CaCO_3$. This means that concrete during its service life and, more important, after demolition is able to absorb up to 50% of the CO_2 emissions from cement in the concrete. Other studies show that sequestration of CO_2 by concrete surfaces through carbonation can continue for hundreds of years, even reaching up to 86% of absorption of the CO_2 released during the cement manufacturing.

Because the CO_2 from the atmosphere diffuses into the concrete via the surface, most of the carbonation will occur after demolition and crushing of the concrete as these processes drastically increase the surface area.

During the use or operation stage, the degree of carbonation depends on the strength of the concrete and the exposure condition. An indoor concrete with low strength will absorb more CO_2 during use stage than a high-strength concrete exposed to an outdoor climate. Surface treatments will most likely limit the carbonation. In the end-of-life stage the carbonation will depend on the actions taken. Most effective is a crushing of the concrete and here the particle size is important, the smaller the better. The time exposed to atmospheric air is important as well, and positive results have been seen with periodically "stirring" of the pile of crushed concrete.

There are several methodologies to estimate the carbonation rate during the service stage depending many factors as we described before, besides others such as compactness of the precast concrete product and its geometry and surface area, exposure conditions to carbon dioxide (for example, exposed to open air, outdoors/ indoors, submerged in water, buried, humidity, and the like), the quantity and nature of cement used in the product, nature of additions and clinker content, surface treatment (for example, paint and plaster coating) or the amount of CaO within the product available for reaction with carbon dioxide. It is estimated that the use stage will result in 15 % carbonation.

During the end-of-life period the carbonation capacity of concrete is much greater and depends on parameters such as the change in the surface area exposed due to crushing (particle size) and the later use (sent to landfill, used as recycled concrete aggregate). The carbonation has at this time reached up to 75 %.

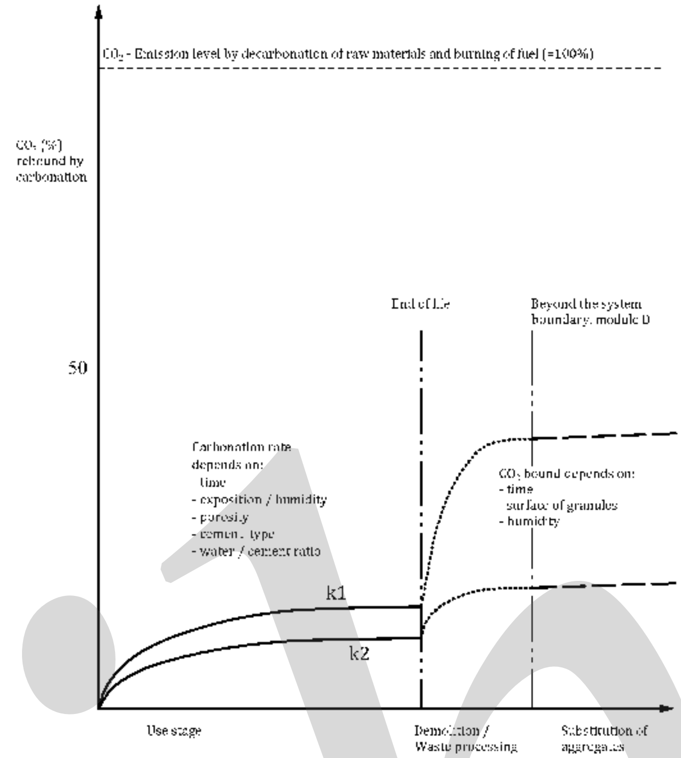


Fig. 5-2 Carbonation along service life. General principle of rebinding of CO_2 by carbonation of concrete[2]

Example from EN 16757: 1 m³ (1.3 yd³) of concrete is made with 300 kg/m³ (506 lb/yd³) cement. The CO_2 emission for the cement production is in this example 900 kg/tonne (1'800 lb/ton). This means that the cement in the concrete has a CO_2 emission of 270 kg/m³ (455 lb/yd³). Up to 50 % of this can be absorbed due to carbonation: 135 kg/m³ (228 lb/yd³). The concrete is a medium strength concrete exposed to outdoor climate with no surface treatment. The service life is 100 years. After the use stage the concrete is crushed to fine particles and exposed to air for 10 years before being used as road fill. Carbonation will reduce the total CO_2 emission of the precast concrete product to: 75 % * 135 = 101 kg CO_2 per m³ (171 lb CO_2 per yd³) of concrete.

5.2.9 Photocatalysis[3]

The environmental pollution in urban areas is one of the causes for poor indoor air quality in buildings, particularly in suburban areas. Moreover, gaseous emissions from daily traffic in the same areas are continuously increasing and often exceeding the allowable concentration in the atmosphere, raising public concerns and problems to the traffic itself. Within this frame the development of photocatalytic construction materials, particularly when applied to infrastructure works, can contribute to clean the air and improve sustainability levels. As a matter of fact, photocatalytic cementitious materials represent a new frontier in air quality improvement, since photocatalysis is able to accelerate natural oxidation process, promoting a faster decomposition of pollutants, preventing them from accumulating and favoring their decay.

The photocatalytic principle is the basis of the photoactive cements and binders used for manufacturing a wide range of cementitious products – from paints to mortars and precast elements – with which pavements, claddings and any type of horizontal or vertical structure and coating can be made. Due to aesthetic qualities and environmental benefits, the photoactive cements and binders, based on titanium oxide, represent a good choice in order to meet a variety of objectives, first of all sustainability:

- TiO_2 is added to a cement mortar in order to diminish the air polluting effect by exhaust gasses. In particular, the conversion of NO_x to NO_{3-} is measured (ordinary values from 4% to 10%);
- As a self-cleaning effect due to redox reactions promoted by sunlight, or in general weak ultraviolet light, on the photocatalyst surface is evident;
- Photocatalytic cement-based materials could represent one of the most efficient solutions for the mitigation of urban heat island effect, a phenomenon that causes urban areas to be 2 to 4°C (3.6 to 7.2°F) warmer than their surrounding areas.

5.2.10 Thermal Mass

Thermal inertia of precast concrete deck elements can be used to reduce the energy used for cooling and heating the whole building.

Thermal capacity of reinforced concrete is about 2.20 to 2.50MJ/m^3°K (1.2 to 1.4 BTU/yd^3°F. With an average volume of 30 m^3 (39 yd^3) concrete per apartment, this energy of about 70 MJ (66,000 BTU or 19.4 kW-hr), is stored in the concrete structure for each degree as the temperature rises. This energy can be released and can contribute to heating/cooling when the temperature decreases/increases. An example of this system of using thermal mass is the Elizabeth Fry Building, University of East Anglia in 1998.

To get an idea of how much energy this is, it can be compared with the total energy required to heat an apartment in a modern building in a Nordic country. On an annual basis, the energy needed it is up to 150 kWh/m^2 (14 kW-hr/ft^2), which is 45 GJ (43 million BTU or 12,500 kW-hr) in an apartment of 80 m^2 (861 ft^2). Therefore, daily energy consumption in the cold season will be at least 250 MJ (237,000 BTU or 69 kW-hr)[4].

It is well known that in a life-cycle perspective, energy consumption while using the building is essential. Hence, any measure that would reduce energy consumption when the building is in use will have a significant effect on the environmental record of the construction. However, in a climate where heating energy dominates the total energy demand the thermal mass has only a minor impact on the energy use.

Thermal mass can reduce 2 to 12 % of a buildings' heating energy demand[5] in the Nordic climates for buildings of late 1990s and early 2000. The difference is lower for nearly zero energy buildings. Airaksinen and Vuolle[6] compared a building built according to the Finnish building code level and a very low energy building (close to passive house level). Two building types were compared, a massive concrete building and a light weight building with a concrete floor. There were no big differences if the structures had more thermal mass or if they were thermally lightweight especially in energy-efficient buildings (Table 5-1).

Table 5-1 Space heating energy consumption[6]

Cases	Space heating energy consumption (kWh/m^2)	Space heating peak power demand (W/m^2)
Massive building code	70.5	32.1
Massive building code with sun shading	73.1	30.3
Light building code	72.0	34.2
Light building code with sun shading	74.4	32.4
Massive very low energy	27.1	21.5
Massive very low energy with sun shading	32.5	21.7
Light very low energy	27.9	22.4
Light very low energy with sun shading	33.2	22.6

Note: 1 kWh/m^2 = 0.09 $kW\text{-}hr/ft^2$ or 1 kWh/m^2 = 317 BTU/ft2; 1 W/m^2 = 0.09 W/ft^2 or 1 W/m^2 = 3.2 BTU/hr- ft^2.

The impact of the thermal mass on energy demand of the building depends on, for example, climate (cold, temperate, warm), window area and orientation, window properties (U-factor and g-value), ventilation rate, temperature controls, and the like. In warm climates where cooling is the major energy use the thermal mass has a higher impact compared to cold countries. Also, buildings with natural ventilation and efficient solar shading can benefit from the mass.

Thermal comfort is one of the key social indicators of buildings. The lower indoor temperature fluctuations in a warm climate improves indoor conditions and comfort and reduces demand for mechanical cooling. Thermal mass inside a good insulation layer is also an economic benefit.

Several systems have been developed in precast concrete structures that utilise concrete structures as heat storage. The systems use the storage for space heating and cooling by charging and discharging the storage. Hollow-core slabs allow for the utilization of a thermal system in which the air is distributed in the voids of the hollow-core slab elements.

The system aims at minimizing the installed heating and cooling power and generates energy savings especially in warm climates and up to some level also in cold climates. It also allows cooling in the warm summer months. To get the full benefit of this system of concrete precast concrete structures, surfaces on roofs should be exposed. Eliminating false ceiling systems allows a great savings in the overall height of the building that can provide 5% to 7% of construction cost savings.

The concrete slabs behave as a normal steel duct, according to independent reports. Thus, the ducts can be used and maintained just the same as normal steel ducts. However, the national requirements on the cleanness of ventilation ductwork may ban the use ducts with concrete surfaces. Therefore, a hollow-core slab as a ventilation duct may require surface coatings or installation of separate ducts in the slab for ventilation purposes. A ventilation ductwork needs to be cleaned timely which needs to be considered in the system design.

A comfortable indoor temperature improves productivity of people working in the building. Another possibility is to use false open ceiling elements to allow air exchange between the upper part and lower part. Figure 5-3 presents an example of the use of thermal mass in reinforced or prestressed precast concrete floors at night time conditions during summer.

On summer nights, fresh air is blown through the roof with hollow-core slabs using mechanical ventilation fans. This cools the concrete slab and acts as a cold store space for the next day (Figs. 5-3 and 5-4).

Thus, intensive energy air-conditioning demand can be reduced to a great extent or even eliminated. Another advantage is that cooling elements can operate with cheap electricity rates at night, while the traditional electric cooling is required during peak hours during the day.

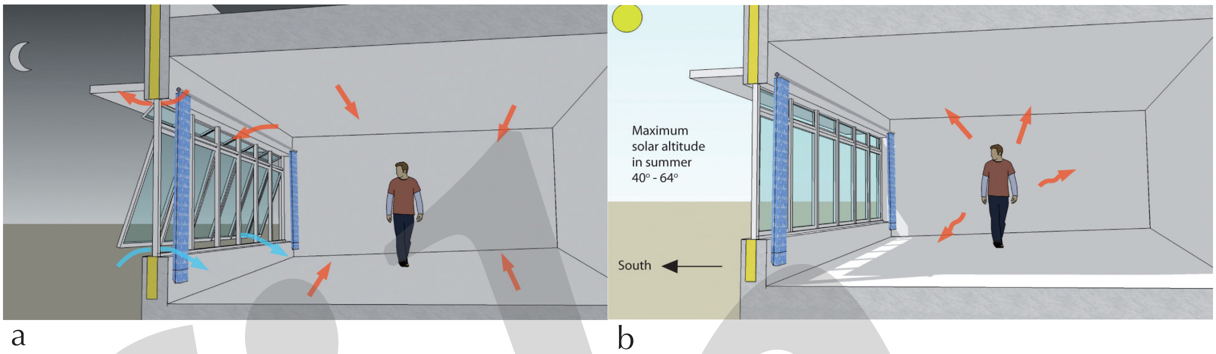


Fig. 5-3 Example of the use of thermal mass in decks during summer: a) night and b) day (courtesy of the Concrete Centre)

In summer daytime conditions, with warm days, cold from the previous night stored in the hollow-core slab roof improves comfort in two ways:

- by absorbing the heat produced by people and machinery.
- by cooling air that goes through the roof slab and cools before entering the room

The use of thermal mass contributes to save energy and allows more freedom for the occupants because, if necessary, they can open the windows. Alternatively, in winter night time situations as seen in Figure 5-4, the building is closed at night to keep some of the heat gains, produced by people and machinery during the day. Night-time ventilation reduces the gains. Reduced night time ventilation is a necessity to prevent dust or other impurities to accumulate in the ductwork and to ensure good indoor climate all through the day. Anyhow, in cold climates additional heating is required.

The ventilation heating will start with design air volume two hours before the working hours to ensure that the room temperature is suitable at the beginning of the working day. If the building cools at night below the preset limits, air conditioning equipment will initiate air recirculation, and a slight warming will start.

With regard to winter conditions, even though in daylight conditions, the heat generated by the occupants and machinery will be radiated to the hollow-core slabs and it will be also recovered from the exhaust air, which goes again through the slab across the rooms.

This design approach using these systems reduces ventilation needs for heating and cooling ducts or ventilation, and hence reduces cost and improves space utilization. It also uses very efficiently the thermal mass available.

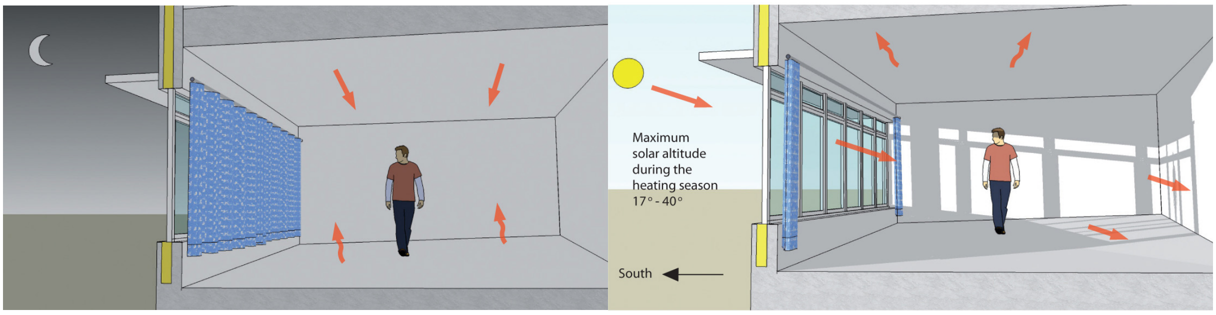


Fig. 5-4 Example of use of thermal mass in decks during winter: a) night and b) day (courtesy of the Concrete Centre)

There is no additional capital cost with the use of thermal mass as it does not add any extra material or equipment. In fact, since the installed air-conditioning equipment is smaller sized, generally about half of a conventional installation, the installation cost is lower than that of a conventional system.

- Depending on the climate, a lower energy consumption may be reached and thus lower CO_2 emissions.
- Savings in power demand during peak hours are possible.
- The building height may also reduce as the false ceilings may be lower in size (lower construction costs)
- The system is silent and there are no draughts. The hollow cores act as efficient silencers, which makes the system completely silent. Since the supply air is warmed or cooled when passing through the slabs before entering the room, the temperature of the supply air is very similar to the room temperature

There are also benefits in cold and temperate climates as in milder climates, such as Sweden and UK, the slabs are primarily cooled during night with the outdoor air. Small chillers, if any, are needed. Heating will also be reduced since the heat accumulated in the slabs during daytime can be used to warm the building during cold nights. The energy savings will therefore be from medium to sometimes high if there is a variation in temperature in the outside air from day to night.

The use of night cooling ventilation in addition to phase change materials (PCM) is a very powerful strategy for reducing the cooling demand of buildings. The efficiency of a night cooling strategy lies in the ability of the building inertia to store cool during the night and to use it during the next day. There are several alternatives to incorporate PCM in buildings (such as, walls, subfloor or ceiling systems, separate heat or cold storage systems). One of the most useful systems are precast concrete hollow-core slabs due to the simple fact that the cores themselves enable to introduce the encapsulation system with the PCM and it activate the thermal inertia as well[7] (Figs 5-5 and 5-6).

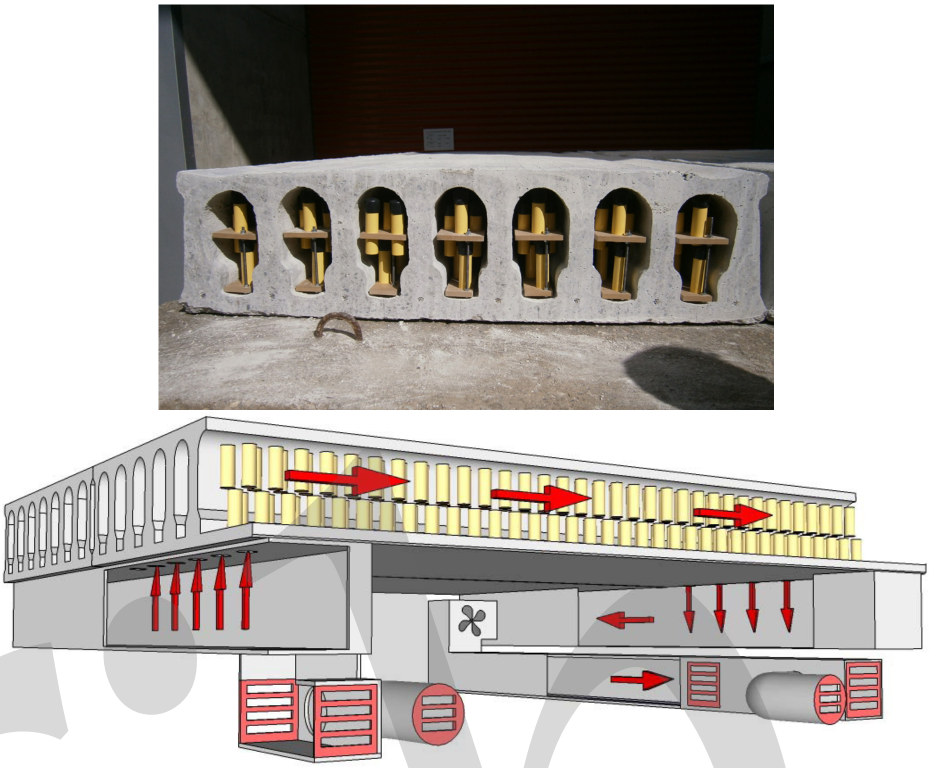


Fig. 5-5 PCM cylinders introduced in hollow-core slabs

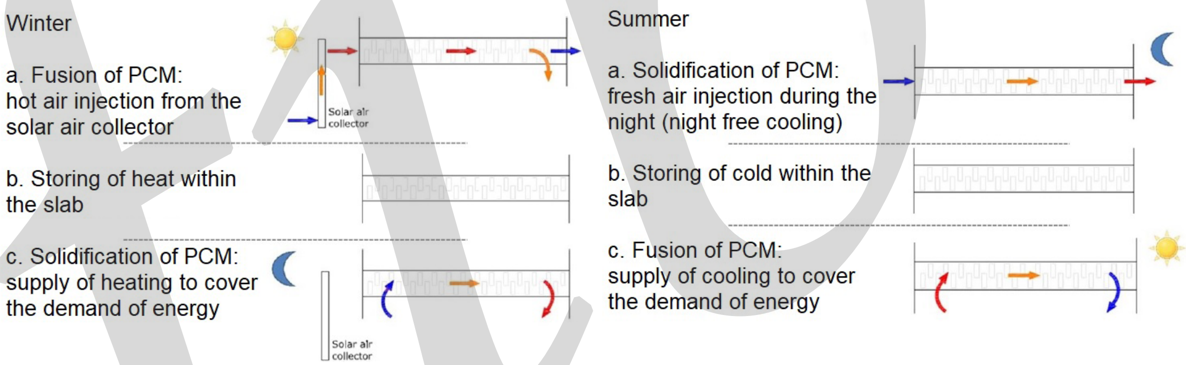


Fig. 5-6 Operation procedure of Phase Change Material (PCM)

The objective of this solution is that it can be easily incorporated in the construction of new buildings and for building refurbishment. It has been found that the use of this element reduces the thermal load peak and shift it several hours so in summer it is possible to have no need to turn on the air conditioning under some indoor temperature value (Figs. 5-7 and 5-8).

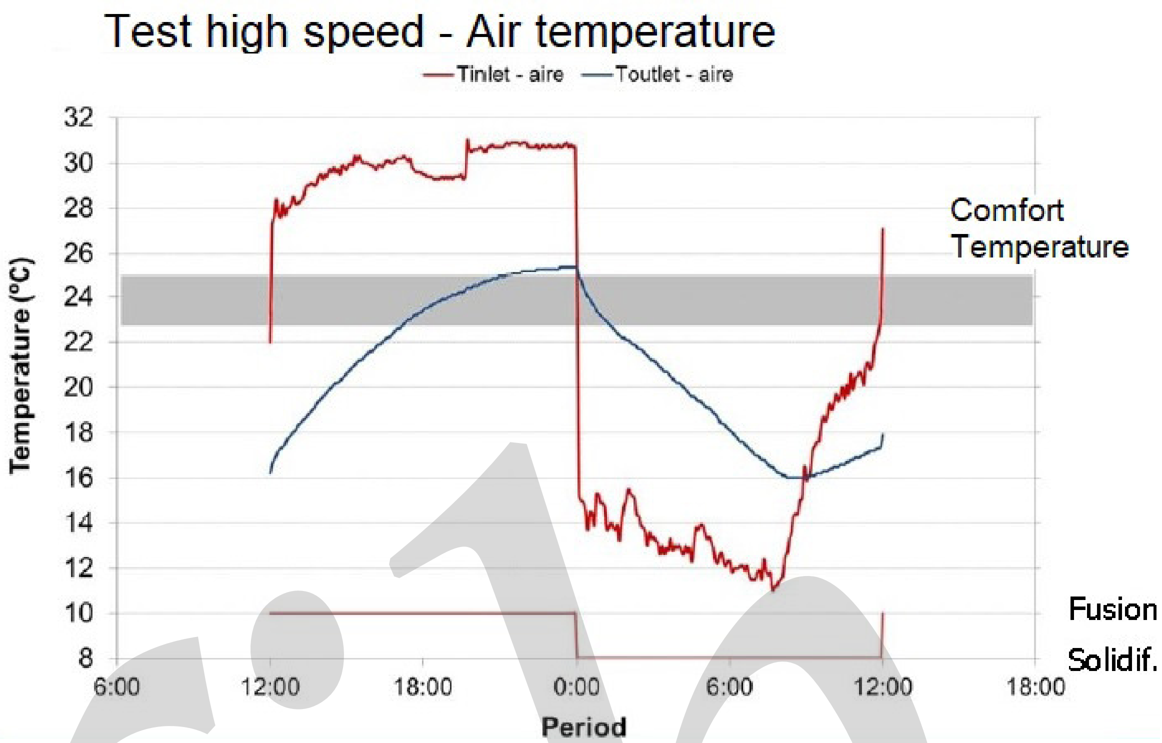


Fig. 5-7 Indoor temperature evolution during a summer day, source: Andece
Note: ºC = (ºF – 32)/1.8.

5.2.11 A good example of an industry really committed to new sustainable demands[8]

The UK precast concrete industry acknowledges that it has a responsibility to improve its performance on sustainability. British Precast has therefore established a research programme to develop and deliver a sustainability strategy for the industry. This programme was first initiated in 2007 establishing a roadmap for some sustainability indicator targets. First period of analysis was from 2008 to 2012 and 12 of 14 affixed goals were achieved:

- Reducing overall kWh / tonne of energy used in production by 10% ✓ Achieved
- Reducing CO_2 emissions from production by 10% ✓ Achieved
- Reducing kg / tonne waste to landfill by 10% ✓ Achieved
- Increasing the proportion of alternative cement additions (as a % of total cement) to 25% Failed at 23.8%
- Increasing the proportion of recycled / secondary aggregates (as a % of total aggregates) to 25% Failed at 21.3%
- Reducing main water consumption by 5% ✓ Achieved
- Reducing ground water consumption by 5%✓ Achieved
- Reducing reportable injuries per 100,000 direct employees by 10% per year ✓ Achieved
- Increasing the % of production sites covered by an EMS (for example, ISO 14001) to 85% ✓ Achieved
- Increasing the % of production sites covered by a Quality system (for example,

ISO 9001) to 85% ✓ Achieved

- Reducing the convictions for air and water emissions to zero ✓ Achieved
- Improving the capture of transport data ✓ Achieved
- Increasing the % of employees covered by a certified management system (for example, ISO 9001 / ISO 14001 / OHSAS 18001) to 85% ✓ Achieved
- Maintaining the % of relevant production sites that have community liaison activities at 100% ✓ Achieved

A new set of Sustainability Charter targets were approved by British Precast in 2013. All their members are committed to supporting the industry in achieving the following targets by 2020, adding new goals like:

- 90% reduction in waste to landfill
- 30% reduction in CO_2 emissions from concrete production by 2020 (from 1990 baseline)
- 95% of production certified to responsible sourcing standard BES 6001.

5.3 Social Aspects

5.3.1 Public Disturbance

The short construction period leads to less public disturbance as noise and dust normally associated with construction is reduced. Due to the size of the prefabricated units, large precast components of the building are transported on trailers, compared to erection of scaffolding, shuttering material, cement, aggregates, among others, that is transported separately.

Hence the considerable reduction in traffic and less obstruction to the general public leads to less disturbance for the public. Many construction sites are in densely populated areas within urban centers, and therefore such work activities can disturb a large number of people.

5.4 Economic Aspects

5.4.1 Structural Systems

Comparisons have been made of the structures of buildings with various heights for both homes and offices. The functional unit is one square metre of ground used for the life of the building, including both horizontal and vertical structural components and supplementary materials, that is, the total environmental load of the building. Life-time expectation was taken as 50 years. Several schemes for handling the demolition debris have been investigated.

Differences can be seen in Figure 5-8.

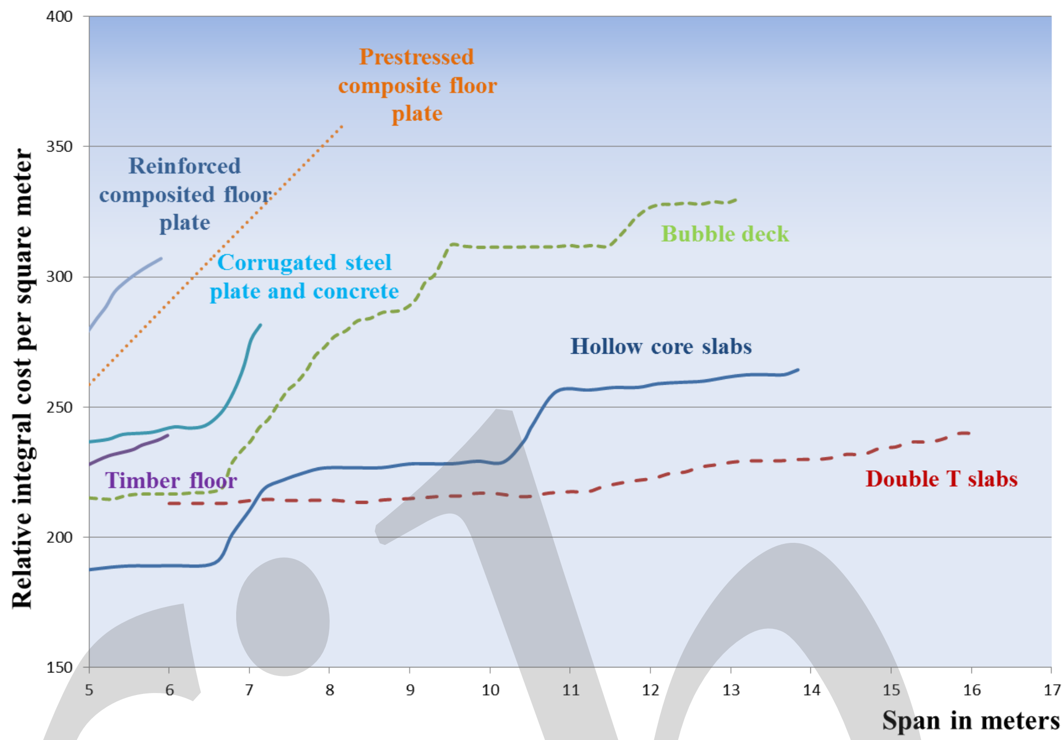


Fig. 5-8 Relative Costs of different type of flooring system for housing[9]

The example is basically a review of the environmental contributions of each kind of structural system referred to a given number, and thus the ambient hazards, like the greenhouse effect or acidification can be defined.

The example has been developed in the Netherlands, and can be adjusted according to local conditions. The different effect categories are weighted according to local political environmental goals and regulations.

In the production of the structure of the load bearing components, 75 to 95% of the environmental impact is generated. Total cost is set as the sum of the environmental impact and economic integral cost. Loads are calculated in two aspects that must be articulated in monetary terms. This is done by calculating or estimating the costs necessary to restore the environmental impact caused by the use of raw materials, energy, water, among others. These effects could be further normalized according to ISO 14041.

In any comparison, it is fundamental that the functional unit always includes the same parameters, in this case regardless of soil type. The functional unit may include a selection of parameters such as structural performance, safety, comfort, among others.

5.4.2 Durability and Flexibility

The production of precast elements, under climatic controlled conditions, allows a precise control of the outcome, such as tolerances and concrete quality.

Usually, there are higher design concrete strengths and performances used in precast concrete structures than in ordinary in situ structures. These two facts, high strength and controlled curing of concrete, have the potential to produce very dense and durable concrete. Furthermore, concrete used in precast elements has usually high resistance and is a dense material that inhibits or delays deterioration. The most common damage in concrete structures is reinforcement corrosion. In the production of precast concrete cover is easy to secure accurately and as a result durable components are created.

This positive effect of high-quality concrete can be used with minor requirements for a useful life or with improved lifetime when maintaining the same cover. The ultimate symbol of durability is to be able to reuse a precast concrete structure. In concrete whose life is mainly sheltered from the weather, for instance in all building structures, life expectancy is a hundred years.

If the structure is made in such a way that the building can be changed without a major demolition process, undoubtedly the building itself may have a long life, and it will only need to adapt its interior architectural layout for new uses. Lately the practice of reusing concrete structures with old concrete removed from new buildings has become more and more frequent, as well as dismantling existing structures and reassembling them again. Several examples are well known in the Netherlands, Sweden, and Norway.

Precast concrete structures are flexible in many respects. First, when using prestressing, design spans are usually long, so it is easy to adapt the building to future needs of change or forthcoming use demands. After then, life design for the structure and external walls is at least 50 to 100 years, while for the interior partitions is just about 10 years.

Connections are an essential part of the design and the construction of precast concrete buildings. Regarding durability, it is necessary to consider the risk of reinforcing steel corrosion and cracking and spalling of concrete related to, and always taking into account, the actual environment. Steel exposed to an aggressive environment should be provided with a permanent protection. This can be achieved by applying a layer of epoxy, rust proof paint, or bitumen, or by casting-in with concrete or mortar. In many cases the connections cannot be inspected or maintained after the building has been completed. In such a case the connection, without maintenance, should have life expectancy that exceeds that of the structure.

In secondary buildings that have structures built with precast concrete elements, such as mezzanine floors in industrial buildings, structures can be installed or removed at request. When buildings are designed as demountable, it is adviseable to use bolted connections that are demountable and provide immediate fixity. Several systems that are fully demountable are in use for precast buildings. However, to overcome construction deviations, tolerances in three-dimensional space must be accommodated.

6. Methodologies for Precast Structures

6.1 Existing applications or tools

A tool developed by the Canadian Precast/Prestressed Concrete Institute (CPCI) allows precast concrete manufacturers to track life-cycle inventory data. The goal of the North American Precast Concrete Sustainable Plant is to benchmark the precast industry's impact on the environment in the areas of global warming potential, energy use, water use, and waste, dust, and noise generation. Ultimately, the precast industry is striving to reduce the environmental impact at the manufacturing level.

The tool is web based Software Tracking Programme and is provided by the CPCI, National Precast Concrete Association (NPCA) and the Precast/Prestressed Concrete Institute (PCI) for its member plants to track environmental-performance measures, gauge track changes and improvements in performance, and enhance their environmental and economic performance.

Sustainability performance builds on the North American Precast Concrete LCA research already completed by the North American Precast Concrete Industry. The programme is not intended to replace municipal, provincial/state or federal environmental acts and their requirements; it is a programme designed to track the improvements implemented by each manufacturer.

The industry software, Precast Plant Sustainability Tracking Programme (Version 2.1), enables individual manufacturers to measure their “cradle to gate” environmental footprint (with cradle being raw material resource extraction and gate being the finished product leaving the precast plant for the construction site).

A manufacturing facility enters their raw material usage, electricity, natural gas, gas, diesel, heavy fuel oil, and liquefied propane gas usage the software uses the ASMI database to calculate the environmental indicators – global warming potential (GWP), total primary energy (TPE), and water usage for the plant. The facility also self-evaluates and reports their environmental performance indicators – dust, noise, and waste materials.

Participating plants report their tracked results on a quarterly basis, the results of which are presented in this report along with the year to date results. Individual plants are also provided a customized report on a quarterly basis for their own internal benchmarking. Specifiers and owners can request the sustainability impacts on a project-by-project basis and are also encouraged to include this requirement in their contract specifications.

The Canadian industry has now been reporting since 2012, and provides a summary report at www.sustainableprecast.ca. The United States began reporting in 2015.

LivingHomes have created a number of custom homes for clients with land and special needs. These homes are based on the LivingHomes standard models and connection details, but they have customized floorplans, layouts and/or finishes. They follow the same LEED guidelines and must be at least LEED Gold certified, the same as for standard model homes. It enables the web users and/or final clients to choice how they want some units to be made of, such as cladding units or floorings built with precast concrete elements.

6.1.1 Existing sustainability measurement systems

The different approaches to energy consumption and climate impact in the EU and U.S. have been reflected in a very direct way with the specific requirements of the buildings. The EU, from its international commitments, adopted in 2002 a Directive on energy efficiency in the buildings, which has been amended in 2010 to require all privately owned buildings almost zero consumption of energy from the year 2021 (in 2019 for public buildings).

The U.S. building codes have established energy requirements much less demanding than in the EU, but have grown so much faster in these certification procedures of the buildings. Some of the tools are:

- LEED, which analyzes the sustainability of buildings from a holistic perspective, and
- ENERGY STAR PROGRAM, developed by the U.S. Environmental Protection U.S., which measures only the energy efficiency of the building.

In short, in the EU the tools for building certification from the point of view of sustainability are modest, but are rapidly developing, and Europe is engaged in extraordinarily demanding regulatory amendment and also very ambitious targets up to 2020 and, very likely, will continue later.

In U.S., however, the penetration of the building rating tools has achieved a much greater diffusion, which has grown relatively quickly.

6.1.2 Sustainability certification tools for buildings

The following describes very succinctly the building certification tools most used in the world:

- BREEAM (Building Research Establishment Environmental Assessment Method). It was the first building certification process and was developed in 1990 in the UK by the Building Research Institute, which was a public body until its privatization 12 years ago. It has served as a model to other tools developed later.
- LEED (Leadership in Energy and Environmental Design). It was developed in 1996 and is operated by the U.S. Green Building Council, a non-governmental organization. It has become the standard for sustainable buildings in the U.S., having spread into many other countries.
- Sustainable Building Tool (SBTool). This tool was developed in 1996 in Canada by a group of researchers from iiSBE. Establishing a general framework to be adapted to local conditions, this is done through the variation of weights of the different parameters analyzed.
- HQE. France developed its own system in 1996, called Haute Qualité Environmentale and is operated by the “Association pour la HQE”.
- Green tools, developed and operated by Green Building Council Spain, and Protocol Ithaca, tailored in Italy, are two examples of the use of the tool frame.
- DGNB. Germany did not develop its own certification tool until 2009, when it created the so-called German Sustainable Building Certificate. The system was developed by the Ministry of Transport, Building and Urban Development and is one of the most comprehensive procedures of those existing in the world.

There are several other certification systems, but hardly any of them is known outside the borders of the country that created it. The two most commonly used tools are LEED and BREEAM, used primarily in their home countries. However, in recent years LEED has extended in Europe. In any case, the penetration of building certifications is only important in the U.S. and in the UK.

If the number of certified commercial buildings in the UK and the U.S. are compared, it can be seen that LEED has surpassed BREEAM in 2009, but this is due in part to larger tertiary market in the latter country. However, BREEAM has certified many more residential, more than 100,000 total by 2010 (Fig. 6-1).

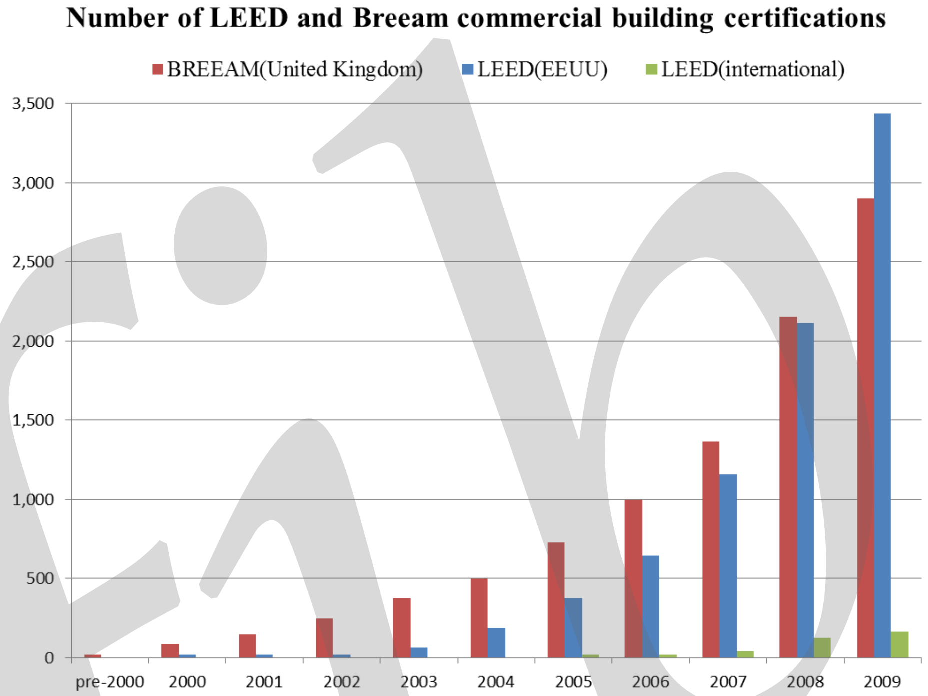


Fig. 6-1 Number of Commercial Building Certifications of LEED and Breeam, Source: RREEF Research

LEED has grown to become the world's most widely used green building rating system, with nearly 80,000 projects participating in LEED across 162 countries, including more than 32,500 certified commercial projects. With the launch of LEED v4, USGBC took a different approach that has resulted in smoother trends for growth from v2009 to v4. There are currently 773 v4 projects registered (data from April 2016), indicating a steady rate consistent with a gradual transition. The green building movement continues to be supported by its growing network of accredited professionals, currently counted as more than 200,000 LEED credential holders.

Globally there are more than 558,900 BREEAM certified developments for, and almost 2,261,300 buildings registered for assessment in 78 countries, since it was first launched in 1990.

It does not seem likely that in the coming years a high level of normalization or standardization of certification tools will be reached, but, rather, that more competition will be created for better market share and positioning of each existing tool. Results of some studies on the economic efficiency of green buildings in Europe show that developers, builders and investors focus their attention and efforts on the development of construction technologies that enable them to meet the growing requirements of the respective building codes.

Some countries, such as Denmark, have established a roadmap to tentatively identify needs and requirements of the buildings until 2020. Others, such as Spain, have not yet adopted a building code that implements the methodology established in the European Directive on energy efficiency in buildings (2010) for minimum cost in the life cycle (including CTE draft, not yet approved), has not made the leap to the requirements of the building as primary energy or CO_2 emissions per m^2 built and year.

With this regulatory uncertainty and increasingly demanding requirements in the EU, the industry is challenged in an unprecedented way in recent times and this industry has just no more capability that can be dedicated to the implementing of tools for sustainability certification of buildings.

In any case, the energy requirements of the building and sustainability are not exactly the same, although sustainability always includes energy efficiency as an important element, so the above does not prevent the current situation changing in the future in the EU.

Therefore, when there are few tools that certify buildings and measure sustainability, there are hardly any studies in the EU on the economic efficiency of green buildings. However, in the U.S. there are some very thorough analyses of this issue.

6.1.3 Comparison of parameters within several tools[1]

Tools have their own considerations. If we compare the importance that different tools give to sustainability aspects they differ greatly.

In the case of LEED procedure, environmental aspects are divided into parts with different weights:

- Sustainable development of the ground, 24%
- Water Efficiency, 9%
- Energy and atmosphere, 32%
- Materials and resources, 13%
- Internal quality of air, 14%
- Innovation in design, 5%
- Regional priority, 3%

In the case of BREEAM chapters are divided:

- Management, 11.5%
- Health, 14%
- Energy, 18%
- Transport, 8%
- Water, 10.5%
- Materials, 12%

- Waste, 7%
- Land Use and ecology, 9.5%
- Pollution, 9.5%
- Innovation, 10%

In the case of Verde chapters are divided:

- Land use,
- Energy and Atmosphere
- Natural Resources
- Internal quality of air
- Service quality,
- Social and Economic aspects

These chapters are divided into impacts that are:

- Climate Change 27%
- Loss of fertility 5%
- Loss of water life 4%
- Health problems 8%
- Biodiversity changes 4%
- Loss of resources 17%
- Loss of drinking water 10%
- Generation of not dangerous waste 6%
- Loss of health 12%
- Financial risk 5%

When comparing LEED, BREEAM, and Verde procedures it is evident that they already differ for general aspects. They all give the greatest value to environmental impacts, between 46% and 55%. Social and economic impacts are not always in the same place. Economic credits vary between 15.8% for BREEAM and 26.1% for LEED. Then social credits have a value from 19.5% in BREEAM to 26.0 in Verde. BREEAM and LEED have a quite important value for other considerations, between 5.3% to 9.7%. There is a need to have common rules that are normalized for all tools that are used for the evaluation of sustainability of buildings and constructions in general.

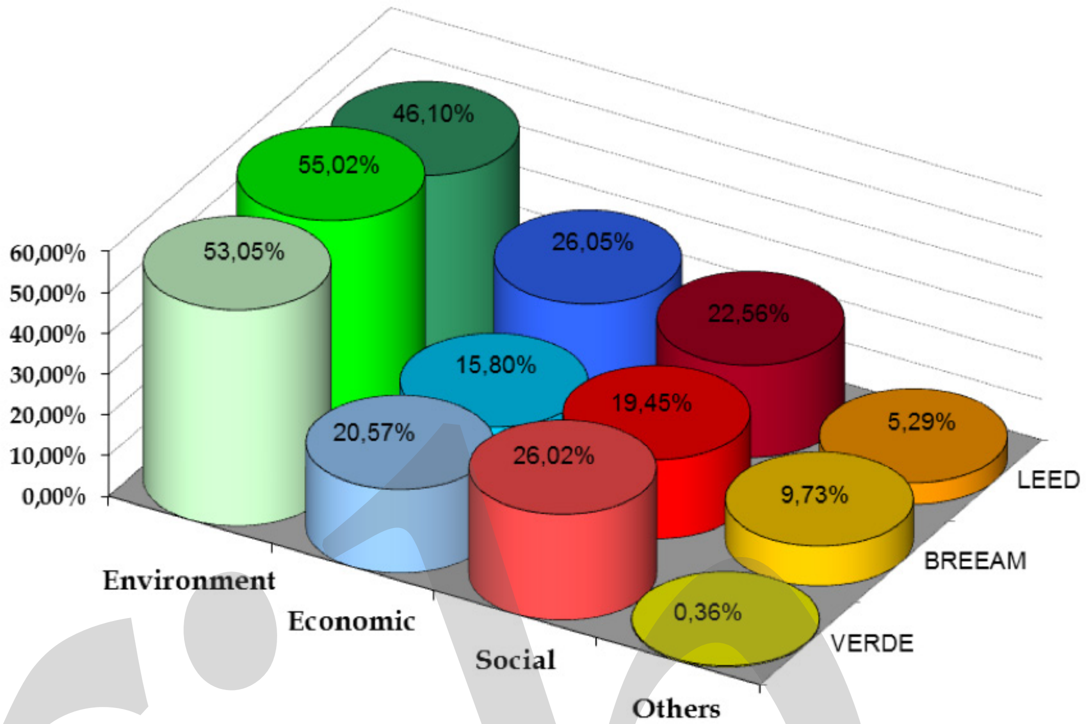


Fig. 6-2 Comparison of weights of parameters between several sustainability tools

6.2 Common rules to retrieve the data

The North American Precast Concrete Industry began developing a set of product category rules (PCR) for the North American context in early 2014. With ASTM International serving as the programme operator, the Canadian Precast/Prestressed Concrete Institute (CPCI), National Precast Concrete Association (NPCA) and the Precast/Prestressed Concrete Institute (PCI) all have equal representation on the technical advisory committee developing the PCR.

The PCR specifies rules, requirements, and guidelines for developing EPDs for precast concrete and underlying requirements of related life-cycle assessments (LCAs). These PCR are valid for, and provide requirements for, Business-to-Business (BtoB) EPDs, also known as cradle-to–gate or information module EPDs.

The PCR are consistent and compliant with the mandatory requirements contained in the following standards:

- International Organization for Standardization (ISO) 21930: 2007. Building construction — Sustainability in building construction — Environmental declaration of building products.
- ISO 14025: 2006. Environmental labelling and declarations — Type III environmental declarations — Principles and procedures.
- ISO 14040: 2006. Environmental management — Life cycle assessment — Principles and framework.
- ISO 14044: 2006. Environmental management — Life cycle assessment — Requirements and guidelines.

In 2008, a team under the direction of Petr Hajek made for SBA (Sustainable Building Alliance) a complex analysis of weighting systems used in 17 sustainability rating tools:

- NF Bâtiments Tertiaires – Démarche HQE (2006)
- The Code for Sustainable Homes (2008)
- Habitat & Environment (2003)
- BREEAM Offices 2008
- SBTool-VERDE
- Protocollo ITACA
- Protocollo SBC_Retail
- Protocollo SBC_Offices
- PromisE for Residential Buildings
- SBTool Tiny (2007), design phase
- SBTool CZ
- LEnSE
- LEED for New construction 2009
- LEED for Homes (Jan 2008)
- Green Star - Multi Unit Residential PILOT (2008)
- CASBEE for New Construction (2006)
- SBTool (2007), design phase*

From that study the main results and considerations were:

1. Settings of weightings in all searched tools was very different.
2. Setting of weightings between three main sustainability categories (eco - env - soc) is just a political decision.
3. From the analysis followed that environmental issues were dominating in the number of criteria and their weightings (71%). One of the possible (and "probable") reasons was that most of the analyzed tools were originally developed as green tools and in the next steps some issues were added from social and economic groups of issues. Some new tools (after the report that was elaborated in 2008) have more comparable distribution of weightings: LEnSE (Env 44.4%, Soc 36.7, Eco 18.9), SBToolCZ (Env 50%, Soc 35%, Eco 15%). DGNB has almost equal weight distribution among three main sustainability issue groups.
4. Weighting of sustainability criteria is very dependent on the characteristic of the structures under consideration. For example, for different types of buildings you can have different weightings and eventually also different sets of criteria.

The suggestion arising from these studies is that weighting distribution obtained in an expert survey should be strictly considered for specific types of structures.

At national and international levels, several EPD programme operators exist. The list of the operators is given in the following Table 6-1. The programme with the largest EPD database of building products include already hundreds of EPDs, for example, French INIES or German IBU.

Table 6-1 List of EPD programme operators in different countries

Shortcut	Programme operator	Origin	Reference
ALCA	American Center for Life Cycle Assessment	US	http://lcacenter.org
BRE	BRE Trust	UK	http://www.bre.co.uk/
CEC	China Environmental United Certification Center	CN	http://www.sepacec.com/cecen/
CNEDEC	Centre for Environmental Product Declarations	CZ	http://cendec.cz/
EcoLeaf	Japan Environmental Management Association For Industry	INT	http://www.ecoleaf-jemai.jp/eng/
EDF	Environment and Development Foundation	TW	http://www.edf.org.tw/english
Environdec	The International EPDsystem	SE	http://www.environdec.com/
epddanmark	Technologisk Institute	DK	http://www.epd-danmark.dk/
EPD-Norge	The Norwegian EPD Foundation	NO	http://www.epd-norge.no/
IBU	Institut Bauen und Umwelt e.V.	DE	http://bau-umwelt.de
IGBC	Indian Green Building Council	IN	http://www.igbc.in/site/igbc/index.jsp
INIES	Association pour la Haute Qualité Environnementale des bâtiments	FR	http://www.inies.fr/
KEITI	Korea Environmental Industry & Technology Institute	KR	http://eng.keiti.re.kr/
UL	UL	US	http://www.ul.com
ECOPLATFORM	EPD Programmers Europe	EU	http://www.eco-platform.org/
ICMQ	EPD Italy	IT	www.epditaly.it

6.3 The sustainable structural design methodology (SSD)

6.3.1 Introduction

The construction industry, as a main energy consumer and a foremost contributor to greenhouse gas emissions, has been undergoing a "green revolution" in recent years. Generally, all recent directives and regulations of the European Union in the building sector dictate that design and construction of structures should adopt a balanced approach between economic, environmental and social aspects, enhancing sustainability and competitiveness of the sector[2, 3, 4, 5, 6, 7]. Particularly after the further commitments undertaken with the Paris climate deal, the turning point in tackling global warming needs to be even simpler in order to be even more effective[8].

Although the term of sustainable constructions is one of the most talked about, current environmental impact assessment methods cannot be effectively used in the comparison of building solutions, as they do not consider the structural performance of the building during its entire life. Existing impact assessment methods can be applied, typically at the end, independently from the architectural and structural design process, so that no real optimisation can be achieved, because a good structural solution may correspond to a poor environmental performance and vice versa[9]. The presented Sustainable Structural Design (SSD) method considers both environmental and structural parameters in a life cycle perspective. The integration of environmental data in the structural performance is the focus of the method. Structural performances are considered in a probabilistic approach, through the introduction of a simplified Performance Based Assessment method.

6.3.2 Development of the SSD Method

The Sustainable Structural Design method is conceived as a supporting tool for the general process of building design that takes into account technical-structural aspects along with environmental ones, during the life cycle of the structure. It aims at optimising the process of building design in terms of structural and environmental performance[10], configuring a design method both for safety and sustainability. SSD is not intended as just another new framework to perform multi-criteria evaluations, its ambition is sharing and coordinating the best practices already available and used by different experts in the building sector. To this end, in conceiving the architecture of SSD method, two main objectives were pursued: the Openness and the Sustainability of the method itself.

The Openness is necessary to ensure that a largest number of practitioners may be involved and allowed to use and fit the procedure according to their needs. For this purpose SSD should be Modular, Portable, and Scalable.

Modular: separating the functions into independent, interchangeable modules, such that each contains everything necessary to execute all the aspects of the desired functions. Naturally, all modules should be connected to communicate using the same language and the same metrics: thus the final layer is converted in purely economic terms.

Portable: the same procedure should be used in different scenarios. Very often the stakeholders must provide a response to questions like these: – Is it better to refurbish an old building or demolish it and rebuild a new one? – Which technique could assure the best balance between safety and sustainability, building a new construction? For this reason, it is also necessary to provide responses for a paramount of questions that could further include other natural hazards, such as exceptional climatic events, or man-made hazards like fire or explosion.

Scalable: stakeholders need to analyse and compare different solutions ranging from a single building to (in principle) an urban/regional/national level[11]. The method should be capable to handle an increasing amount of data, potentially to be enlarged to accommodate that increase.

The sustainability of the method itself is a transversal objective: whenever a process has been developed and tested already, it should be used instead of inventing a new one. Besides avoiding reinventing the wheel, this is the base to spread the procedure across different experts' communities. Everyone, indeed, may account using their own tools simply integrating with each other's outputs. For this reason, any LCA procedure should be based on existing standards, such as the ISO 14000[12, 13] (Fig. 6-3).

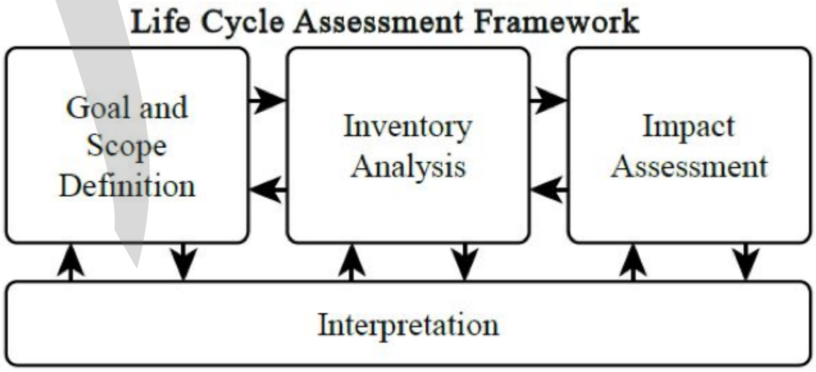


Fig. 6-3 Steps of the LCA methodology according to ISO 14040

The framework of the SSD method, as shown, is based on three main pillars, corresponding to the three evaluation steps: Energy Performance Assessment; Life Cycle Assessment and Structural Performance Assessment. The following sections describe the details of each component (Fig. 6-4).

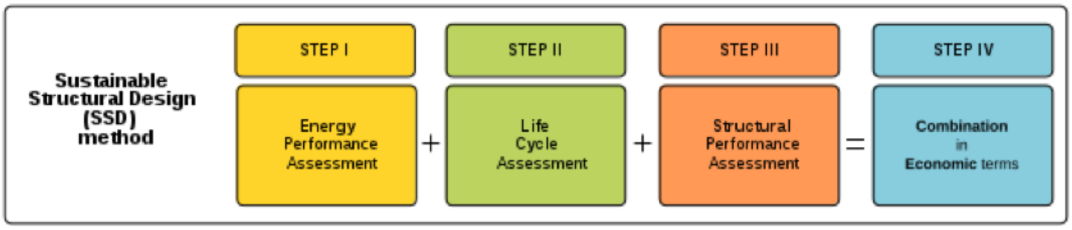


Fig. 6-4 Steps of the SSD method

6.3.2.1 STEP I: Energy Performance Assessment

The operational Life Cycle Energy Assessment (LCEA), which formally should be part of the Life Cycle Assessment (LCA), corresponds to the evaluation of the total energy during the operation phase only. It is performed independently from the other LCEA components. Even though the output of this step, the operating energy EO, corresponds to an environmental impact, it is more convenient to treat it independently from the LCA.

The theoretical reason for this decision is the fact that the cost of energy typically includes a tax that is intended to represent the environmental impact corresponding to the production and use of the energy, from whatever source the energy is produced. Such tax, which is fixed by the relevant authorities, is in principle accounting for the full environmental impact and therefore it should not be included in the LCA. Another, and more practical reason is that the energy performance assessment is routinely performed by professionals, mechanical, electric and plumbing (MEP) engineers, who have specific competences that are different from the competences required for the LCA. However, one should be aware of the fact that the operating energy represents the largest portion of the total environmental impact, as it will be shown in an example.

6.3.2.2 STEP II: Life Cycle Assessment

Following the proposed methodology, LCA should be performed using the common practices. The life cycle assessment is performed according to the standard cradle to grave approach. The contribution of the operating phase will be determined using the results of the first step and the output of this phase will be expressed in terms of total equivalent CO_2 emissions (Fig. 6-5).

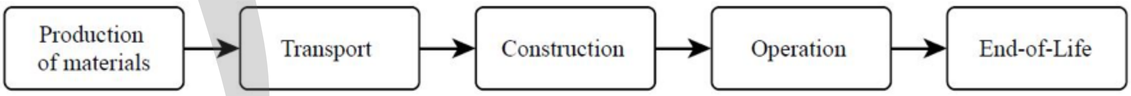


Fig. 6-5 Flowchart of the LCA of a building

Introducing the Life Cycle Impact Assessment (LCIA) in a LCA, the emissions and resources consumed that can be attributed to a specific product are compiled and documented in a LC Inventory. An impact assessment is then performed, considering human health, the natural environment, and issues related to natural resource use. Impacts considered in a LCIA include climate change, ozone depletion, eutrophication, acidification, human toxicity (cancer and non-cancer related) respiratory inorganics, ionizing radiation, ecotoxicity, photochemical ozone formation, land use, and resource depletion. Different emissions and resources consumed, as well as different product options, can then be cross-compared in terms of the impact indicators.

6.3.2.3 STEP III: Structural Performance-Based Assessment

The third step of the SSD method deals with the structural design using a Performance-Based Assessment (PBA). In other terms, the design process should not consider solely the aspect of structural response but also the aspect of structural performance[15]. This is expressed in predefined design targets that the structure is required to meet over its design life[16].

The structural PBA consists of the implementation of probabilistic scenarios that can occur during the lifespan of the structure in terms of uncertainties[17]. Therefore, not only loads imposed on the structure but uncertainty and probabilistic response should also be taken into account in the structural analysis[18]. The uncertainties are grouped into three main categories namely hazard uncertainty (e.g. earthquakes, winds), structural uncertainty (e.g. stiffness, material properties) and interaction mechanism uncertainty (e.g. pressure duration)[17, 19]. In this respect, the PBA allows structural systems to be designed in a way that meets performance targets in terms of capacity, safety and quality[16].

The final results of the structural PBA are presented in economic context by evaluating all the costs associated with a structural solution, as well as the expected losses that may occur to the building during its life for all the design targets. Afterwards, the specialists can evaluate, compare and make decisions between alternative structural design solutions and/or rehabilitation measures[16].

- Simplified Performance-Based Assessment (sPBA) method

The development of PBA methods is gaining big interest in the field of structural engineering. This interest originates from the successful implementation of the Performance-Based Earthquake Engineering (PBEE) method from the Pacific Earthquake Engineering Research (PEER) Centre[20]. The PEER's PBEE method has been fundamental in addressing the importance of integrating loss-assessment within structural design. However, such a method seems too complicated to be applied to ordinary projects due to complex probabilistic relations and high number of parameters[10].

Considering the latter, a simplified Performance-Based Assessment (sPBA) method has been introduced by Safety & Security of Buildings Unit of the Directorate Space Security & Migration – European Commission, Joint Research Centre (JRC)[10, 21]. The framework of the sPBA method aims at reducing the complexity and the amount of data needed as well as simplifying the procedure of estimating losses due to uncertainties. The method has been developed for seismic actions, but the same approach could, mutati mutandis, be applied to other actions on the structure.

The output of the analysis determines the cost of the structure together with expected losses for each defined limit state, corresponding to different Peak Ground Acceleration (PGA) and Inter-storey Drift Ratio (IDR)[22]. The steps of the sPBA method are detailed in the follows.

- Limit States Definition

The limit states are defined in terms of damageability and the expected costs for each limit state are calculated. The damage (limit) states that can be defined in a building are low damage, heavy damage, severe structural damage and loss of the building/collapse. The Engineering Demand Parameter (EDP) that measures the structural damage is the Inter-storey Drift Ratio, thus the IDR values are calculated for each damage level by using fragility curves.

- Structural Analysis

The structural analysis step consists of the calculation of the PGA values that cause the IDR values defined in the previous step. This correlation is defined through skeleton curves that may be obtained from the Incremental Dynamic Analysis (IDA), according to the FEMA-350 guidelines[23], or simply from a standard pushover analysis. After performing this analysis of a structural system, the PGA versus IDR can be defined for each configuration of damage state.

- Hazard Analysis

In the hazard analysis, the output of the structural analysis is used to estimate the probability of exceedance. Modern seismic codes provide the relation between the Return Period (TR) and the PGA[24]. For example, the Italian seismic code[25] provides a set of values of PGAs for nine return periods (30, 50, 72, 101, 240, 201, 475, 975 and 2475 years) along with the interpolation formula for values in between:

$$\log\left(a_g\right)=\log\left(a_{g1}\right)+\log\left(\frac{a_{g2}}{a_{g1}}\right)\log\left(\frac{T_R}{T_{R1}}\right)\left[\log\left(\frac{T_{R2}}{T_{R1}}\right)\right]^{-1} \tag{6-1}$$

where:

a_g is the PGA calculated for a defined damage state,

T_R is the return period which corresponds to that state,

a_{gi} are the intermediary values of PGA taken from the seismic map,

T_{Ri} are the return periods corresponding to a_{gi}.

After determining ag from the previous step, the return period T_R can be defined for each damage state. The probability of exceeding R_N in N years is expressed from the following equation[25]:

$$R_N=1-\left(1-\frac{1}{T_R}\right)^N \tag{6-2}$$

- Cost Analysis

The total cost of the building CTOT is the sum of the initial construction cost (investment: I) and the expected total loss (L) over the project's life cycle (Equation). While the initial cost includes the expenses related to the initial establishment of the facility, the estimation of expected total loss is more complex and involves different stakeholder categories[10].

$$C_{TOT}=I+L \tag{6-3}$$

More specifically, the contractor estimates in advance the time needed to repair the damages of each limit state. This information about time, needed for each limit state, is associated with the downtime loss. Downtime refers to the period of time in which the system fails to provide its primary function and therefore downtime loss expresses the amount of money that will be spent (lost) while the building is not used. Later, for each state, the structural engineer calculates the cost of repair of the damages[10]. Therefore, the expected loss C_i for each limit state *i* is expressed as the sum of monetary loss (the amount of money needed to repair the damaged building) and downtime loss (the amount of money spent during the repairing actions e.g. for rent, removal, etc...).

$$C_i = E\left(Loss_{repair} \mid IM\right) + E\left(Loss_{downtime} \mid IM\right) \tag{6-4}$$

$$L = \sum_{i=1} C_i \left(R_i - R_{i+1}\right) \tag{6-5}$$

6.3.2.4 STEP IV: Global Assessment Parameter of the SSD method

The outputs of the previous phases are expressed in terms of different units of measurements: energy for the Energy Performance Assessment, mass of the equivalent carbon dioxide emissions for the Life Cycle Analysis and costs for the Structural Performance Assessment. These quantities cannot be summed up to obtain a single global parameter. Therefore outputs of the energy and environmental impact will be converted into monetary units (costs) as it will be explained in the following. At this stage, all the financial issues related to discount costs and benefits over time, to calculate the net present value, may be performed following common financial procedures.

- Energy performance into monetary unit

The calculated amount of energy corresponds to energy consumed during the use phase and usually it is expressed in *kilowatt-hour* (kWh) or in cubic metres of natural gas (m^3 gas)[26]. The price for gas and electricity in Europe can be determined using the data of the *Statistical Office of the European Union* (Eurostat)[27] for each member state or the average price of all the Union in the household or industrial category. Therefore the total energy price $R_{E(Energy)}$ can be calculated for a specific country or using the average price by the following equation:

$$R_{E(Energy)} = Q_{(Energy)} \cdot P_{(Energy)} \tag{6-6}$$

where:

Q_{Energy} is the amount of the energy consumption (kWh or m^3 gas),

P_{Energy} is the price of one kWh or m^3 of gas (€/kWh or €/m^3 gas).

- Environmental performance into monetary unit

Until today in Europe there are market prices only for the carbon dioxide (CO_2), therefore only the environmental impacts associated with the global warming potential (carbon footprint) can be converted into economic costs[10]. To this end, ILCD is a crucial element to convert all the considered impacts into a CO_2 equivalent amount, and from this calculate an equivalent economic impact[14].

Carbon footprint is defined as the total amount of greenhouse gases (GHG) emissions caused by building life cycle phases, usually expressed in equivalent tonnes of carbon dioxide (CO_{2eq}). Otherwise, the embodied energy includes the energy consumed by processes associated with the production, use and demolition of the building, usually expressed in MegaJoule (MJ), kiloWatt-hour (kWh) or cubic metres of natural gas (m^3 gas)[26]. The conversion of the results into monetary units can be done following the EU directives.

The carbon dioxide price per tonne is linked with the European Union Emissions Trading System (EU ETS). According to the EU ETS, each member state agrees on maximum national emission limits that should be approved by the European Commission. Then the Union countries allocate allowance values to their industrial operators, who are able to buy or sell such allowances named European Emission Allowances (EUA)[28]. The total number of permits issued, either auctioned or allocated, defines the price per carbon which is therefore, determined by stock exchange rules.

Considering the carbon prices deriving from EU ETS, the monetary cost of the environmental impact referring to carbon footprint $R_{E(CO2)}$ can be expressed as follows:

$$R_{E(CO_2)} = Q_{(CO_2)} \cdot P_{(CO_2)} \qquad (6\text{-}7)$$

where:

Q_{CO_2} is the amount of the CO_{2eq} emissions calculated from the analysis (tonne),

P_{CO_2} is the price of one tonne CO_2 according to the EUA (€/tonne).

6.3.2.5 Equation of the Global Assessment Parameter RSSD

After converting environmental impacts into monetary units, the Global Assessment Parameter RSSD of SSD method can be expressed as the total sum of environmental and structural impact as follows:

$$R_{SSD} = R_{E(CO_2)} + R_{E(Energy)} + C_{TOT} \qquad (6\text{-}8)$$

where

$$R_{E(Env)} = R_{E(CO_2)} + R_{E(Energy)},$$

$$C_{TOT} = I + L$$

- Significance of the Global Assessment Parameter RSSD

The breakdown of SSD method, as represented in 0, points out that the proposed method supports the traditional design process and does not replace it.

The traditional participants in the design phase (Architect, Civil-, MEP- and Structural engineer) are assisted by additional practitioners, namely the LCA experts. Each outcome is expressed in terms of the same monetary unit, therefore the decision makers can compare and evaluate all parameters, which are independently regulated by their respective markets.

The Global Assessment Parameter, which is the main outcome of the procedure, represents a direct evolution of the more traditional process, based on the (initial) Price of the building, which indeed represents the greater part of RSSD. The procedure is scalable to be extended to other processes: building renovation or retrofitting, even to compare different solutions including demolition; infrastructure projects...; for this purpose it remains open to include other risk assessments, such as fire, wind, floods, etc.

Some operative examples of the use of the SSD methods, comparing Precast and Cast-in-situ structures are provided in[29, 30] (Fig. 6-6).

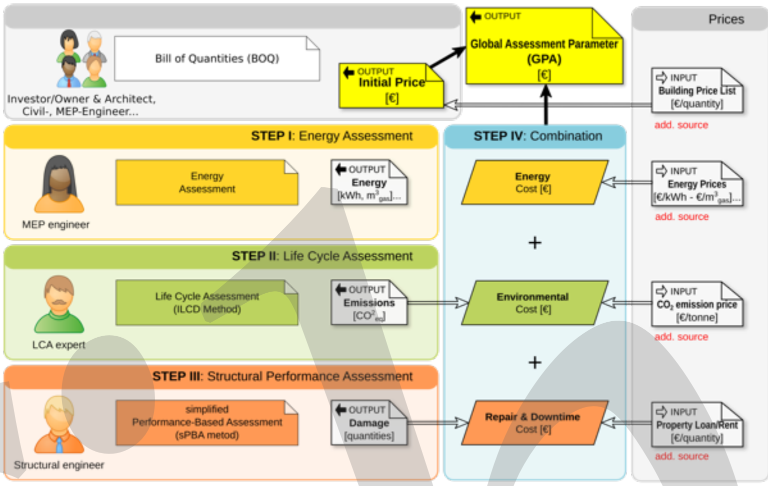


Fig. 6-6 Breakdown of SSD method

6.4 Mives Method

6.4.1 Introduction

MIVES is a multi-criteria decision-making method capable of defining specialised and holistic sustainability assessment models to obtain global sustainability indexes. MIVES combines: a) a specific holistic discriminatory tree of requirements; b) the assignation of weights for each requirement, criteria and indicator; c) the value function concept[31] to obtain particular and global indexes and d) seminars with experts using Analytic Hierarchy Process (AHP)[32, 33] to define the aforementioned parts.

There have already been numerous applications of MCDM in engineering[34], most focusing on economic aspects and fewer about environmental issues or social aspects. The MIVES method is a unique MCDM based on the use of value functions[35] to assess the satisfaction of the different stakeholders involved in the decision-making process. The use of these functions allows minimizing the subjectivity in the assessment. So far, MIVES has already been used for industrial buildings[36-39], underground infrastructures[40], hydraulic structures[41-42], wind towers[43], sewage systems[44], post-disaster sites and housing selection[45-46], and construction projects[47-48]. It should be highlighted that in the current Spanish Structural Concrete Code[49], MIVES method is proposed for assessing the sustainability of concrete structures[50]. Finally, it must be added that the MIVES method has even been expanded to include the uncertainties involved in the process of analysis[51].

6.4.2 Procedure

The assessment of the sustainability index by using the MIVES method should be carried out following these steps:

Step 1: Define the problem to be solved and the decisions to be made.

Step 2: Produce a basic diagram of the decision model, establishing all those aspects that will be part of a requirements tree that may include qualitative and quantitative variables.

Step 3: Establish the value functions to convert the qualitative and quantitative variables into a set of variables with the same units and scales.

Step 4: Define the importance or relative weight of each of the aspects to be taken into account in the assessment.

Step 5: Define the various design alternatives that could be considered to solve the previously identified problem.

Step 6: Assess the alternatives by using the established model.

Step 7: Make the right decisions and choose the most appropriate alternative.

In this case, the problem to be solved (step 1) consists of assessing the sustainability index of a certain precast concrete structure to be compared with other possible alternatives.

Regarding the requirements tree (step 2), this is a hierarchical diagram (Figure 6-7) in which the various characteristics of the precast concrete structure to be evaluated are defined in an organized manner, normally at three levels: indicators, sub-criteria, and criteria. At the final level, the specific requirements under evaluation are defined and the previous levels (criteria and indicators) are included in order to de-aggregate the requirements; this allowing, on the one hand: (1) having a global view of the problem; (2) organizing the ideas and (3) facilitating the comprehension of the model by any stakeholder involved in the decision process. On the other hand, the tree is useful to carry out the subsequent mathematical analysis.

Afterwards, mathematical methods from the general multi-criteria decision theory are used to convert the different criteria magnitudes and units into a common, non-dimensional, unit that will be called value (step 3). It must be noticed that this method accounts for both qualitative and quantitative variables related with the indicators.

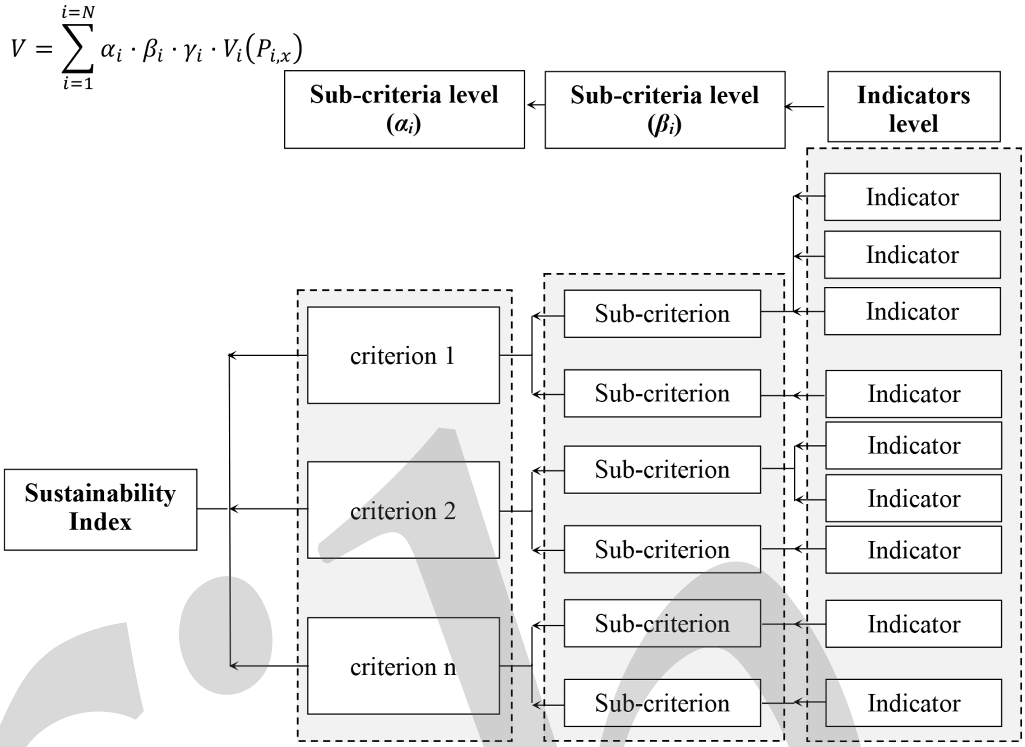


Fig. 6-7 General requirements tree

In any multi-criteria decision problem, the decision makers have to choose between a group of alternatives, these being either discrete or continuous. Thus, when the preferences of the decision maker are known with respect to a set of design alternatives, x∈X, the existence of a value function $V{:}P \rightarrow R$ can be considered such that $P_x > P'_x \leftrightarrow V(P_x) > V(P'_x)$, where P is equal to a set of criteria to be evaluated for alternative x. The problem consists of generating a non-dimensional value function $V(P_x)$, that, integrating all the criteria $P_x = (P_{1,x}; P_{2,x}; \ldots; P_{N,x})$, reflects the preferences of the decision maker for each alternative. The solution is a function V, that is the sum of N value functions V_i corresponding to the N criteria, which comply with $V_i{:}P \rightarrow R$ such that $P_{1,x} > P'_{i,x} \leftrightarrow V_i(P_{i,x}) > V_i(P'_{i,x})$. For the case of problems structured in the form of a requirements tree, the resulting V function takes the form Equation 6-9.

$$V\left(P_x\right) = \sum_{i=1}^{i=N} \alpha_i \cdot \beta_i \cdot \gamma_i \cdot V_i\left(P_{i,x}\right) \quad (6\text{-}9)$$

In Equation 6-9, $V(P_x)$ measures the degree of sustainability (value or satisfaction) for the alternative x that is evaluated, with respect to the various criteria $P_x = (P_{1,x}; P_{2,x}; \ldots; P_{N,x})$; α_i and β_i are the weights of the criteria and sub-criteria to which each criteria i belongs; γ_i being the weights of the different indicators; $V_i(P_{i,x})$ are the value functions used to measure the degree of sustainability for alternative x with respect to a given criterion i; and, finally, N is the total number of criteria that are taken into account. Weights α_i, β_i, and γ_i are factors that represent the preference, respectively, of certain indicator (γ_i), sub-criterion (β_i), and criterion (α_i).

The V_i functions must meet certain requirements. Their main objective is to homogenize the criteria units, but it is also highly recommended to limit the values that these functions can generate. In this way, all the criteria have one single scale of assessment, normally between 0 and 1. These values represent the minimum and maximum degree of sustainability, respectively. It also makes it easier to obtain these weights (α_i, β_i, and γ_i) since by using these only is necessary to establish the relative priority of certain criteria, sub-criteria, or indicator with respect to the others, regardless of whether some may present different scales of quantification.

Once the value functions have been defined, it is necessary to estimate weights α_i, β_i, and γ_i for each branch of the requirements tree (step 4). To this end, numerical values established by experts can be considered. Sometimes trees are excessively complex, or discrepancies occur among the experts, or, simply, it is desirable to carry out an organized process to avoid difficulties in establishing those weights. In these situations, the analytic hierarchy process (AHP)2-3 may be used. Afterward, to compensate for possible subjective bias, a subsequent process of analyzing, comparing, and – if appropriate – modifying the resultant weights is recommended.

The definition of the potential alternatives *x* – in case of several existing to be compared – are defined in the step 5. The sustainability index of each alternative is evaluated by using Equation 1 in the step 6. Finally, in step 7, those stakeholders involved in the decision-making process should choose the alternative that best meets all the requirements. This does not necessarily mean that the alternative with the highest sustainability index is finally selected since there may be other alternatives that generate sufficiently high degree of satisfaction; and possibly meeting various other requirements, such as functional ones. However, with more comprehensive future models, the alternative with the highest sustainability index must be the one selected.

6.4.3 Value Functions

Defining the value function implies establish preferences or the degree of satisfaction produced by a certain alternative option for a certain variable (indicator). Each variable may be given in different units; therefore, it is necessary to standardise these into units or satisfaction, which is basically what the value function does. The method allows rating satisfaction on a scale from 0.0 to 1.0, where 0.0 is the minimum satisfaction (P_{min}) and 1.0 the maximum (P_{max}).

To determine the satisfaction value for an indicator, the MIVES model[52-55] outlines a procedure consisting of:

Stage 1. Definition of the tendency (increase or decrease) of the value function.

Stage 2. Definition of the points corresponding to P_{min} and P_{max}.

Stage 3. Definition of the shape of the value functions (linear, concave, convex, S-shaped).

Stage 4. Definition of the mathematical expression of the value function.

6.4.3.1 Stage 1: Definition of the tendency of the value function (Increasing/Decreasing)

The value function (Figure 6-8) can be increasing or decreasing depending on the nature of the indicator (or measurement variable) to be evaluated. An increasing function is used when an increase in the measurement variable results in an increase in the decision maker's satisfaction. In contrast, a decreasing value function shows that an increase in the measurement unit causes a decrease in satisfaction.

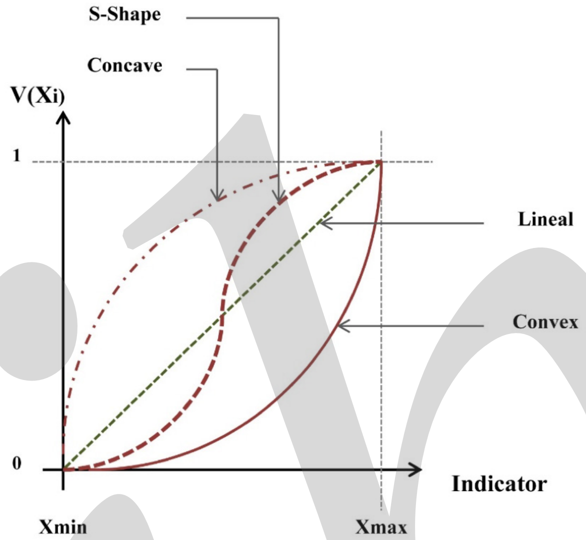


Fig. 6-8 Different value function shapes

Examples of indicators with a decreasing tendency as applied to precast concrete technology include economic cost, time of execution or emissions to the environment. Examples of this type of indicator with an increasing tendency would be those that reflect the degree of adaptability to the surroundings, the flexibility of different elements or components of the precast elements. Defining the different indicators and the corresponding assessment and quantification will naturally vary in difficulty depending on the case.

Other value functions will have a mixed tendency, that is, functions that increase at first but later decrease. This type of function is characteristic of indicators with two points of minimum satisfaction and one maximum in between, as explained in the following section.

6.4.3.2 Stage 2: Definition of the points of minimum (P_{min}) and maximum satisfaction (P_{max})

The points of minimum and maximum satisfaction define the limits of the value function on the x-axis: P_{min} and P_{max}, points of minim and maximum satisfaction, respectively. These points have a satisfaction value of 0.0 (P_{min}) and 1.0 (P_{max}). These limits correspond to the satisfaction values and not necessarily to the minimum and maximum values of the measurement variables, which may have (and will generally have) a wider range.

These points are usually established according to three criteria: (1) existing rules and regulations; (2) experience with previous projects, and (3) values produced by the different alternatives with respect to the indicator.

1. Rules and regulations. The measurement variables are regulated by existing standards and are therefore limited to the values given, or to the minimum and maximum values included within the interval defined by these. The limits defined according to this criterion are quite inflexible since they usually must be complied with. As an example, the minimum fire resistance time of a structure. In this case, the minimum satisfaction is located at the point of minimum fire resistance time established by the corresponding regulations and cannot be changed. In the majority of cases, only one limit (minimum or maximum) is defined (for example, minimum strength, maximum content). Sometimes, however, both limits (minimum and maximum) may exist (for instance in the case of temperature, see Figure 6-9).

2. Experience with previous projects. When information on measurement variables is not provided by rules and regulations, these values can be determined by experience, from historical data, from data found in the literature, or from data gathered in previous projects. The range of values is slightly more flexible than when complying with rules and regulations.

3. The value produced by the different alternatives with respect to an indicator. In this case, the limits of the value function are provided by the minimum and maximum values of the different alternatives with respect to an indicator. Consequently, if a new alternative appears, the limits of the function and the corresponding value of the indicators may change.

In the case of having alternatives that generate values for variables that fall outside the established limits, these can be disregarded if the minimum or maximum values cannot be surpassed (for example if these correspond to regulatory limits) or, alternatively, the value of the limit surpassed (0.0 or 1.0) can be assigned to these. Choosing one option over another clearly depends on the variable considered.

If there are two points of minimum satisfaction and only one maximum, as shown in Figure 6-9 (where the indicator corresponds to the comfort temperature), it is necessary to adjust the limiting values with respect to the best or most satisfactory value (for instance, the distance to optimum instead of the actual value of the variable) in order to have a continuously increasing or decreasing relationship.

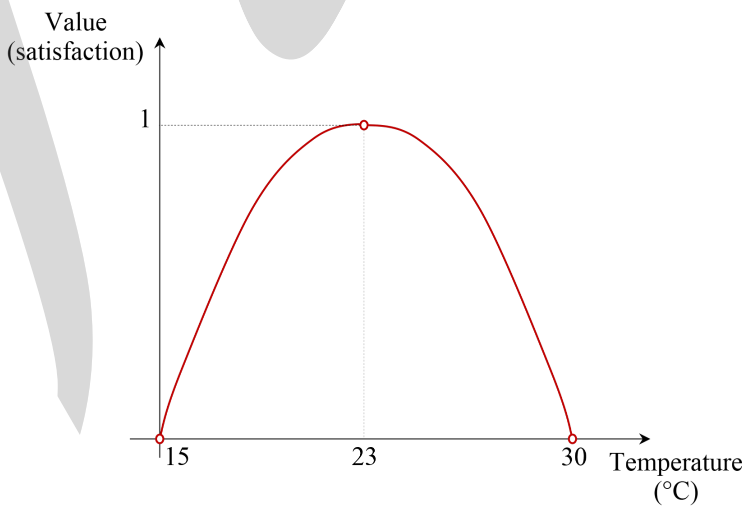


Fig. 6-9 Function with two minimum points and only one maximum

6.4.3.3 Stage 3: Definition of the value function shape (linear, concave, convex, S-shaped)

A concave curve is used when, starting from a minimum condition, satisfaction rapidly increases at first in relation to the indicator. In this case, small changes around the point that generates minimum satisfaction are highly valuated. This type of relationship is chosen when it is more important to move away from the point of minimum satisfaction than to approach the point of maximum satisfaction. It is also used when the majority of alternatives are close to the point of minimum satisfaction. In this case, discrimination between alternatives is better and the incentive for higher improvement.

A convex function is appropriate when there is hardly any increase in satisfaction for small changes around the point that generates minimum satisfaction. In contrast to the previous case, this type of relationship is selected when it is more important to approach the point of maximum satisfaction than to move away from the point of minimum satisfaction. This type of function is often used for economic or environmental indicators since the aim is to ensure that the alternatives are located as close to the point of maximum satisfaction as possible. It is also used when the majority of alternatives are close to the point of maximum satisfaction. In this case, as in the previous one, the discrimination of alternatives is better and the incentive for higher improvement.

A linear function reflects a steady increase in the satisfaction produced by the alternatives. There is a proportional relationship throughout the range. This function is the default option when no specific criteria can be defined.

S-shaped function is a combination of the concave and convex functions. A significant increase in satisfaction is detected at central values, while satisfaction changes little as the minimum and maximum points are approached. This type of relationship can be chosen when the majority of alternatives are concentrated into a middle range between the points of minimum and maximum satisfaction. In this case, as in the cases of concave and convex curves, the discrimination of alternatives is better and the incentive for higher improvement.

MIVES uses Equation 6-10 as the basis for defining individual value functions V_i.

$$V_i = K_i \left[1 - e^{-m_i \left(\left| P_{i,x} - P_{i,\min} \right| / n_i \right)^{A_i}} \right] \tag{6-10}$$

In Equation 6-10, variable K_i is a factor that ensures that the value function will remain within the range of [0.0-1.0] and that the best response is associated with a value equal to the unit (see Equation 6-11).

$$K_i = \frac{1}{1 - e^{-m_i \left(\left| P_{i,\max} - P_{i,\min} \right| / n_i \right)^{A_i}}} \tag{6-11}$$

In Equations 6-10 and 6-11:

4. $P_{i,max}$ and $P_{i,min}$ are the maximum and minimum points in the scale of the indicator under consideration.

5. $P_{i,x}$ is the score of alternative *x* that is under assessment, with respect to indicator i under consideration, which is between $P_{i,min}$ and $P_{i,max}$. This score generates a value that is equal to $V_i(P_{i,x})$, which has to be calculated.

6. A_i is the shape factor that defines approximately, in this case, whether the curve is concave ($A_i < 1.0$), whether it tends to be a straight line ($A_i \approx 1.0$), or whether it is convex or S-shaped ($A_i > 1.0$). This field will be covered in the next section
7. n_i is the value that is used, if $A_i > 1.0$, to build convex or S-shaped curves as it coincides approximately with the value of the abscissa on which the inflection point occurs.
8. m_i defines the value of the ordinate for point ni, in the former case where $A_i > 1.0$.

The geometry of the functions V_i allows to establish greater or lesser exigency when complying with the requisites needed to satisfy a given criterion. For example, convex functions experience a great increase in value for scores that are close to the minimum value, and the increase in value diminishes as the score approaches the maximum. This type of low demand function is used when one wishes to encourage compliance with minimum requirements. The latter may be the case, for instance, with sufficiently exacting standards in which mere compliance is highly satisfactory. Another instance may be when the aim is to reward the use of new technologies, and their implementation is seen as very positive (even when it is a partial or minor one), with a view to encouraging better practices. This is particularly the case, for instance, of using recycled aggregate.

It can be seen that the shape of the function depends on the values that the parameters A_i, n_i and m_i take in each case. The interpretation of these parameters makes it easier to understand and use Equation 6-10. Table 6-2 gives some characteristic values of these parameters for the construction of different types of value functions. This is simply a rough guide as the parameters may vary according to the preferences of the decision maker. The final shape of the value function when specific values for A_i, A_i, n_i and m_i are introduced must always be checked in order to assure that it matches the desired relationship.

Table 6-2 Typical values of n_i, m_i and A_i

Increasing function		
$\boldsymbol{n_i}$	$\boldsymbol{m_i}$	$\boldsymbol{A_i}$
$n_i \approx P_{i,min}$	≈0.0	≈1.0
$P_{i,\min} + \frac{P_{i,\max} - P_{i,\min}}{2} < n_i < P_{i,\min}$	<0.5	>1.0
$P_{i,\min} < n_i < P_{i,\min} + \frac{P_{i,\max} - P_{i,\min}}{2}$	>0.5	<1.0
$P_{i,\min} + \frac{P_{i,\max} - P_{i,\min}}{5} < n_i < P_{i,\min} + \left(\frac{P_{i,\max} - P_{i,\min}}{2}\right)\frac{4}{5}$	0.2 - 0.8	>1.0

Increasing and decreasing function		
n_i	m_i	A_i
$n_i \approx P_{i,min}$	$\approx A_o$	≈1.0
$P_{i,\max} + \frac{P_{i,\min} - P_{i,\max}}{2} < n_i < P_{i,\max}$	<0.5	>1.0
$P_{i,\max} < n_i < P_{i,\max} + \frac{P_{i,\min} - P_{i,\max}}{2}$	>0.5	<1.0
$P_{i,\max} + \frac{P_{i,\min} - P_{i,\max}}{5} < n_i < P_{i,\max} + \left(\frac{P_{i,\min} - P_{i,\max}}{2}\right)\frac{4}{5}$	0.2 - 0.8	>1.0

When the specific shape of the value function for an indicator is unclear, it may be defined by a working group. When this is the case, several value functions (discrete or continuous) may initially be defined according to the proposals given by each or some of the members of the group for the measurement variable (indicator). This means that rather than a single function, a family of functions is obtained, as shown in Figure 6-10.

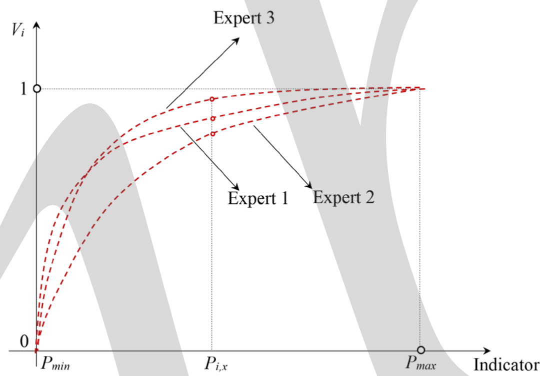


Fig. 6-10 Value function generated by a working group composed by different decision makers

According to Figure 6-10, several values on the y-axis (one for each initial value function) correspond to the value labeled $P_{i,x}$. As these values are obtained, it is necessary to establish another value that allows each alternative to be evaluated. The simplest way to do this is to take the mean of the different values (after excluding extreme cases, if needed). The parameters A_i, n_i and m_i can then be estimated through a minimum squares approach. It is also possible to work with a range of values in such a way that two values correspond to each y-value: the mean and the standard deviation. This would call for a statistical approach in the subsequent decision process.

6.5 Model for assessing sustainability of precast concrete products

6.5.1 Introduction

After a thorough review of the alternative existing methods it has been confirmed that, among the vast variety and typology of methods that already consider the three pillars of the sustainability, it is difficult to establish one procedure specific to precast concrete while, at the same time, flexible enough to be adapted to each particular analysis case. In this sense, it is necessary to propose an approach able to cover the sustainability assessment of any precast concrete member/product/structure including, besides the three sustainability pillars, the preferences and needs of all involved stakeholders.

To this end, MIVES has been adopted as a suitable tool to deal with the assessment of the sustainability index of precast concrete structures since this fits with the generality and flexibility required for this kind of analyses.

The importance of these parameters and the breakdown into other criteria and indicators has been taken into account for the specific case of precast structures. In this regard, for the Economic Requirement (R_1) the criteria are: (C_1) Total Costs, (C_2) Quality, (C_3) Dismantling and (C_4) Service Life; For the Environmental Requirement (R_2): (C_5) Consumption, (C_6) Emissions, and (C_7) Energy. Finally, for the Social Requirement, two criteria are considered: (C_8) Third Parties and (C_9) Health and Safety.

6.5.2 Requirements' tree

Various workshops were carried out in order to define the approach that the committee would propose as a sustainability assessment method for precast concrete structures. As a result, the requirements' tree presented in Table 6-3 has been established by the experts.

Table 6-3 Requirements' tree proposed to assess the sustainability index of precast concrete structures

Requirement	Criteria	Indicator	Units	Value Function
R_1 Economic (λ_{R1} = 35%)	C_1 Total Costs (λ_{C1} = 42%)	I_1 Direct and indirect costs (λ_{I1} = 100%)	€	DS
	C_2 Quality (λ_{C2} = 19%)	I_2 Non quality costs (λ_{I2} = 100%)	Attrib.	
	C_3 Dismantling (λ_{C3} = 9%)	I_3 Dismantling costs (λ_{I3} = 100%)	€	DS
	C_4 Service Life (λ_{C4} = 30%)	I_4 Service costs (λ_{I4} = 61%)		
		I_5 Resilience (λ_{I5} = 39%)		IS
R_2 Environmental (λ_{R2} = 38%)	C_5 Consumption (λ_{C5} = 44%)	I_6 Cement (λ_{I6} = 22%)	Ton	DS
		I_7 Aggregates (λ_{I7} = 21%)		
		I_8 Steel (λ_{I8} = 21%)		
		I_9 Water (λ_{I9} = 12%)		
		I_{10} Plastics and others (λ_{I10} = 10%)		
		I_{11} Reused materials (λ_{I11} = 14%)		IS
	C_6 Emissions (λ_{C6} = 32%)	I_{12} CO_2 emissions (λ_{I12} = 62%)	$TnCO_2$-eq	DS
		I_{13} Total waste (λ_{I13} = 38%)	Ton	
	C_7 Energy (λ_{C7} = 24%)	I_{14} Materials (λ_{I14} = 37%)	MWh	
		I_{15} Construction (λ_{I15} = 26%)		
		I_{16} Service (λ_{I16} = 37%)		
R_3 Social (λ_{R3} = 26%)	C_8 Third parties (λ_{C8} = 37%)	I_{17} Comfort (λ_{I17} = 52%)	Attrib.	
		I_{18} Noise pollution (λ_{I18} =15%)	Db.	
		I_{19} Particles pollution (λ_{I19} = 20%)	Ton	
		I_{20} Traffic disturbances (λ_{I20} = 13%)	Attrib.	
	C_9 Health and Safety (λ_{C9} = 63%)	I_{21} Risks. Production (λ_{I21} = 23%)		
		I_{22} Risks. Construction (λ_{I22} = 23%)		
		I_{23} Risks. Service life (λ_{I23} = 55%)		

The requirements' tree presented in Table 6-3 gathers a total of 9 criteria (*C*) and 23 indicators (*I*) which were established as the most representative. From these elements, it can be noticed that:

1. The LCA embraces from cradle (from materials' extraction) to the end of life (including dismantling). In this sense, other time boundaries could be considered whenever these are more representative of the sustainability assessment to be carried out.

2. Increasing and decreasing value functions have been established. The particular forms of these functions (for example, S-shape, linear) were not fixed at this point so that future users of this method can decide the actual shape of individual value function depending on local sensitivities and priorities.

3. The units are fixed so as to allow measuring either a particular element (for example, panels, beams, columns) or the whole precast concrete structure. Attributes were established as a measurement systems for some cases; particularly for those depending on local standards (Health & Safety indicators, for instance) and those with a high statistical component (non-quality costs, which depend on the type of elements, materials used, structural configuration, transport and handling methods, among others).

6.5.3 Requirements' weights

A survey was distributed among the *fib* TG 6.3 members in order to establish the possible weights to be used in the requirements' tree (Table 6-3). A total of 12 weights' distributions were obtained and, from these, different statistical studies were carried out. In this regard, it must be highlighted that the weights gathered in Table 6-3 respond to the average values obtained from the survey.

Table 6.4 gathers the average, maximum and minimum values for the requirements' weights obtained from the statistical study. From these results, it can be noticed that the weight of the economic requirement (λ_{R1} = 35%) presents the narrower range of variation between minimum and maximum assigned values (30% to 40%) while the coefficient of variation is relatively high (23%). Contrarily, the environmental requirement weight resulted to be the higher (λ_{R2} = 38%) with also the higher coefficient of variation (33%). For the social requirement weight (λ_{R3} = 26%) the wider variation range (10% to 33%) was obtained.

Table 6-4 Statistical values of the requirements' weight derived from the survey distributed among the *fib* TG 6.3 members

	λ_{Rim}	CV_R	$\lambda_{Ri,min}$	$\lambda_{Ri,max}$
Economic (R_1)	35%	23%	30%	40%
Environmental (R_2)	38%	16%	33%	50%
Social (R_3)	26%	33%	10%	33%
Others (R_4)	0%	33%	10%	33%

These weights could be accepted as representative since various continents and countries are represented in the *fib* TG 6.3. However, as the proposed framework intends to be of general use, these might be modified according the stakeholder's preferences in relation with the economic, environmental and social requirements.

In terms of comparison with other sustainability or certification tools for buildings, Table 6-5 compares the weights' distribution proposed in these alternative sustainability assessment approaches.

Table 6-5 Weights' distributions for various sustainability/certification tools for buildings

	fib TG 6.3	LEED	BREAM	VERDE	DGNB	LEnSE	SBToolCZ	λ_{Rim}	CV_R	$\lambda_{Ri,min}$	$\lambda_{Ri,max}$
Economic (R_1)	35%	26%	16%	21%	33%	19%	15%	24%	34%	15%	35%
Environmental (R_2)	38%	46%	55%	53%	33%	44%	50%	46%	17%	33%	55%
Social (R_3)	26%	23%	20%	26%	33%	37%	35%	29%	22%	20%	37%
Others (R_4)	0%	5%	10%	0%	0%	0%	0%	2%	-	0%	10%

The data gathered in Table 6-5 reflects that the average value of the economic requirement weight, λ_{Rim}, would reduce to 24% respect to the 35% agreed in the *fib* TG 6.3 whilst the environmental requirement weight would increase up to 46% in contrast the 38% assumed in the *fib* committee. Finally, average values between 25% to 30% for the social requirement weight seems to be well-accepted.

It is important to note that the environmental sensitivity is highly independent of the assessment method since values ranging from 33% to 55%, with a coefficient of variation of 17%, have been found.

6.5.4 Assessment of Indicators

The assessment of the indicators is the most time-demanding task of this method if an accurate sustainability analysis is to be performed. In this respect, the examples presented in the next sections could be useful as guide on how to apply this method.

6.5.4.1 Economic Requirement (R_1)

The objective of this requirement consist in assessing the stakeholders' satisfaction in economic terms aspects considering the whole life cycle (construction to dismantling). This requirement embraces 5 indicators:

- C_1 Total costs. Represented by the sum of the direct and indirect costs (I_1) associated with the construction of the precast concrete structure. The satisfaction function considered is DS, which allows to take into account the increase of value when there is a reduction of the cost – whenever the technical requirements are fulfilled.

- C_2 Quality. Non quality costs (I_2) that can occur during production, transport and construction stages are considered in this indicator. To assess this indicator a representative data source is required, which is often not available. Alternatively, this indicator could be measured by using attributes and the experience of technicians.

- C_3 Dismantling. Dismantling costs (I_3) should include the costs associated with dismantling (or demolition), transport and recycling or dumping.

- C_4 Service Life. This criterion is represented by the service costs (I_4) expected to maintain the structure in proper condition, including maintenance, repairs and other anticipated engineering works. Likewise, this indicator must take into consideration the costs required to guarantee the proper living-operational conditions (for example, temperature, noise reductions) in case of buildings, for instance. The concept of resilience (I_5) is also included in these criteria.

6.5.4.2 Environmental Requirement (R_2)

The objective of this requirement consists of converting the environmental impact generated during the whole cycle into a satisfaction value. Three criteria are included in this requirement:

- C_5 Consumption. This criterion is meant to assess the impact related to the use of natural non-renewable sources to produce the construction materials: Cement (I_6), aggregates (I_7), steel (I_8), water (I_9) and plastics and petrol derivate materials (I_{10}). It should be highlighted that the total amount of water consumption is that involved for the production of the materials (extraction and manufacturing) and that used in the concrete dosage. The reuse of materials (I_{11}) is also considered in this criteria.

- C_6 Emissions. These emissions could be in gas form, measured by means of the CO_2 equivalent (I_{12}), or solid waste (I_{13}) involved from the extraction of the materials to the dismantling of the structure, including service life.

- C_7 Energy. This criterion aims at considering the energy consumed, as a source, for obtaining the construction materials (I_{14}), to carry out the construction (I_{15}) process and to develop the service (I_{16}) operations (for example, repair, maintenance, cooling, heating).

6.5.4.3 Social Requirement (R_3)

The goal of including this requirement consists of taking into account the satisfaction perceived for all those stakeholders involved from the construction phase to the service life of the structure. This requirement embraces seven indicators:

- C_8 Third parties. This criterion deals with aspects related to comfort (I_{17}), which is intended to measure the satisfaction degree of the final users of the structure. This comfort can consider thermal and visual comfort, and others variants. Likewise, this criteria is meant to include the interferences associated to noise (I_{18}) and particles (I_{19}) pollution and traffic disturbances during construction.

- C_9 Health and Safety. This criterion distinguishes between risks during production (I_{20}), during construction (I_{21}) and during service (I_{22}). These risks can be expressed in terms of probability if this information is available; however, the use of attributes used to be also a representative way to assess these indicators.

7. Case Studies

7.1 Buildings

7.1.1 Net zero buildings Kuopio and Järvenpää

7.1.1.1 Introduction

A zero energy building aims at compensating the building's energy use by renewable energy sources. A net zero energy approach is based on the annual balance between non-renewable energy use and onsite generated renewable energy supply. The amount of energy provided by onsite renewable energy sources is equal to the amount of non-renewable energy used by the building.

A nearly zero energy building refers to an energy efficient building whose energy demand is covered by a substantial amount of building-integrated or nearby produced renewable energy.

Two precast net zero apartment buildings were built in Finland, in Kuopio and in Järvenpää 2010 -2011, Fig. 7-1. The projects aim at showing the builder and occupant the benefits of very low energy demand and on-site renewable energy production. The yearly energy balance is measured as delivered non-renewable and supplied renewable energy. Thus, the focus is primarily in energy efficient system solutions that enable low delivered energy demand of a building. The window-to-wall ratio in this building is limited, which favours the energy efficiency.

Fig. 7-1 Net zero energy buildings in Järvenpää and Kuopio

7.1.1.2 Building systems

The net zero energy buildings in Kuopio and Järvenpää have basically the same architecture, structural, HVAC and energy supply systems. There are differences in room layout and service facilities. The Kuopio case is a student dormitory and Järvenpää case an elderly home (Fig. 7-1).

The buildings' properties are shown in Table 7-1. The buildings are total precast buildings. The main components are sandwich panels in exterior walls, hollow core slabs in floors, and load bearing partition walls.

As shown in Table 7-1, the precast components can have a wide variation of building properties. The present reference *U*-factor for an exterior wall in Finland is $U = 0.17$ W/m²K and for roof 0.09 W/m²K. Fig. 7-2 show different phases of construction.

Table 7-1 Building properties and systems

Building information		
Net volume, m³	5,367	190,000 ft³
Net floor area, m²	1,945	21,000 ft²
Structures W/m²K		
Exterior wall (concrete sandwich panel)	0.08	0.01 BTU/hr-ft²-ºF
Roof (hollow core slab)	0.07	0.01 BTU/hr-ft²-ºF
Floor (cast in situ concrete)	0.10	0.02 BTU/hr-ft²-ºF
Intermediate floor (hollow core slab)		
Windows	0.76	0.13 BTU/hr-ft²-ºF
Doors	0.74	0.13 BTU/hr-ft²-ºF
Airtightness n_{50}, 1/h (measured)	0.40	0.07 BTU/hr-ft²-ºF
Systems and equipment		
All equipment energy classified: A++		
Low-energy / LED lighting		
Low electricity demand of all HVAC equipment		
Water saving fixtures, low pipe pressure, metering		
Energy recovery from lifts		
Solar thermal system		
PV-system		
Solar shading		

Renewable energy systems in the buildings include: PV system (Fig. 7-3a); solar thermal collectors (Figs. 7-3a and 7-3b); ground source preheating and precooling of supply air (Fig. 7-3d) and energy recovery (brake energy) from lifts converted to electricity.

7.1.1.3 Energy balance

Table 7-2 shows energy balance of the Järvenpää building. According to balance year 2014, the building produces renewable energy more than non-renewable energy delivered to the building (Fig. 7-2).

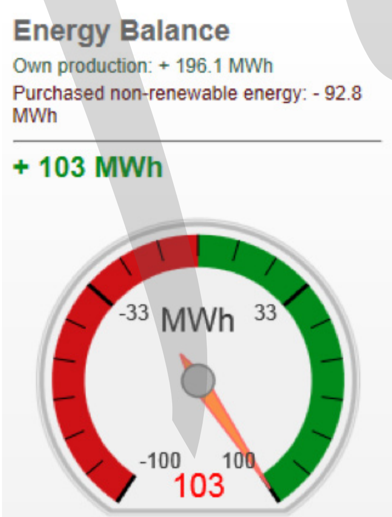
7.1.1.4 Life cycle costs

The extra costs due to energy efficiency and renewable energy systems of the Järvenpää case are roughly 400 €/m² (37 €/ft²) or 15% higher than typical new corresponding buildings. The extra costs due to energy efficiency and renewable energy systems of the

Järvenpää case are at this stage higher than with a typical building but the estimated extra costs are expected to be within 10% of same order of magnitude in the near future. The pilot buildings were financed with a long-term interest subsidized loan for social housing. The analysis of the case shows that, if the building can sell energy to neighbouring buildings, the total impact of the costs of operation on occupants' rent is lower than with, for example, passive buildings built with the same financing incentives, Fig. 7-4.

Fig. 7-2 Construction phases of the Järvenpää net zero energy building: (a) Foundations; (b) floor and intermediate walls; (c) sandwich panels and (d) Roof under construction (nollaenergia.fi)

Table 7-2 Energy balance of the Järvenpää net zero energy building (nollaenergia.fi)

Net balance	Energy efficiency KPI's	**MWh/2014**
	Energy produced, total	196
	Solar heating	46
	Geothermal, heating	106
	Geothermal cooling	35
	PV	8
	Lift braking energy	1
	Purchased energy, total	167
	District heating (renewable)	74
	Electricity (non-renewable)	93
	Energy consumption, total	217
	Total electricity	102
	Hot water	50
	Space heating	65
	Sold energy, total	87
	Heat	87
	Electricity	0

Note: 1 MWh = 3.4 million BTU.

Fig. 7-3 (a) Solar PV; (b) solar thermal system; (c) thermal storages and (d) preheating/precooling system (nollaenergia.fi)

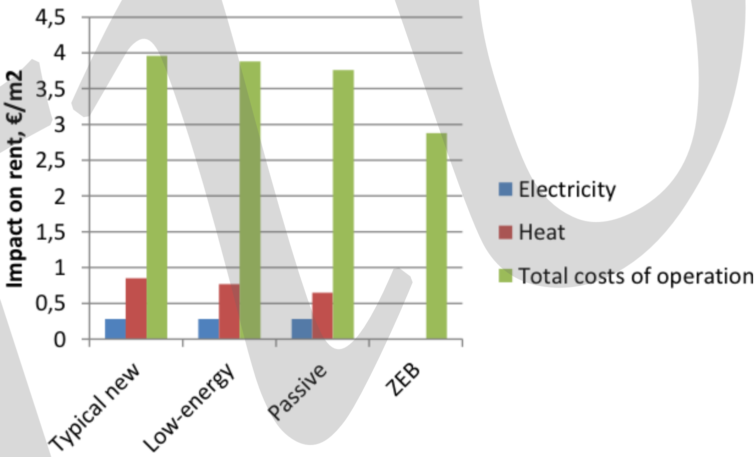


Fig. 7-4 Impact of energy costs on maintenance and administrative costs based rent (Mestariasunnot Oy). Note: 1 €/m² = 0.093 €/ft².

A good thermal insulation is beneficial in all climates. Table 7-3 shows a life cycle cost (LCC) comparison of the same building built in Järvenpää and in Dubai, U.A.E. The Dubai building is adjusted to the climate conditions introducing better thermal insulation than required in the Dubai Green Building Code 2014. The energy price in Dubai is calculated according to the energy demand[1]. Construction cost of the reference building follows the higher limit value of construction costs in Dubai[2]. The extra costs of the zero energy concept is in both cases 10%. It was considered that the building requires system renewal after 20 years of use. Two different interest rates, namely 1% and 3%, were assumed in the calculations. The renewal costs given in the Table 7-3 are included due to different technologies implemented in the design (Fig. 7-4).

Table 7-3 Life cycle costs of the net zero energy building

	Järvenpää, 1000 €		Dubai, 1000 AED	
	Typical	nZEB	Typical	nZEB
Investment[1]	5,512	6,063	10,574	13,217
Heating /year	16.9	0	0	0
Electricity / year[2]	14.3	7.1	217	55
Renewal (20 years)	25	80	20	400
LCC (30 years) 3%	6,327	6,199	16,243	14,870
LCC (30 years) 1%	6,625	6,227	18,306	15,497

7.1.1.5 Summary

The life cycle performance of the buildings is largely based on the cost efficiency of the building structures. The cost of PV systems has, for example, come down by about 30% in the years after construction. However, the aim to build zero energy, net zero energy or nearly zero energy building will increase the costs of heating, ventilation, air-conditioning and building automation costs when compared to those typical of existing buildings. Increasing thermal insulation level will also increase the cost of the building envelope structures but the cost increase is low with concrete sandwich panels. The described approach for mould growth analysis can be used for performance assessment of building structures in any climate. Thus precast concrete structures are arguably a valuable cost efficient choice for energy efficient buildings. The solutions allow for flexibility in design where long spans are required.

7.1.2 The use of high strength concrete

7.1.2.1 Introduction

Current models of social, economic and industrial development, based on the fast and growing consumption of natural resources, when mismanaged, could result in degradation and environmental pollution. According to Mehta & Monteiro[3], decision making approaches aiming to achieve results exclusively in the short term and simplistic goals are contributing to further aggravate the global situation.

On the other hand, in recent decades, there is a growing awareness of society with regard to the limitation of natural resources and the need to adopt practices with less environmental impact and the search for a development model that is more sustainable.

Sustainable development must act in three dimensions[4], as illustrated in Fig. 7-5:

1. Environmental: in order to find a balance between protecting the physical environment and its resources and use these resources so that the planet continue to provide an acceptable quality of life for human being;

2. Economic: requiring the development of an economic system that facilitates access to resources and opportunities, promoting prosperity within what is environmentally possible and without violating basic human rights;

3. Social: seeking the development of fair societies that allow human development and ensure opportunities for personal improvement and acceptable quality of life.

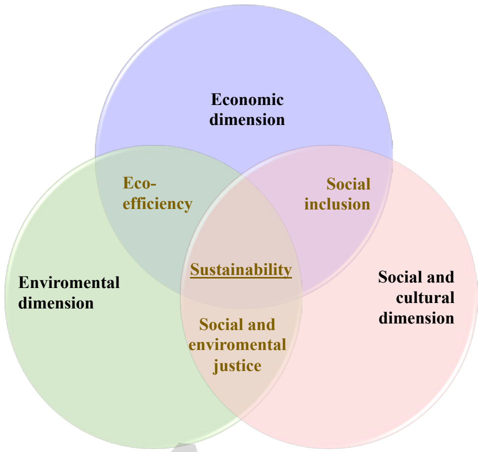


Fig. 7-5 Sustainability dimensions (translated from Elkington[5])

In the construction industry, a sector that, according to Valdés[6], employs 7% of the world population, uses 2/5 of all energy produced in the world and consumes 50% of the natural resources of the earth's crust, concrete is the material that occupies the most prominent position, being the manufactured product most used by society, with current global consumption estimated at 19 billion tons per year[7]. The authors emphasize that, with the exception of water, there is no other material consumed in such quantity per capita.

Therefore, the study of concrete in the context of sustainable construction becomes every day more crucial. This design example retrieves the concepts of environmental management and proposes the observation of new sustainability criteria in the design and construction of reinforced concrete structures, employing, paradoxically, high strength concrete with high cement consumption.

This example is part of document published the proceedings of the Second International Conference on Concrete Sustainability (ICCS 16) held in Madrid during the 13th-15th of June 2016[8].

7.1.2.2 Environmental management

When the chase for economic development started to seriously jeopardize ecosystems and human health through pollution and natural resources depletion, the issue of sustainability has surfaced. Since then, several conferences focusing on this topic took place in order to draw prescriptive standards up, starting in 1992 with the RIO-92 Conference.

In response to this global demand for a more reliable, aware and fair environmental management, the Technical Committee 207 for ISO (TC 207), in 1994, developed the ISO 14000 series of standards, which proposed the concept of Life Cycle Assessment – LCA. This concept involves analyzing and determining the environmental impacts of products or services at all stages of their life cycle: acquisition of raw materials, production, use and after-use treatment, recycling, until final disposal of this product or waste resulting from service.

Through the Life Cycle Assessment it is also possible to produce Environmental Product Declarations (EPDs), which are considered one of the best and most complete references of sustainability today.

As anticipated in the literature review of this Bulletin, the EN 15804:2012 establishes three types of EPD, described below, based on the life cycle stages covered in the study of each product or service (Fig. 7-6):

1. cradle to gate: mandatory, only comprehends the production stage (supply of materials, transportation, manufacturing and associated processes);

2. cradle to gate with options: optional, comprehends the stage of production and other additional stages, chosen by the product or service provider;

3. cradle to grave: optional, involves production processes, installation, use, maintenance, repair or replacement, demolition, treatment for reuse, reconstruction, recycling and final disposal, considered the most correct option but more laborious analysis.

Yet, according to EN 15804:2012[9], environmental impact indicators, quantified in different categories at each stage of EPDs, involve the analysis of the following parameters:

1. global warming potential, in kg of CO_2 equivalent;
2. the stratospheric ozone layer depletion potential, in kg of equivalent CFC 11;
3. ground and water acidification potential, in kg of equivalent SO_2;
4. eutrophication potential, in kg of $(PO_4)^{3-}$ equivalent;
5. tropospheric ozone formation potential, in kg of equivalent ethylene;
6. abiotic resources (elements) depletion potential, in kg of equivalent Sb;
7. abiotic resources (fossil fuel) depletion potential, in MJ.

In addition to these indicators of environmental impact, the same standard also sets parameters describing the use of natural resources (renewable or not), energy and water.

The EPDs are valid for 5 years and after this period, must be reviewed and verified. It is not necessary to recalculate them if the underlying information does not present substantial changes. If any of the environmental impact indicators suffer change of at least 10% (for more or less), the EPD should be updated.

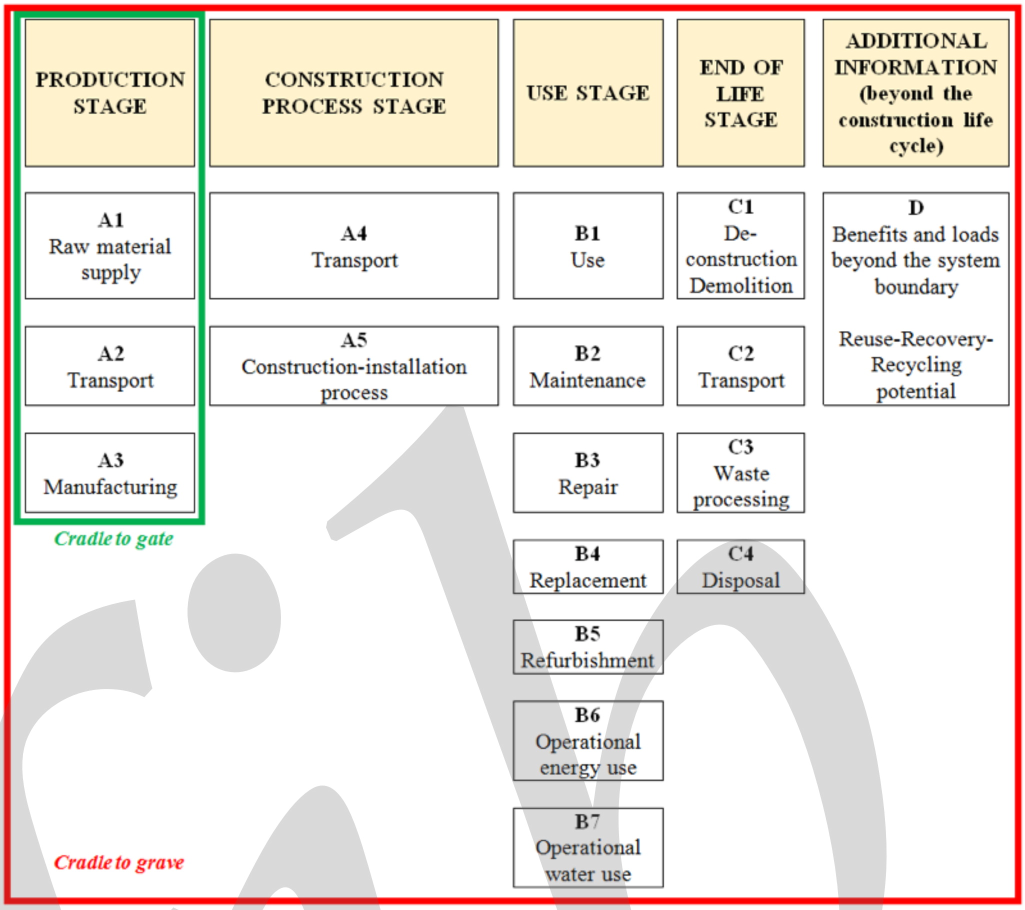


Fig. 7-6 Stages of the life cycle of a product or service (adapted from EN 15804:2012[9])

Also in the context of sustainable buildings, various international organizations, aiming to encourage this construction segment, created certifications to enhance and guide the transformation of conventional projects in environmentally friendly projects. Among these certifications, described in more details in the previous sessions, can be highlighted the LEED (Leadership in Energy and Environmental Design), Casa Azul Seal (Brazilian certification system developed by Caixa Econômica Federal), HQE (Haute Qualité Environmentale), BREEAM (Building Research Establishment Environmental Assessment Method) and DGNB (German Sustainable Building Council).

However, the evaluation criteria of the certifications, mistakenly, do not contemplate the use of high-strength concrete in the positive composition of the scores.

Although it seems a paradox, throughout this design example, the many advantages involved in the adoption of this type of concrete will be presented, aiming to support the proposal for its inclusion in certification systems.

7.1.2.3 Sustainable concrete?

As already discussed, concrete is the building material widely used worldwide, mainly due to its resistance, flexibility, durability, easy implementation and low cost. However, as with any other product to be used in construction, the production of concrete and its components (especially cement) requires energy, consumes water and results in CO_2 generation[10].

According to a study[11], cement production consumes 5.5 GJ energy and releases around of 1 ton of CO_2 per ton of clinker. Another study[12] points out that cement production is responsible for about 6% to 7% of total CO_2 emissions in the world. Brazil, with an annual production of 40 million tons of cement and about 16 million tons of clinker, contributes with about 1% to 2% of total carbon emissions in Brazil.

The environmental impact of the concrete, however, is not caused only by the cement. For the production of concrete, materials and non-renewable natural resources such as sand and gravel are also used, approaching the amount of consumption of 12 billion tons annually. Considering the impact of exploration, processing and transport of this raw material, it is observed that all specific concrete manufacturing processes seem to adversely affect the environment[13], although it is essential for the improvement of human life quality through building houses, bridges, roads, viaducts, harbors, water and wastewater treatment plants, schools, and hospitals.

The concrete industry also uses large amounts of potable water, about 1 trillion liters each year, just as concrete water content, to which are added large portions of wash water for concrete mixers and equipment and curing water of the concrete[14].

Thus, in order to reduce the consumption of potable water, natural resources and energy, reducing environmental impact, there is a need to consider the service life, durability and strength of concrete structures, taking into account the long-term (more than 50 years) of constructions in concrete.

However, according to EN 15804:2012[15], only the cradle to gate life-cycle assessment is currently recommended and even required in certain circumstances. Therefore, the concrete service companies, for example, are concentrating on accomplishing it, discouraging, mistakenly, the use of high-strength concrete. Corresponding to this erroneous view, the environmental impacts exposed in Table 7-4 refer only to the production of ready-mix concrete.

Table 7-4a. Environmental impacts for 1.0 m³ of ready-mixed concrete produced by concrete services company Allied Concrete[16]

Parameter	**Impact/m³**						
Compressive strength (MPa)	**20**	**25**	**30**	**35**	**40**	**45**	**50**
Global warming potential (kg CO_2 eq.)	333	366	395	445	513	539	609
Stratospheric ozone layer depletion potential (kg CFC 11 eq. 10^{-5})	1.10	1.19	1.26	1.39	1.57	1.56	1.83
Ground and water acidification potential (kg SO_2 eq.)	1.42	1.56	1.68	1.89	2.18	2.29	2.60
Eutrophication potential (kg $(PO_4)^{3-}$ eq.)	0.339	0.372	0.402	0.451	0.519	0.548	0.620
Tropospheric ozone formation potential (kg ethylene eq.)	0.069	0.076	0.082	0.092	0.106	0.112	0.127
Potential depletion of non-fossil resources (kg Sb eq.$\cdot 10^{-4}$)	1.10	1.18	1.25	1.41	1.44	1.49	1.83
Potential depletion of fossil resources (MJ)	3080	3390	3650	4090	4700	4900	5570

Table 7-4b Environmental impacts for 1.0 cu.yd of ready-mixed concrete produced by concrete services company Allied Concrete[17]

Parameter	Impact/yd³						
Compressive strength (psi)	**2,900**	**3,600**	**4,400**	**5,000**	**5,800**	**6,500**	**7,300**
Global warming potential (lb CO_2 eq.)	559	615	664	445	748	906	1023
Stratospheric ozone layer depletion potential (lb CFC 11 eq. 10^{-5})	1.60	2.00	2.13	2.34	2.64	2.62	3.07
Ground and water acidification potential (lb SO_2 eq.)	2.39	2.62	2.82	3.18	3.66	3.85	4.37
Eutrophication potential (lb $(PO_4)^{3-}$ eq.)	0.570	0.625	0.675	0.758	0.872	0.921	1.042
Tropospheric ozone formation potential (lb ethylene eq.)	0.116	0.128	0.138	0.155	0.178	0.188	0.213
Potential depletion of non-fossil resources (lb Sb eq.$\cdot 10^{-4}$)	1.85	1.98	2.10	2.37	2.42	2.50	3.07
Potential depletion of fossil resources (million BTU)	2.9	3.2	3.5	3.9	4.5	4.6	5.3

However, this incomplete and misplaced analysis does not reflected the overall environmental impacts of a concrete structure. Contrary to this view, a study[12] points out that high-performance concrete (HPC) has a more compact pore structure and, in its formulation, superplasticizers additives and mineral additions that react with the free lime and improve its strength. Thus, in these HPCs, the water/cement ratio is lower than in a conventional concrete, which increases their mechanical properties and durability.

The superior mechanical behavior of HPCs also allows significant reductions of structural sections, generating large cement, steel, water and aggregates economy, as well as possible economic gain by increase in useful areas for use, rental and parking on enterprises.

An important example of the application of this concept in Brazil is the colored HPC with f_{ck} 80 MPa (11,600 psi), used in e-Tower building in São Paulo, which enabled a significant reduction in the area occupied by columns in parking areas[18], as shown in Fig. 7-7.

This modification (reduction in the size of the columns) made the project compatible with the architectural requirements and made it possible to meet the criteria of a sustainable structure. Under the service life and sustainability point of view, one of the main deleterious mechanisms of a concrete structure is the corrosion of steel, a very unlikely phenomenon in structures built with high strength concrete.

All carbon steel is eternally protected by a high alkaline environment with a pH greater than 11.5. This fact is legitimately observed in the case of chloride free Portland cement concrete structures, since the hydration products of the curing reaction between the anhydrous grains of cement and water release large quantities of $Ca(OH)_2$, NaOH and KOH, which are strong bases[19], able to chemical and effectively protect steel from deleterious corrosion.

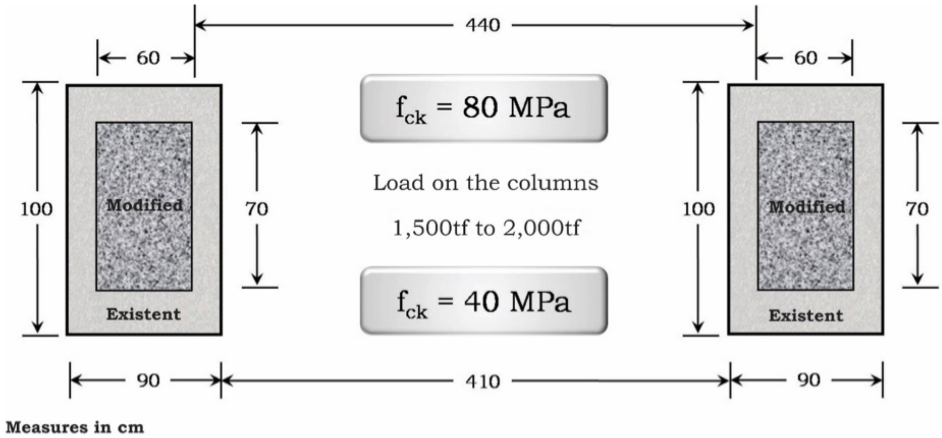


Fig. 7-7 Project design of the e-Tower: existing columns on the original design with 40MPa (5800 psi) f_{ck} (90x100 cm [35.4 in.·39.4 in.]) and modified columns with 80MPa (11,600 osi) f_{ck} (60·70 cm [23.6 in. ·27.6 in.])

This protection capability by passivation can be lost over time due to various actions of which the most important are the chloride penetration and the reaction of carbon dioxide CO_2 with the hydration products of these alkalis, resulting in low alkaline salts, a phenomenon known by carbonation of concrete.

With the increase in concrete strength, there is an important reduction of the risk associated with the reinforcement corrosion, given the high difficulty of aggressive agents' penetration. According to the study[12], with smaller and not connected pores, high strength concrete is less subject to the action of aggressive agents present in the atmosphere and water, which increases its durability and hence service life of the structure.

From the point of view of sustainable construction, some important parameters were achieved with this design change: increase of the service life, reduction of natural resources use, environmental impacts, energy and the total volume of the work concrete (even with a cement consumption per cubic metre of concrete top to the original design of concrete – with f_{ck} 40 MPa [5,800 psi]).

Specifically about the elevation of service life, some standardised values from[20] were adopted to illustrate the magnitude of the growth, as shown in Table 7-5, where it can be seen an increase of ten times on the service life of project.

Table 7-5 Data collected in the case study on the concrete pillars of the building and high strength-Tower, for the growth of life

Element	Design characteristic cover (1) (cm)	Carbonation constant adopted(2): kCO_2 (mm/ year $^{1/2}$)	Estimated design service life (years)
Structural column (90cm x 100cm) with f_{ck} = 40MPa	3.0	2.45	150
Structural column (60cm x 70cm) with f_{ck} = 80MPa	3.0	0.77	1500

(1) It was considered as the design characteristic cover within the tolerance of the NBR 6118:2014, i.e. the minimum admitted cover.

(2) This value was adopted depending on the Prática Recomendada do IBRACON only for the purpose of demonstrating that the structure service life increases tenfold when the concrete strength changes. It is noteworthy, however, that these coefficients were estimated.

Element	Design characteristic cover (1) (in.)	Carbonation constant adopted(2): kCO_2 (in./year $^{1/2}$)	Estimated design service life (years)
Structural column (35.4 in. x39.4 in.) with f_{ck} = 5,800 psi	1.18	0.096	150
Structural column (23.6 in. x27.6 in.) with f_{ck} = 11,600 psi	1.18	0.030	1,500

As for saving natural resources, it was found that there was a considerable reduction of all materials used in the concrete composition and design of columns with f_{ck} = 80 MPa (11,600 psi), compared to the f_{ck} = 40 MPa (5,800 psi). The volume of aggregates was reduced by 70%, while the cement in 20%, according to Table 7.6.

Table 7-6 Data collected in a study about e-Tower high-strength concrete columns, referring to the reductions of materials and concrete

Material	Reduction
Sand	70%
Gravel	70%
Cement	20%
Water	53%
Steel	43%
Formwork	31%
Concrete	53%

Confirming this view, other studies[21] showed that the design of buildings of 41 storeys with high strength concrete is advantageous, both from an economic and a sustainable point of view, when compared with those designed with conventional concrete. It was observed that it is possible to obtain a reduction of approximately 11% in the overall cost of the structure, changing the strength from a f_{ck} 25 MPa (3,600 psi) to a f_{ck} 50 MPa (7,300 psi).

So, with holistic and long-term vision, it is necessary to perform the concrete life cycle analysis taking into account the whole life cycle of this material and not only from the "cradle to gate".

A doctoral study[22] shows the importance of a holistic view, result of a cradle to grave analysis of a residential building hypothetically designed, consisting of eight floors and a ground floor type. In this study different strength classes f_{ck} of 25 MPa (3,600 psi), 30 MPa (4,400 psi), 35 MPa (5,100 psi), 40 MPa (5,800 psi), 45 MPa (6,500 psi), and 50 MPa (7,300 psi) were analyzed, as shown in Table 7-7.

This study considered the section reduction in two stages, in C35 and C45 concrete strength classes. It was concluded that, in this case, the strength class with less environmental impact would be the C40. Thereafter, increasing the load capacity would not result in a significant decrease of resistant section of flexed elements and it would not be advantageous for the loading determined initially.

Table 7-7 Overall balance of impact categories with results obtained for each structure strength[22]

Impact category	C25	C30	C35	C40	C45	C50
Eutrophication (g NO_3^-)	($2,33 \cdot 10^2$)	Larger ($2,43 \cdot 10^2$)	($2,15 \cdot 10^2$)	Minor ($2,09 \cdot 10^2$)	($2,10 \cdot 10^2$)	($2,13 \cdot 10^2$)
Photochemical ozone formation (g C_2H_4 eq.)	($4,03 \cdot 10^4$)	Larger ($4,10 \cdot 10^4$)	($3,83 \cdot 10^4$)	Minor ($3,55 \cdot 10^4$)	($3,61 \cdot 10^4$)	($3,72 \cdot 10^4$)
Consumption of material resources (kg)	Larger ($6,93 \cdot 10^2$)	($6,56 \cdot 10^2$)	($5,43 \cdot 10^2$)	($5,00 \cdot 10^2$)	Minor ($4,95 \cdot 10^2$)	($4,90 \cdot 10^2$)
Consumption of energy resources (kWh)	($4,20 \cdot 10^1$)	Larger ($4,30 \cdot 10^1$)	($4,01 \cdot 10^1$)	Minor ($2,17 \cdot 10^1$)	($2,20 \cdot 10^1$)	($2,26 \cdot 10^1$)
Ecotoxicity (m^3 compartment)	($2,54 \cdot 10^2$)	Larger ($2,64 \cdot 10^2$)	($2,20 \cdot 10^2$)	Minor ($2,10 \cdot 10^2$)	Minor ($2,10 \cdot 10^2$)	Minor ($2,10 \cdot 10^2$)
Global warming (g CO_2 eq.)	Larger ($6,75 \cdot 10^3$)	($6,67 \cdot 10^3$)	($6,12 \cdot 10^3$)	($5,74 \cdot 10^3$)	Minor ($5,71 \cdot 10^3$)	Medium ($5,67 \cdot 10^3$)
Human toxicity (m^3 compartment)	Larger ($1,80 \cdot 10^8$)	($1,78 \cdot 10^8$)	Minor ($1,68 \cdot 10^8$)	($1,76 \cdot 10^8$)	($1,76 \cdot 10^8$)	($1,76 \cdot 10^8$)
Acidification (g SO_2^- eq)	($9,52 \cdot 10^1$)	Larger ($1,00 \cdot 10^2$)	($9,19 \cdot 10^1$)	Minor ($8,90 \cdot 10^1$)	($9,03 \cdot 10^1$)	($9,23 \cdot 10^1$)
Waste (kg)	Larger ($2,30 \cdot 10^{-1}$)	Larger ($2,30 \cdot 10^{-1}$)	($1,90 \cdot 10^{-1}$)	($1,70 \cdot 10^{-1}$)	Minor ($1,68 \cdot 10^{-1}$)	Minor ($1,68 \cdot 10^{-1}$)

Impact category	3,600 psi	4,400 psi	5,100 psi	5,800 psi	6,500 psi	7,300 psi
Eutrophication (lb NO_3^-)	(0.51)	Larger (0.54)	(0.47)	Minor (0.46)	(0.46)	(0.47)
Photochemical ozone formation (lb C_2H_4 eq.)	(88.9)	Larger (90.4)	(84.4)	Minor (78.3)	(79.6)	(82.0)
Consumption of material resources (lb)	Larger (1528)	(1446)	(1197)	(1102)	Minor (1091)	(1080)
Consumption of energy resources (kWh)	(4.20)	Larger (4.,30)	(4.01)	Minor (2.17)	(2.20)	(2.26)
Ecotoxicity (ft^3 compartment)	(8970)	Larger (9323)	(7769)	Minor (7416)	Minor (7416)	Minor (7416)
Global warming (lb CO_2 eq.)	Larger (14.9)	(14.7)	(13.5)	(12.7)	Minor (12.6)	Medium (12.5)
Human toxicity (10^9 ft^3 compartment)	Larger (6.36)	(6.29)	Minor (5.93)	(6.22)	(6.22)	(6.22)
Acidification (lb SO_2^- eq)	(0.21)	Larger (0.22)	(0.20)	Minor (0.20)	(0.20)	(0.20)
Waste (lb)	Larger (0.51)	Larger (0.51)	(0.42)	(0.37)	Minor (0.37)	Minor (0.37)

Another study[23], on the construction of a bridge with lattice structure in prestressed concrete (work of art), also concluded that the ultra-high performance concrete (UHPC), with f_{ck} = 200 MPa (29,000 psi), proves to be much more sustainable than the conventional concrete, resulting in a lower consumption of raw materials and energy, as shown in Table 7-8.

Indeed, it is clear that the use of high performance concrete (counter-intuitively, given its higher cement consumption per cubic metre) brings significant advantages, not only with respect to mechanical properties, but also to environmental and sustainable aspects. However, as already explained, these benefits appear only in the long term and over a review of the service life of the material, when a full analysis ('cradle to grave' type) is performed.

Besides the importance of high resistance in reducing total input demand, it is also important to investigate the specific emissions by concreting service companies in m^3 of the product supplied. The concrete generally has CO_2 at around 7% to 15% of the produced concrete mass[24], depending on the designed proportions.

These values are closely related to the clinkering of used cement, the optimization of the production process of the plants and also the quantity of cement per m^3 calculated for the concrete mixes. Along with analysis of the total energy used for the entire structure, a proper study and the optimization of the inputs of the m^3 of concrete can also help to mitigate their environmental impact.

Table 7-8 Demand for materials (in tons) and energy (in MJ) for the construction of a bridge with lattice structure with conventional concrete and high performance concrete[25]

Material	**C25/C30**	**f_{ck} 200 MPa**
Cement	120	98
Aggregates	620	170
Water	60	21
Silica fume	-	18
Steel (passive reinforcement)	70	22
Steel Fibers	-	10
Steel (active reinforcement)	10	12
Total energy (MJ)	2,050,256	1,148,517

Material	**f_{ck} 3,600/4,400 psi**	**f_{ck} 29,000 psi**
Cement	132	108
Aggregates	683	187
Water	66	23
Silica fume	-	20
Steel (passive reinforcement)	77	24
Steel Fibers	-	11
Steel (active reinforcement)	11	13
Total energy (10^9 BTU)	1.94	1.09

In the case of a simplistic analysis of 1.0 m³ concrete alone, the environmental impact can be evaluated through the concept of yield, expressed by the ratio of compressive strength (MPa)/cement consumption (C_{cim}). The fact that the efficiency of a concrete is closely linked to the amount of cement required to achieve the desired strengths is evident. According to a study[26], the yield has a great peak for each concrete mix and must be studied through the dosage diagram, in order to obtain the most sustainable concrete, which must also be an economically viable solution.

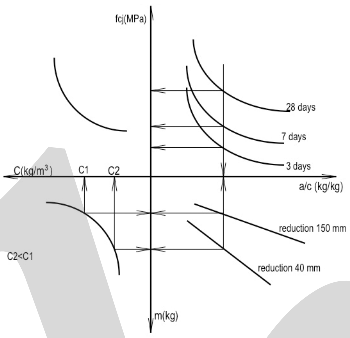


Fig. 7-8 Dosage diagram of Portland cement concrete[27]

That said, other studies[28] bring an assessment of the efficiency factor or concrete yield calculated for concrete with strengths between 20 MPa and 40 MPa, dosed according to IBRACON method (Table 7-9).

Table 7-9 Efficiency factor or concrete yield evaluation for different strengths (adapted from Boggio[28])

Strengths f_{c28} (MPa)	**Efficiency factor**	
	$f_{c28}/C_{cim}\left(\frac{MPa}{kg/m^3}\right)$	$C_{cim}/f_{c28}\left(\frac{kg/m^3}{MPa}\right)$
20	0,082	12,20
25	0,091	10,93
30	0,099	10,10
35	0,109	9,18
40	0,109	9,14
80*	0,174	5,75

* Data collected in the study of high strength concrete columns of e-Tower building.

Strengths f_{c28} (psi)	**Efficiency factor**	
	$f_{c28}/C_{cim}\left(\frac{psi}{lb/yd^3}\right)$	$C_{cim}/f_{c28}\left(\frac{lb/yd^3}{psi}\right)$
2,900	7.03	0.142
3,600	7.80	0.128
4,400	8.48	0.118
5,100	9.34	0.107
5,800	9.34	0.106
11,600*	14.91	0.067

Given the importance of concrete in the construction chain and in the development of a nation and given the benefits of high strength concrete employment, it is paradoxical to use consumption of cement as an environmental degradation index, because the correct approach would be to consider the entire construction life cycle with a global and holistic view, not only limited to the cement consumption of concrete.

7.1.2.4 Final considerations

As shown, even when having a higher consumption of cement per m^3, and hence, a larger amount of CO_2 emission per m^3, the reduction in the volume of concrete and a considerably increased service life justify the use of high strength concrete from the point of view of sustainability. As pointed out by another study[29], using materials with better physical and mechanical characteristics is a realistic means of achieving substantial advantages from the perspective of materials and energy savings, allowing, in the case of concrete, the preparation of designs with optimized sections, increased durability and strengths and, ultimately, the generation of less environmental impact. In this context, it is suggested that the use of high-strength concrete is included in the score evaluation of existing tools for sustainable construction, such as LEED, Casa Azul Seal, HQE, BREEAM and DGNB, considering that its (high-strength concrete) use provides high performance in environmental quality, productivity, global economy of materials and resources.

7.1.3 Reinforced concrete columns

7.1.3.1 Introduction

Columns are crucial elements for the mechanical functionality and safety of the vast majority of the buildings. In this regard, columns transmit loads from each floor to the floor below and down to the foundation components. Columns can total up to 25% of the concrete and steel consumption of a building. Therefore, these can significantly reduce a building's environmental impact by being designed and constructed with the optimum geometry, materials and construction process.

In this sense, this sustainability MIVES approach was designed to analyze different concrete technologies (self-compacting and/or high strength concrete) and geometries of the cross – section (circular and square). With these types of concrete it is possible to build columns with smaller cross-sections and higher load capacity. So, these allows consuming less material, reducing transversal section and achieving a more optimum profit in available edifice space. These types of concrete also increase the work performance with shorter construction timeframes. As a result, several social impact factors such as construction noises and transportation needs are reduced.

It must be highlighted that this specific MIVES model has been extensively described in a paper published in 2016 in the Sustainability with the title "The use of MIVES as a sustainability assessment MCDM method for architecture and civil engineering applications"[30].

7.1.3.2 Sustainability assessment MIVES for reinforced concrete building columns

Table 7-10 presents the most representative criteria and indicators to deal with the sustainability assessment of building columns according to the experts involved in the workshops carried out for this study case.

Table 7-10 Requirements tree, weights and value functions shapes for structural concrete columns

Requirements	Criteria	**Indicators and value function shape**
R_1. Economic (50%)	C_1. Construction costs (67%)	I_1. Building costs (85%, DS)
		I_2. Non acceptance costs (15%, IL)
	C_2. Efficiency (33%)	I_3. Maintenance (60%, DS)
		I_4. Habitability (40%, DCv)
R_2. Environmental (33%)	C_3. Emissions (67%)	I_5. CO_2 emissions (100%, DS)
	C_4. Resources consumption (33%)	I_6. Concrete consumption (90%, DCv)
		I_7. Steel consumption (10%, DCx)
R_3. Social (17%)	C_5. Negative effects (80%)	I_8. Workers' inconveniences (20%, DS)
		I_9. Workers' safety (80%, IL)
	C_6. Third parties (20%)	I_{10}. Environment nuisances (100%, IL)

Legend: weights are in percentage between brackets; value functions shapes: DCx stands for decrease convexly, DCv decrease concavely, DS decrease like an S, IL increase lineally.

In the economic requirement (R_1), four indicators were considered. I_1 evaluates construction costs (cost of formwork, concrete, steel, labour, auxiliary means and indirect costs) of the columns in €/m³. I_2 assesses the economic repercussion of nonconformities derived from quality problems, these assessed by assigning points. To assign these points, the following aspects were taken into account: incorrectly positioned reinforcement, incorrectly compacted concrete, liquid concrete loss between joints; these aspects are influenced by: execution control level (which is assumed intense), concrete workability and cross section shape. I_3 takes into account the maintenance cost over a ten year period in €/m³, considering f_{ck}, construction process and formwork typology. I_4 analyses habitability by comparing each column cross-section area and considering a theoretical common distribution of columns for all alternatives. Construction timeframes have not been considered as an isolated indicator but have been taken into account indirectly in I_1, I_8, I_9 and I_{10}.

The environmental requirement (R_2) assesses the environmental effects of each alternative construction process considering the phases comprised from the materials' extraction to construction, including this. I_5 considers CO_2 emissions per concrete volume (kg CO_2/m³). Materials' consumption (in kg) was considered within indicators I_6 and I_7 for a 3.0 m high column. Water consumption was not considered as a sole indicator because the maximum water consumption difference between column solutions was less than 3% of the total concrete process water consumption.

The social requirement (R_3) analyses each alternative's impact on society. I_8 compares workers' inconveniences depending on the noise exposure in dB, discarding vibrations, allergies and other less discriminatory indicators. I_9 studies workers' safety, which was analysed in a workshop by experts and was measured by assigning points. Worker job safety and exposure time were considered depending on the pouring concrete process, its consistency and the volume to be filled. I_{10} evaluates environmental nuisances according to noise produced and effects on sidewalk and street traffic; a points assigning system can also be used.

7.1.3.3 Reinforced concrete columns alternatives compared

The MIVES model presented in Table 7.10 has been used to assess the sustainability of several alternatives of in situ reinforced concrete columns for medium size buildings with a maximum of 6 levels and 500 m^2 (5,382 ft^2) per floor. These columns are 3.0 m (9 ft.-10 in.) high and distributed in a 6 · 6 m net (19 ft.-8 in. · 19 ft.-8 in. grid). These are subjected to moderate compression stresses and not have an excessive reinforcement ratio.

The alternatives differ (Table 7.11) in cross-section shapes (circular and rectangular), dimensions (Φ = 30 [11.8 in.], 35 [13.8 in.], and 50 cm [19.7 in.] and rectangles of 25·25 [9.8 in. · 9.8 in.], 30·30 [11.8 in. · 11.8 in.], and 40·40 cm^2 [15.7 in. ·15.7 in.])), concrete compressive strengths (25 [3,600 psi], 50 [7,300 psi], and 75 N/mm^2 [10,900 psi]) and vibrating process (normal vibration and self-compacting concrete).

7.1.3.4 Final considerations

As a result of this sustainability assessment, it can be concluded that the most sustainable columns are those with smaller cross-sections using high compressive strength concrete. Columns made of self-compacting concrete have a higher Sustainability Index (SI) than those vibrated; circular columns are more sustainable than those square or rectangular shaped due to aesthetic and functional reasons; circular columns have a higher index when using high performance concrete and having small cross-section areas while square and rectangular alternatives are more sustainable when using conventional concretes and having bigger cross-sections.

Table 7-11 Alternatives of columns assessed in this study case

Alternative	**Compressive strength (N/mm^2)**	**Cross-section (cm)**	**Vibration Process**	**Sustainability Index (SI)**
Circular 1	25	Ø 30	Self-compacting	0.56
Circular 2			Vibrated	0.56
Circular 3	50	Ø 35	Self-compacting	0.77
Circular 4			Vibrated	0.72
Circular 5	75	Ø 50	Self-compacting	0.85
Circular 6			Vibrated	0.89
Square 1	25	25 x 25	Self-compacting	0.62
Square 2			Vibrated	0.61
Square 3	50	30 x 30	Self-compacting	0.72
Square 4			Vibrated	0.66
Square 5	75	40 x 40	Self-compacting	0.77
Square 6			Vibrated	0.71

Note: 1 N/mm^2 = 145 psi; 1 cm = 0.394 in.

7.1.4 Temporary courthouse in Amsterdam - designed and built for reassembly

In the end of 2016 Building G of the Amsterdam temporary courthouse was completed and taken into use (Figure 7-9). Together with the existing towers E and F hereof it forms the temporary courthouse as a whole. Over the coming five years the larger part of the jurisdiction will take place in the new building. The courthouse is a temporary building because most of the existing courthouse will be demolished and rebuilt while in the meantime the court needs to continue its activities.

Fig. 7-9 Exterior and interior of temporary courthouse in Amsterdam. Photo credit Jannes Linders (ext.) and Léon van Woerkom (int.)

Building G was realised within a Design, Build, Maintain & Remove (DBMR)-assignment where development consortium DPCP, consisting of an architect and a contractor, is the owner and is responsible for the structure and materials over the whole lifespan of 50 years. This project was specifically aiming at preventing waste and maximizing the building's residual value after its initial period of use of 5 years. The building has therefore been designed with a well adaptable configuration, thus facilitating changing uses by changing users on changing locations in the future; the removal and the re-use are embedded in the contract.

When one has the responsibility not only for a proper realization, but also for what happens next, it is worthwhile to invest in quality materials, flexible solutions and well-considered processes. A standard developer will construct a building as cheap as possible in most of the cases, because he writes the whole building off financially in 10-15 years (Scenario 1 in Figure 7-10). The first idea in this project was to employ reused materials and building components in the building, e.g. cut out second-hand precast concrete hollow-core floors from an existing 90's building, make them demountable and apply in the new building. That way, the DPCP would have had about half of the lifespan under control (Scenario 3 in Figure 7-10). However, it was realised that it is more important to make the building function as a kit of parts, because then in such a way you can get good quality materials and make sure they are reusable afterwards (Scenario 4 in Figure 7-10).

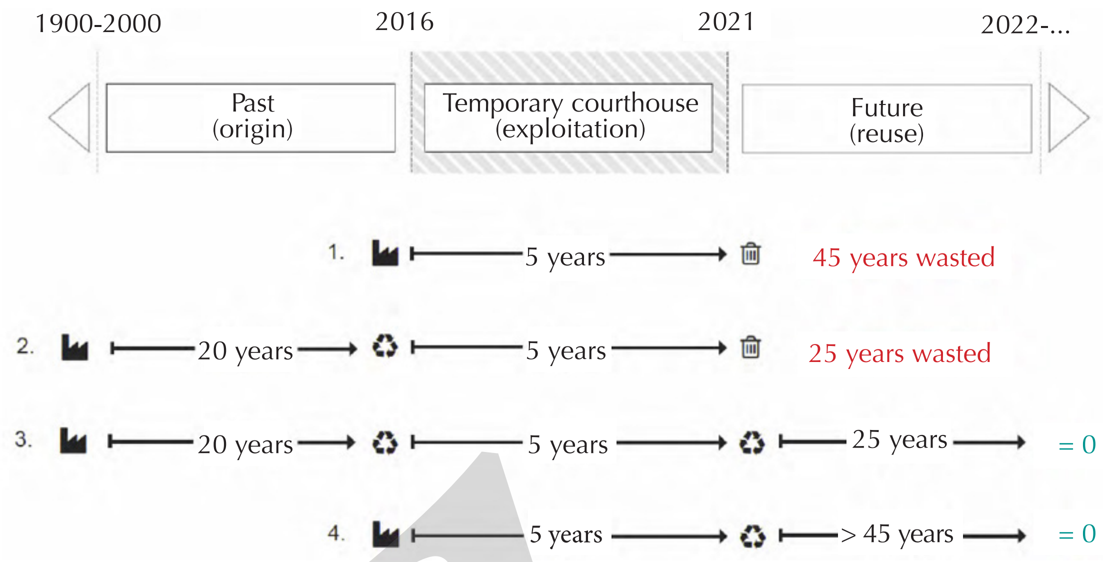


Fig. 7-10 Different scenarios of building use considered while developing the temporary courthouse in Amsterdam

In order to render the structure as customizable and circular as possible, it was designed as a kit of parts that can as easily be assembled and disassembled but also reassembled. For example, a special mounting system was developed for the precast concrete hollow-core floors that optimally facilitates the later decoupling and re-use of the slabs. The connections between the precast concrete hollow-core floors and the steel beams were made on site by opening up the slots in the hollow-core slabs, adding the steel anchors and casting them in concrete. For structural stability reason each slab ending has been provided with two anchors, i.e. one for vertical and one for horizontal fixation to the steel structure (Figure 7-11).

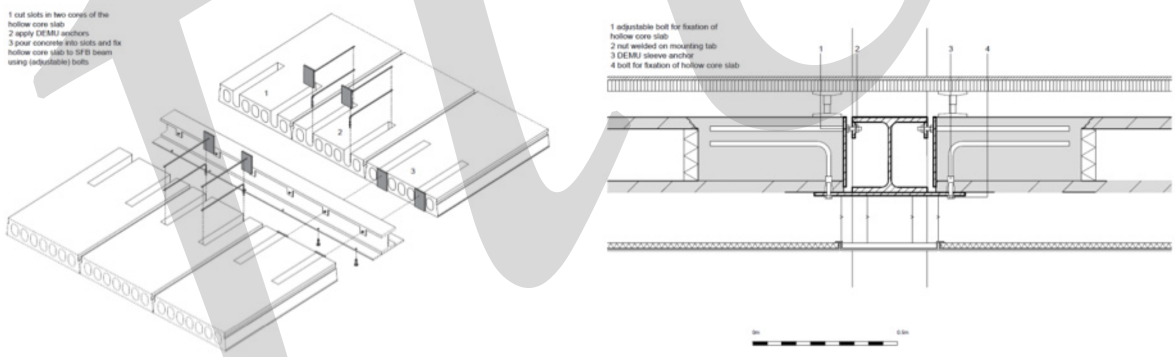


Fig. 7-11 Detail of hollow-core slab to beam joint

Here are some essential aspects considered and applied in this project:

- Setting up a clear plan with a standardisation in mind regarding floor heights, spans, loading etc. For example, columns are designed having a length of one floor height, so the four-storey building can be reconstructed as a three or two-storey building. Further, columns and girders can be reused at different locations during the building's second life. The floor designed having a load bearing capacity of 3,5 kN/m^2 (73 lb/ft^2) is suitable for many other different type of buildings.

- Focusing on the connections between the elements, making them flexible, ensuring there is enough tolerance to mount and demount them.
- Using dry connections, avoiding welded and wet connections as much as possible. For example in conventional buildings it is very common to have a cast in situ concrete topping on top of precast concrete hollow-core floors, which in case of buildings intended for reassembly should be avoided. If done well, with dry assembly and long spanning precast concrete structures a quick, cost efficient, demountable construction and great flexibility in use can be achieved. However, not many buildings will completely be demounted, but often parts will, such as the façades and the interiors. When working with a systemised, flexible kit of parts that are easily assembled and demounted, a much better building with a very high degree of usability can be achieved, because it can adapt quite easily to different functions.

In between the disassembly and reassembly the logistics play a significant role. All building elements must be disassembled and sorted in reverse order, with little or no possibility of temporary storage at the current site. For example, a total of 28 trucks with precast concrete hollow-core slabs have been delivered for this project, so much will have to be transported again. The building is currently designed in such a way that it is suitable for many other locations and purposes. There are different building layouts considered, including different placement of staircases and other vertical installations allowing constructive adjustments to take place during the second life of the building.

Temporary courthouse in Amsterdam - designed and built for reassembly
Project address: Parnassusweg 220, building G, 1076 AV Amsterdam, The Netherlands
Client: RVB
Developing consortium: DPCP
Taken into use / Official opening: October 2016 / November 2016

7.1.5 AGRO NRG office and storage building in Ootmarsum - designed and built for reassembly

AGRO NRG B.V., a supplier of photovoltaic and solar panels, expanded its office and storage building in Ootmarsum, The Netherlands, by using a steel column and beam structure in combination with a precast concrete hollow-core floor (Figure 7-12). The steel bearing structure and hollow-core floor was designed and built for reassembly, thus having a possibility to be reused in the future and in such a way reduce demolition waste to a minimum. Moreover, high sustainability requirements were set for the materials and the structure. A floor of 400 m^2 (4,300 ft^2) of CSC-certified (www.concretesustainabilitycouncil.org) hollow-core slabs was delivered embedding a high amount of secondary materials (>30%) and optimized concrete mix (Consolis VBI GreenScore) resulting in 5,5 tonnes [12,000 lb] of CO_2 reduction. Some slabs were produced using cementless geopolymer concrete.

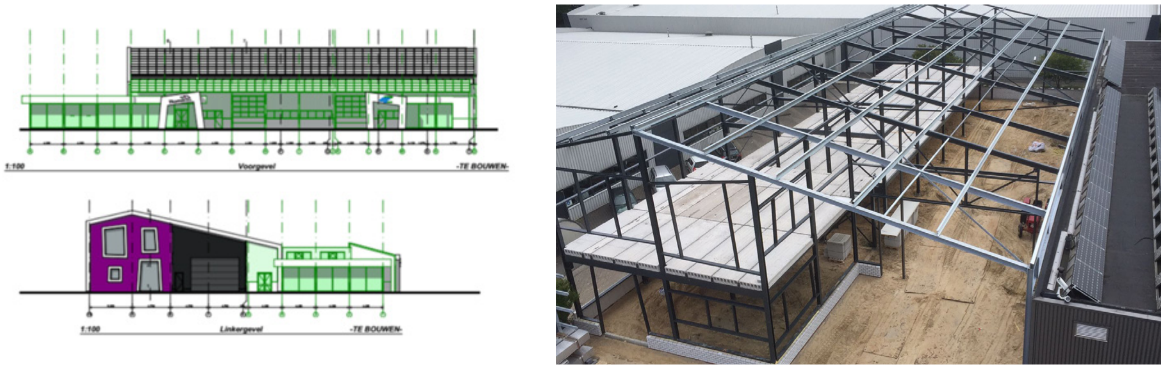


Fig. 7-12 AGRO NRG B.V. office and storage building in Ootmarsum

In general precast concrete is suitable for reassembly but there are some factors limiting the reuse, i.e. non-standard precast elements, recesses, on-site casted connections including structural concrete topping etc. Structural concrete topping is very commonly used in combination with hollow-core slabs ensuring a good diaphragm action by distributing horizontal loads equally within a floor field. But a structural concrete topping makes the reuse of hollow-core slabs more difficult. Therefore, in this project in order to ensure reusability of the hollow-core slabs, several preconditions were implemented during the design stage of the building following guidelines developed during a thesis[31]. The structural concrete topping was eliminated, and the slabs were standardized resulting in a minimum amount of recesses and narrow slabs (<1,2 m [4 ft]).

Moreover, to simplify the disassembly in the future the following adjustments were applied:

- Joints between the hollow-core slabs were filled with lower quality concrete mortar;
- Ends of hollow-core slabs were closed not with conventional core-plugs but with thin plates detaching them from the beams;
- Columns were split per each floor; and
- Unreinforced floor screed of 50 mm (2 in.) was applied, isolated with a foil from the hollow core floor.

Assembly of hollow-core slabs as well as details of hollow-core floor to beam joint in the middle and at the side of the building are showed in the following figures (Figure 7-13 and Figure 7-14).

Fig. 7-13 Detail of hollow-core floor to beam joint in the middle of the building and the floor field where hollow-core slab ends are closed with thin plates detaching them from the beams

Fig. 7-14 Detail of hollow-core floor to beam joint at the side of the building and implementation of the rebar in the joint between two hollow-core slabs

The stability of the building is ensured by the steel frame and hollow-core floor. As there is no structural topping, the diaphragm action was solved in a different way. The steel beams in the steel frame installed around the perimeter of the floor field act as ties. The steel beam ties are connected to the hollow-core floor field through the columns that act as dowels. In the column area the corners of the hollow-core slabs are implemented with recesses which are casted on site with concrete mortar. In the recess area thin plates are implemented around the columns positioning the concrete mortar in order to allow access to the bolted connections (Figure 7-15). This all together creates a diaphragm action. Forces are transferred through the floor to the columns and trusses, and then to the foundations.

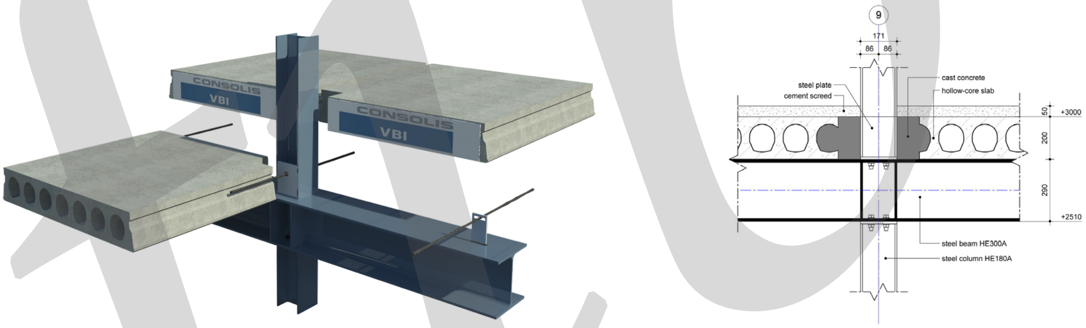


Fig. 7-15 Detail of hollow-core floor to beam and column joint in the middle of the building

However, a better result would be achieved if the hollow-core floor is used in combination with steel box-beams (Figure 7-16). Such a solution would require no recesses in the corners of the slabs because the floor field would be enclosed by the beams. This would be a great advantage from the reusability point of view.

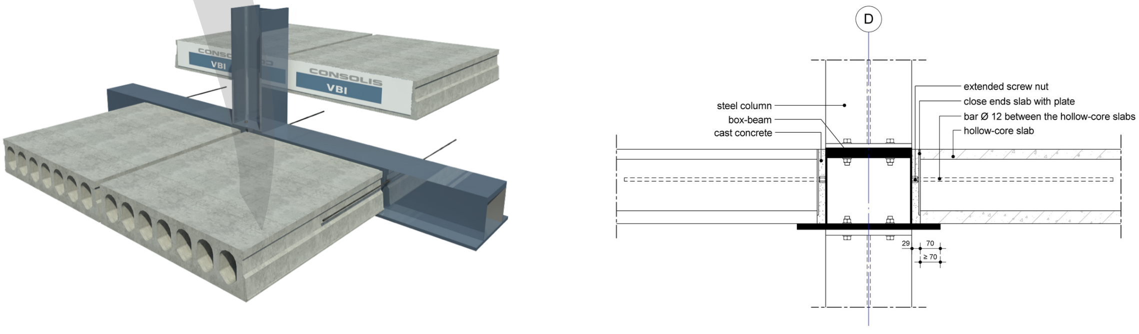


Fig. 7-16 Detail of hollow-core floor to box-beam and column joint in the middle of the building

During future disassembly, the building would be first stripped until the main bearing structure would be still in place. The columns would be removed to disconnect the floor field from the tie beams. Then the beams parallel to the hollow-core floor would be removed creating the space to hoist the first slab from the building. Differently than during the assembly, during the disassembly it would not be possible to hoist the hollow-core slabs with a conventional lifting clamp unless a part of joint cast with concrete mortar would be opened. Alternatively the slabs could be disassembled using fork lift, cast-in anchors or hoisting keys through the vertical openings made in the slab.

AGRO NRG office and storage building in Ootmarsum - designed and built for reassembly
project address: Eerste Stegge 54, Ootmarsum, The Netherlands
client: AGRO NRG B.V.
taken into use: 2017

7.2 Infrastructures

7.2.1 Segmental linings for tunnels

7.2.1.1 Introduction

The use of precast concrete linings to resist the earth actions in TBM-constructed tunnels is a widespread practice. These elements are generally reinforced with steel curved-cages (Figure 7-17a). However, the replacement of this traditional reinforcement with structural fibres (Figure 7-17b) is increasing due to diverse reported technical and economic advantages as well as the acceptance of the fibre reinforced concrete (FRC, hereinafter) as structural material in several standards (for example, in the *fib* MC-2010).

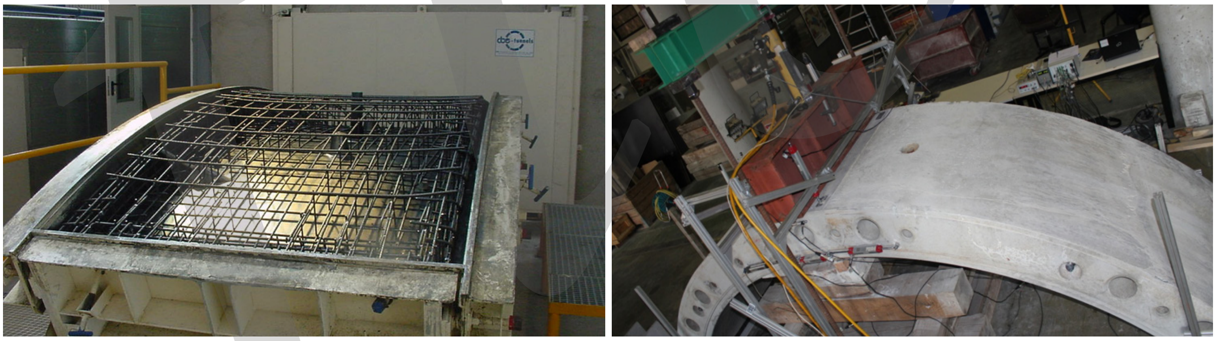


Fig. 7-17 Precast concrete segments: (a) Traditional reinforcement (Metro L9 of Barcelona) and (b) FRC full-scale bending test carried out at the UPC of Barcelona

Besides, it should be kept in mind that these segments are, usually, subjected to reduced bending moments and the likelihood of cracking is relative low (especially during service). In this regard, the highest bending moment basically occurs during transient loading stages (see Figure 7-18) for which the segments are designed not to crack; thus, minimum reinforcement is required. As a consequence, the competitive amount of structural fibres to be used as a replacement of the rebars makes the FRC an attractive material for this application.

Fig. 7-18 Some of the transient load situations in which the segments are subjected to bending moments: (a) demoulding and (b) stacking at the yard

Even though different current codes already permit the use of FRC in structural elements and the solution has proven to be both technically and economically attractive in the segmental linings used in over 50 TBM tunnels built to date, some restrictions still persist concerning the use of FRC in this particular application. Among these, the main factors that designers and contractors consider when comparing traditional and FRC solutions are based solely on direct material costs without taking into account either indirect costs or social and environmental factors, i.e. without considering the sustainability of the alternative solutions.

The aim of this practical example of application of MIVES consist in proposing a multi-criteria decision-making method based on the MIVES to assess the different viable solutions for reinforcement of precast concrete segments.

This example is part of document published the proceedings of the Second International Conference on Concrete Sustainability (ICCS 16) held in Madrid during the 13th-15th of June 2016[31].

7.2.1.2 Sustainability assessment MIVES model for precast concrete segments

The requirements tree defined for the sustainability assessment of precast concrete segments is presented in Table 7-12. In this case, although a "cradle to cradle" LCA could be carried out, a cradle to the placement of the segments inside the tunnel has been considered. This can be assumed since the type of reinforcement is not a variable that affects the rest of operations after the placement of the segments. Based on the results of the seminars, 1 km (0.62 mile) tunnel was considered to be representative enough to integrate all those factors involved in assessing the sustainability of the segment, omitting consideration of infrastructure and other elements not crucial to the analysis, such as vertical shafts and stations.

Table 7-12 Requirements' tree proposed to assess the sustainability of precast concrete linings

Requirement	Criteria	Indicator	Units	Function
R_1 Economic (40%)	C_1 Direct costs (90%)	I_1 Total costs (100%)	M€/km	DS
	C_2 Cost of repairs (10%)	I_2 Probability of repair (100%)	Attributes	
R_2 Environmental (45%)	C_3 Resources consumption (30%)	I_3 Cement and aggregates (50%)	Ton/km	DCx
		I_4 Water (20%)		
		I_5 Reinforcing steel (30%)		
	C_4 Emissions (40%)	I_6 CO_2 emissions (100%)	Ton CO_2-eq/km	DS
	C_5 Energy (30%)	I_7 Embodied energy (100%)	MWh/km	
R_3 Social (15%)	C_6 Labour conditions (100%)	I_8 Noise pollution (70%)	Db	DCx
		I_9 Risks during handling (30%)	Attributes	

It must be emphasized that the reinforcement alternatives for a certain segment, either traditional reinforcement, FRC or hybrid configurations (reinforcing bars + fibres), considered for certain boundary conditions (lining thickness, internal diameter and loads) should comply with the structural and project requirements. Otherwise, these should not be considered as alternatives to be compared.

7.2.2 Case study: segmental lining of the L9 Extension to the Barcelona Airport

- Description of the tunnel

As an example of application of this MIVES model, the segmental lining of the L9 Tunnel Extension to the Barcelona Airport has been considered. This consists of a 2.84 km long TBM-constructed tunnel in service since 2016. The lining (Fig. 7-20) was made up with a universal ring with a mean length of 1.60 m (5.25 ft) and an internal diameter of 9.60 m (31.5 ft). The ring is 0.32 m (12.6 in.) thick and is composed of 6 segments and 1 key.

For the original design, conventional reinforced concrete (CRC) segments with 110 kg/m^3 (185 lb/yd^3) of steel rebars and concrete with a characteristic compressive strength value f_{ck} of 45 N/mm^2 (6500 psi) were proposed. The designers also verified that the design forces do not exceed the crack resistance of the segment in any of the loading stages and fixed a minimum reinforcement to ensure adequate ductile behavior in a hypothetical cracking situation. However, two new solutions for the segments using only FRC have been proposed: (1) using conventionally vibrated FRC concrete and (2) using self-compacting fibre-reinforced concrete (SC-FRC).

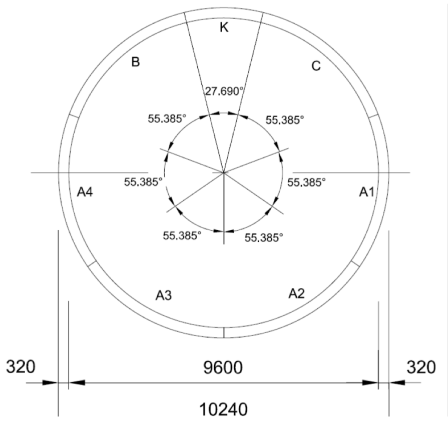


Fig. 7-19 Dimensions (in mm) of the tunnel lining (L9 Extension to the Barcelona Airport)

The different concrete dosages are presented in Table 7-13.

Table 7-13 Dosages (in kg/m³) considered for the different concrete mixes.

MATERIALS	CRC	FRC	SC-FRC
CEM I 52.5	315	315	381
Sand 0/5	817	817	1,200
Fine aggregate 5/12	404	404	500
Coarse aggregate 12/20	810	810	200
Water	150	156	165
Superplasticiser	2.80	2.80	4.60
Steel fibres	0	50	45

Note: 1 kg/m³ = 1.67 lb/yd³.

Hooked-end steel fibres with a yielding strength of 1,000 N/mm² (145 ksi), length of 50 ± 5 mm (2 ± 0.2 in.) and a diameter of 1.0 ± 0.1 mm (39 ± 4 mil) were used for both FRCs. In this regard, the experimental results on notched prismatic specimens according to the testing procedure EN 14651:2005 have confirmed that 50 kg/m³ (84 lb/yd³) (FRC) and 45 kg/m³ (75 lb/yd³) were sufficient to reach the required 4-day strength (f_{R1k} = 4.0 N/mm² (580 psi) and $1.1 \leq f_{R3k}/f_{R1k} < 1.3$ according to MC-2010 strength class to replace all the rebars while guaranteeing the ductile behavior of the segments. It is worth noting that SC-FRC requires 10% less fibre material than FRC because of the better orientation of the fibres in the pouring process of the self-compacting concrete due the flow forces and boundary conditions imposed by the walls of the mould.

The construction of the tunnel lining involves 12,425 segments (1,775 rings), requiring 28,322 m³ (33,120 yd³) of concrete. The segments will be fabricated in an existing plant specifically designed for the purpose. The distance from the plant to the TBM access shaft is 110 km (68.4 mile). The plant is expected to be in operation for a period of 16 months between the start of preparations and final shutdown. It is estimated that the fabrication of all segments will take nine months with two 8-hour work shifts a day.

- Sustainability index assessment

The data gathered in Table 7-14 must be considered to assess each of the 9 indicators fixed in the requirements' tree (Table 7-12). Likewise, the constitutive parameters required to define the specific value functions are presented in Table 7-8.

Table 7-14 Values of the main features of the alternative reinforcement configurations

Indicator	CRCS	FRCS	SC-FRCS
I_1 Direct costs (M€/km)	2.89	2.60	2.61
I_2 Probability of repair	Moderate	Low	Low
I_3 Cement and aggregates (Ton/km)	66,444	66,444	64,603
I_4 Water (Ton/km)	15,590	10,863	11,668
I_5 Reinforcing steel (Ton/km)	1,097	499	449
I_6 CO_2 emissions (TonCO_2-eq/km)	5,305	4,601	5,083
I_7 Embodied energy (MWh/km)	12,411	9,375	9,904
I_8 Noise pollution (Db)	90	90	60
I_9 Risk during handling	Reduced	High	High

Indicator	CRCS	FRCS	SC-FRCS
I_1 Direct costs (M€/mile)	4.65	4.18	4.20
I_2 Probability of repair	Moderate	Low	Low
I_3 Cement and aggregates (ton/mile)	97,008	97,008	97,240
I_4 Water (million gal./mile)	6.62	4.61	4.96
I_5 Reinforcing steel (ton/mile)	1,602	729	656
I_6 CO_2 emissions (ton CO_2-eq/mile)	7,745	6,717	7,421
I_7 Embodied energy (MWh/mile)	19,974	15,088	15,939
I_8 Noise pollution (Db)	90	90	60
I_9 Risk during handling	Reduced	High	High

Table 7-15 Value function parameters for each indicator

Indicator	X_{max}	X_{min}	C	K	P
I_1 Direct costs (M€/km)	4,00	2,24	1,00	1,00	2,50
I_2 Probability of repair	Steel: 0.00 – 0.25 (very high); low fibre content: 0.25 – 0.50 (high); steel + low fibre content: 0.50 - 0.75 (moderate); High fibre content: 075 - 1.00 (low)				
I_3 Cement and aggregates (Ton/km)	70,000	65,000	67,000	0.10	2.50
I_4 Water (Ton/km)	29,000	7,500	15,000	0.10	2.50
I_5 Reinforcing steel (Ton/km)	1,350	450	800	1.00	2.50
I_6 CO_2 emissions (TonCO_2-eq/km)	7,800	3,800	5,000	2.50	200
I_7 Embodied energy (MWh/km)	18,500	7,500	10,000	2.50	2.00
I_8 Noise pollution (Db)	150	0	80	3.00	10.00
I_9 Risks during handling	Very high: 0.00 – 0.25; High: 0.,25 – 0.50; Acceptable: 0.50 – 0.75; Reduced: 0.75 – 1.00				

Indicator	X_{max}	X_{min}	C
I_1 Direct costs (M€/mile)	6.44	3.60	1.61
I_2 Probability of repair			
I_3 Cement and aggregates (ton/mile)	113,000	105,000	108,000
I_4 Water (million gal./mile)	12.3	3.19	6.37
I_5 Reinforcing steel (ton/mile)	2173	724	1290
I_6 CO_2 emissions (ton CO_2-eq/mile)	12,600	6,100	8,050
I_7 Embodied energy (MWh/mile)	29,800	12,100	16,000
I_8 Noise pollution (Db)	150	0	80
I_9 Risks during handling			

By applying the additive formula shown in Equation (7-1), the requirements' satisfaction degrees and the SI of each reinforcement alternative can be estimated (Table 7-16).

Table 7-16 Sustainability index of each reinforcement alternative

	CRCS	FRCS	SC-FRCS
SI	**0.578**	**0.754**	**0.856**
I_{R1}	0.703	0.899	0.909
I_{R2}	0.513	0.786	0.836
I_{R3}	0.438	0.326	0.775

- Final considerations

The results presented in Table 7-16 highlight that using FRC, vibrated and self-compacting concrete, leads to more sustainable solutions that using conventional reinforced concrete. Specifically, SC-FRCS (SI = 0.856) represents an increase of 48% in SI over CRCS (SI = 0.578) and an increase of 14% over FRCS (SI = 0.754).

7.3 Special Works

7.3.1 Precast concrete wind towers

7.3.1.1 Introduction

Precast concrete wind towers have been progressively introduced in the market, gaining importance over other existing alternatives for heights above 100 m (305 ft) due to diverse technical and economic advantages. However, still there is not an objective tool that allows quantification of the sustainability of wind towers considering the three pillars (economic, environmental and social). Therefore, decisions on which kind of tower should be used for certain boundary conditions and requirements are usually made by considering mainly economic criteria. If environmental and social aspect are considered, these are rather subjectively treated and not rigorously.

The aim of this practical example of application of MIVES consists of presenting the whole procedure carried out to establish the components (tree of requirements, value functions, weights and analysis of the results) that permits assessment of the sustainability index of wind towers. As a particular case of sustainability assessment, a precast concrete tower has been chosen. This tower responds to a patented model still in prototype phase.

This example is part of document published the proceedings of the Second International Conference on Concrete Sustainability (ICCS 16) held in Madrid during the 13th-15th of June 2016[32].

7.3.1.2 Sustainability assessment MIVES model for wind towers

In Table 7-17 the requirement tree defined is presented. The LCA embraces from cradle to the deconstruction of the wind field. The unit of analysis consists of the structural elements (foundation and tower). Likewise, the maximum transport distance of the precast concrete elements from plant to site is not more than 350 km (217 mile).

It must be emphasized that this model can be applied to any composition of structural materials that the tower might be made of.

Table 7-17 Requirements' tree proposed to assess the sustainability of wind towers

Requirement	Criteria	Indicator	Unit
R_1 Economic (50%)	C_1 Construction cost (40%)	I_1 Direct cost (50%)	€/tower
		I_2 Cost deviations (50%)	Points
	C_2 Maintenance cost (40%)	I_3 Planned works (100%)	€/tower
	C_3 Deconstruction (20%)	I_4 Deconstruction (100%)	€/tower
R_2 Environmental (35%)	C_4 Resources consumption (33.3%)	I_5 Material (100%)	Tn/MW
	C_5 Energy (33.3%)	I_6 Energy (100%)	GWh/MW
	C_6 Emissions (33.3%)	I_7 CO_2 (100%)	TnCO_2-e/MW
R_3 Social (15%)	C_7 Occupational hazards (30%)	I_8 Risk of accident (100%)	Points
	C_8 Perception (60%)	I_9 Proportions (50%)	
		I_{10} Flexibility (50%)	
	C_9 Technology integration (10%)	I_{11} New patents (100%)	

The economic requirement (R_1) takes into account the impact of the different costs, both direct and indirect, identified during the seminars. The environmental requirement (R_2) is used to consider the impact of the construction process and materials involved in the tower's installation. The social requirement (R_3) is used to assess key factors for the social acceptance of wind farms.

The assigned weights (λ_{R1} = 50%; λ_{R2} = 30% and λ_{R3} = 15%) have been derived from experts' seminars. It can be seen that a higher weight to the economic requirement has been established with respect to the environmental aspects. In this regard, it should be mentioned that wind farms have a lower environmental impact in terms of energy than electricity-generation technologies based on fossil fuels. Furthermore, the difference between the energy produced and consumed is positive over the tower's entire life. Thus, in this specific case, a lower weight can be assigned to the environmental requirements. This tree can be used to assess the sustainability index score for towers in other scenarios (different system constraints and/or social perceptions) and from the viewpoint of other stakeholders by adjusting the weightings and boundary conditions accordingly.

7.3.1.3 Case study: precast concrete tripod

- Description of the wind tower

A prototype precast concrete tripod (Spanish patent No. 7,123,455, see Figure 7-21) is used as an example of sustainability assessment of wind towers. This support is capable of bearing and resisting the forces transmitted by large turbines ($P \geq 3.0$ MW) installed at height ranging between 100 – 120 m (328 – 394 ft). This structural system consists of a three-legged tower of 20 m (60 ft) – length precast prestressed concrete segments joined in by means of post-tensioned tendons. These three legs are reinforced transversely with double-T structural steel profiles.

In Figure 7-21 the geometric details of the foundation designed for this precast concrete tower are presented.

- Sustainability index assessment

The data gathered in Table 7.18 must be considered to assess each of the 11 indicators fixed in the requirements' tree (Table 7-17). Likewise, the constitutive parameters required to define the specific value functions are presented in Table 7-18.

Table 7-18 Values of the main features of the proposed tripod tower

Feature	**Value**	**Unit**
Height	100	M
Power output of supported turbine	3.5	MW
Foundation weight	698	t/tower
Tower weight	1,263	t/tower
Construction cost	1,022,000	€/tower
Maintenance cost	6,545	€/tower·year
Deconstruction cost	120,200	€/tower
Energy consumption (LCA)	0.68	MW/tower
CO_2 emissions (LCA)	299	$TnCO_2$-e/tower

Feature	Value	Unit
Height	328	ft
Power output of supported turbine	3.5	MW
Foundation weight	769	ton/tower
Tower weight	1392	ton/tower
Construction cost	1,022,000	€/tower
Maintenance cost	6,545	€/tower·year
Deconstruction cost	120,200	€/tower
Energy consumption (LCA)	0.68	MW/tower
CO_2 emissions (LCA)	330	ton CO_2-e/tower

Once the value function for each indicator has been defined, the Sustainability Index (SI) can be determined. To this end, the additive formula shown in Equation (7-1) must be applied considering the previously defined indicator values (V_i) and weights (λ_i).

$$SI = \sum_i \lambda_i V_i \left(x_i \right) \tag{7-1}$$

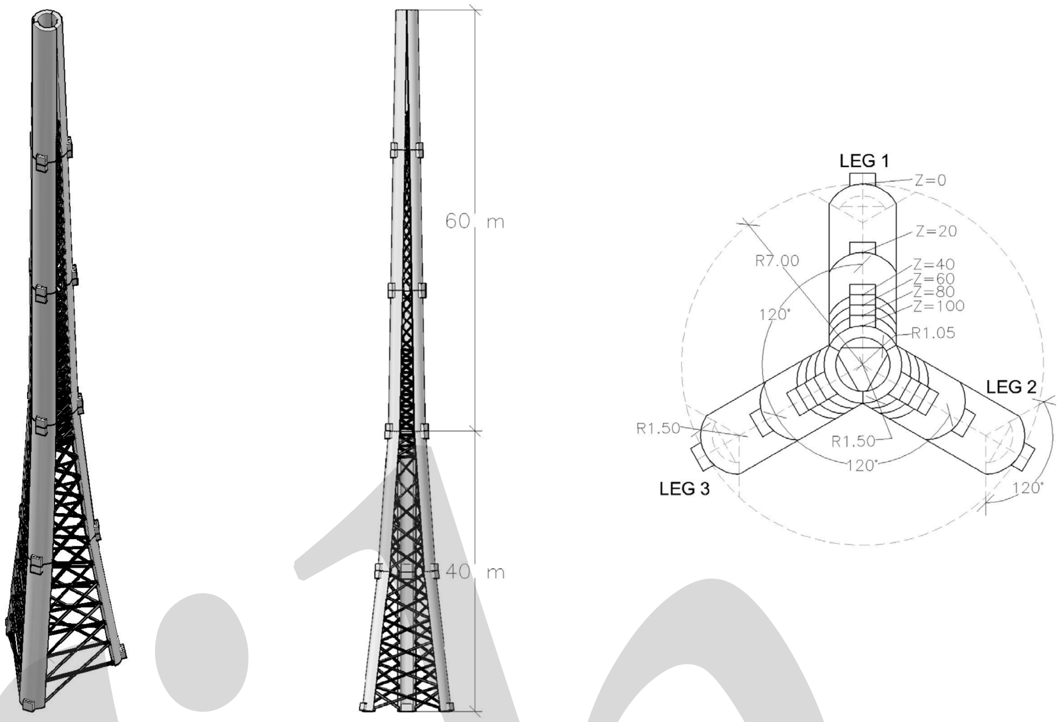


Fig. 7-20 (a) 3D, (b) frontal, and (c) upper views of the precast concrete tripod for wind tower. Note: 1 m = 3.28 ft

Table 7-19 shows the values for each indicator and requirement for the precast concrete tripod. In this regard, considering the weights established for the three requirements (Table 7-17), the sustainability index derived from applying the Equation (7-1) is SI = 0.68.

Had other stakeholders' preferences wanted to be taken into account, the requirement weights could be calibrated according the situation. For instance, on the one hand, in the case of a private owner (or investor) or in a general economic recession panorama, the economic requirement would have higher relative importance. A possible weights' distribution would be λ_{R1} = 75%, λ_{R2} = 15%, λ_{R3} = 15%, being the final SI = 0.65. On the other hand, in case of economic strength and/or a country with strong environmental and social sensitivity, a potential weights' distribution would be λ_{R1} = 35%, λ_{R2} = 45%, λ_{R3} = 20%. In this case, the total SI = 0.71.

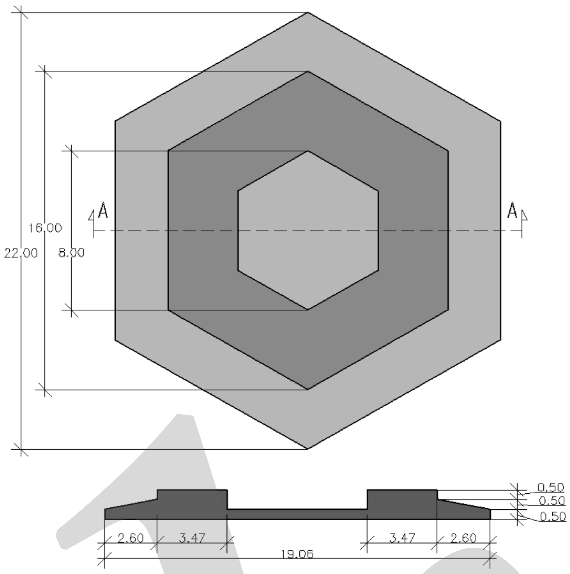


Fig. 7-21 Upper and frontal views of the foundation for the precast concrete tripod for wind tower

Table 7-19 Value function parameters for each indicator

Indicator	Unit	x_{max}	x_{min}	C	K	P	Shape
I_1. Direct cost	€/tower	2,000,000	900,000	1,100,000	1.00	2.5	DCv
I_2. Cost deviations	points	90	40	50	1.00	2.5	DCv
I_3. Maintenance work	€/tower·year	10,000	4,000	5,000	0.05	2.5	DCv
I_4. Deconstruction	€/tower	250,000	20,000	60,000	0.05	2.5	DCv
I_5. Material	Tn/MW	2,000	200	500	0.01	1.0	DL
I_6. Energy	GWh/MW	1.5	0	0.75	1.00	1.0	DCx
I_7. Emissions	ton CO_2-e/MW	1,500	0	750	1.00	1.0	DCx
I_8. Occupational hazards	points	2.5	1.5	2.5	0.01	3.0	DCv
I_9. Proportions	points	100	0	100	0.01	1.0	DL
I_{10}. Flexibility	points	100	0	100	0.01	1.0	DL
I_{11}. New patents	points	1	0	1	0.01	1.0	DCx

Note: 1 tonne = 1.102 ton.

Table 7-20 Satisfaction values for each indicator and requirement

Indicator	R_1	I_1	I_2	I_3	I_4	R_2	I_5	I_6	I_7	R_3	I_8	I_9	I_{10}	I_{11}	**Total**
Index V_i	0.57	0.83	1.00	0.33	0.38	0.86	0.80	0.86	0.98	0.64	0.31	0.90	0.60	1.00	0.68

7.3.1.4 Final considerations

In view of the results, it is evident that the model allows the decision-maker to contemplate different scenarios taking into account different preferences. This model can be applied independently of the structural material of the tower, height, turbine power and transport distance. So, it can be stated that this MIVES model is general for assessing the sustainability of wind towers.

8. Conclusions and recommendations

Sustainability is increasingly becoming a key aspect for decision making for building structures and infrastructure. In any scenario that we may think of in the future this means that considerations of sustainability, regarding economic, environmental and social aspects will be considered. Also it is of the greatest relevance that the whole life cycle of the structure should be considered, that includes as commonly said, from the cradle to the grave. In the case of precast structures, as one of the most relevant industrialised construction methods, they have at the earliest moment in the development of the project a greater input of manufacturing and thus to take into account all aspects of sustainability including the whole life cycle is relevant.

This publication emphasizes the importance of considering sustainability in precast concrete structures. To consider sustainability in a complete way it is necessary to take into account the full life of the structure, also with the consideration of demolishing and recycling of part or the complete structure.

The use of prefabrication in construction provides the advantage of using industrialized methods for construction into the work site. The greatest impact that involves industrialized elements transport and erection at the site is greatly compensated by the advantages of industrial facilities within controlled plants.

The use of available resources in industry provides materials optimization and means of implementation for structures. It can be either because they assure to minimize work at site, or because structures can be constructed with fewer materials and higher quality. It also results in a more controlled environment in which it is possible and economically viable to make tests on special aspect of the materials or the structure to optimize the design thus avoiding costlier simplifications that come from the codes that need to be taken into account for more general design conditions.

At the present time there are several tools to help consider sustainability mostly for building. These tools do not consider in a complete way all aspects of sustainability and the evaluation systems are not completely open for evaluation by the designers or the final users. In this document a proposal for a decision framework using multi-criteria decision theory has been described to provide designers and users with a new possibility. The methodology has a defined background and it is possible to adapt the evaluation to each need, in case of different kinds of structures or places where they are located.

Several examples of the use of such a methodology to evaluate sustainability have been developed for buildings, infrastructures and other kind of structures.

The future work of this group in the *fib* will be dedicated to the development of design guides and detailed examples on how to equate each indicator, from the economic ones to the social and environmental. In this way the intention of the future work is that designers and final user will be able to adapt or develop their specific decision-making tool to evaluate sustainability of their own design or already built structure.

Annex 1. Environmental Product Declaration (EPD) examples

In this annex are listed some examples of EPDs from North America, Norway and United Kingdom.

From North America:

- 1 metric ton (1.1 ton) of structural precast concrete
- 1 metric ton of architectural precast concrete
- 1 metric ton of insulated precast concrete
- 1 metric ton of underground precast concrete

From Norway:

- 1 m^3 (1.31 yd^3) of lightweight concrete block (88 mm) (3.5 in.)
- 1 m^3 of lightweight concrete block with PUR-insulation (35 cm) (13.8 in.)
- 1 m^3 of lightweight concrete block (20 cm) (7.9 in.)
- 1 m^3 of lightweight concrete block (15 cm) (5.9 in.)

From the United Kingdom

- 1 m^3 of silver grey EcoKerb
- 1 m^3 of Enviroblock lightweight block
- 1 m^3 of Enviroblock dense block

A.1 North America

In North America, the three precast concrete industry associations—Canadian Precast/Prestressed Concrete Institute (CPCI), National Precast Concrete Association (NPCA), and Precast/Prestressed Concrete Institute (PCI)—collected data and produced four industry average EPDs. Precast concrete products were grouped into the following categories: structural, architectural, insulated, and underground[1].

A.1-1 Description of product: Structural

Programme operator	ASTM International
PCR	ASTM PCR for Precast Concrete[2]
Declaration date	2015-11-11
Standard	ISO 14025[3] and ISO 21930[4]
Scope (information modules)	A1 to A3 (cradle to gate)
Declared unit	1 metric ton of structural precast concrete

Table A-1 Results of LCA for 1 metric ton of structural precast concrete

Environmental Impacts	**Unit**	**A1 to A3**
Global warming potential	kg CO_2 eq.	298.8
Acidification potential	kg SO_2 eq.	5.0
Eutrophication potential	kg N eq.	0.3
Smog creation potential	kg O_3 eq.	58.6
Ozone depletion potential	kg CFC-11 eq.	1.9E-03
Resource Use	**Unit**	**A1 to A3**
Total Primary Energy	MJ, HHV	2620.2
Non-renewable (fossil, nuclear)	MJ, HHV	2574.1
Renewable (solar, wind, biomass, hydroelectric, geothermal)	MJ, HHV	46.1
Total Material Resource Consumption	kg	1066.7
Non-renewable materials	kg	1065.8
Renewable materials	kg	0.9
Fresh water	L	1597.3
Waste	**Unit**	**A1 to A3**
Non-hazardous	kg	65.2
Hazardous	kg	10.0

Table A-2 Results of LCA for 1 ton of structural precast concrete

Environmental Impacts	**Unit**	**A1 to A3**
Global warming potential	lb CO_2 eq.	597.6
Acidification potential	lb SO_2 eq.	10.0
Eutrophication potential	lb N eq.	0.6
Smog creation potential	lb O_3 eq.	117.2
Ozone depletion potential	lb CFC-11 eq.	0.0038
Resource Use	**Unit**	**A1 to A3**
Total Primary Energy	10^6 BTU	1.72
Non-renewable (fossil, nuclear)	10^6 BTU	1.69
Renewable (solar, wind, biomass, hydroelectric, geothermal)	10^3 BTU	30.3
Total Material Resource Consumption	lb	2133
Non-renewable materials	lb	2132
Renewable materials	lb	1.8
Fresh water	gal.	384
Waste	**Unit**	**A1 to A3**
Non-hazardous	lb	130.4
Hazardous	lb	22.0

A.1-2 Description of product: Architectural

Programme operator	ASTM International
PCR	ASTM PCR for Precast Concrete[5]
Declaration date	2015-11-11
Standard	ISO 14025[6] and ISO 21930[7]
Scope (information modules)	A1 to A3 (cradle to gate)
Declared unit	1 metric ton of architectural precast concrete

Table A-3 Results of LCA for 1 metric ton of architectural precast concrete

Environmental Impacts	**Unit**	**A1 to A3**
Global warming potential	kg CO_2 eq.	307.7
Acidification potential	kg SO_2 eq.	5.8
Eutrophication potential	kg N eq.	0.3
Smog creation potential	kg O_3 eq.	67.6
Ozone depletion potential	kg CFC-11 eq.	1.6E-03
Resource Use	**Unit**	**A1 to A3**
Total Primary Energy	MJ, HHV	2814.4
Non-renewable (fossil, nuclear)	MJ, HHV	2760.4
Renewable (solar, wind, biomass, hydroelectric, geothermal)	MJ, HHV	53.9
Total Material Resource Consumption	kg	1057.9
Non-renewable materials	kg	1056.7
Renewable materials	kg	1.2
Fresh water	L	1734.4
Waste	**Unit**	**A1 to A3**
Non-hazardous	kg	65.3
Hazardous	kg	10.0

Table A-4 Results of LCA for 1 ton of architectural precast concrete

Environmental Impacts	**Unit**	**A1 to A3**
Global warming potential	lb CO_2 eq.	615.4
Acidification potential	lb SO_2 eq.	11.6
Eutrophication potential	lb N eq.	0.6
Smog creation potential	lb O_3 eq.	135.2
Ozone depletion potential	lb CFC-11 eq.	0.032
Resource Use	**Unit**	**A1 to A3**
Total Primary Energy	10^6 BTU	1.79
Non-renewable (fossil, nuclear)	10^6 BTU	1.82
Renewable (solar, wind, biomass, hydroelectric, geothermal)	10^3 BTU	35.5
Total Material Resource Consumption	lb	2116
Non-renewable materials	lb	2113
Renewable materials	lb	2.4
Fresh water	gal.	416
Waste	**Unit**	**A1 to A3**
Non-hazardous	lb	130.6
Hazardous	lb	20.0

A.1-3 Description of product: Insulated

Programme operator	ASTM International
PCR	ASTM PCR for Precast Concrete[8]
Declaration date	2015-11-11
Standard	ISO 14025[9] and ISO 21930[10]
Scope (information modules)	A1 to A3 (cradle to gate)
Declared unit	1 metric ton of insulated precast concrete

Table A-5 Results of LCA for 1 metric ton of insulated precast concrete

Environmental Impacts	**Unit**	**A1 to A3**
Global warming potential	kg CO_2 eq.	321.4
Acidification potential	kg SO_2 eq.	4.8
Eutrophication potential	kg N eq.	0.3
Smog creation potential	kg O_3 eq.	55.1
Ozone depletion potential	kg CFC-11 eq.	3.8E-03
Resource Use	**Unit**	**A1 to A3**
Total Primary Energy	MJ, HHV	2830.3
Non-renewable (fossil, nuclear)	MJ, HHV	2780.9
Renewable (solar, wind, biomass, hydroelectric, geothermal)	MJ, HHV	49.3
Total Material Resource Consumption	kg	1040.7
Non-renewable materials	kg	1039.9
Renewable materials	kg	0.8
Fresh water	L	1564.1
Waste	**Unit**	**A1 to A3**
Non-hazardous	kg	65.3
Hazardous	kg	10.0

Table A-6 Results of LCA for 1 ton of insulated precast concrete

Environmental Impacts	**Unit**	**A1 to A3**
Global warming potential	lb CO_2 eq.	642.8
Acidification potential	lb SO_2 eq.	9.6
Eutrophication potential	lb N eq.	0.6
Smog creation potential	lb O_3 eq.	110.2
Ozone depletion potential	lb CFC-11 eq.	0.0076
Resource Use	**Unit**	**A1 to A3**
Total Primary Energy	10^6 BTU	1.86
Non-renewable (fossil, nuclear)	10^6 BTU	1.83
Renewable (solar, wind, biomass, hydroelectric, geothermal)	10^3 BTU	32.4
Total Material Resource Consumption	lb	2081.4
Non-renewable materials	lb	2079.8
Renewable materials	lb	1.6
Fresh water	gal.	376
Waste	**Unit**	**A1 to A3**
Non-hazardous	lb	130.6
Hazardous	lb	20.0

A.1-4 Description of product: Underground

Programme operator	ASTM International
PCR	ASTM PCR for Precast Concrete[11]
Declaration date	2015-11-11
Standard	ISO 14025[12] and ISO 21930[13]
Scope (information modules)	A1 to A3 (cradle to gate)
Declared unit	1 metric ton of underground precast concrete

Table A-7 Results of LCA for 1 metric ton of underground precast concrete

Environmental Impacts	**Unit**	**A1 to A3**
Global warming potential	kg CO_2 eq.	259.1
Acidification potential	kg SO_2 eq.	4.4
Eutrophication potential	kg N eq.	0.2
Smog creation potential	kg O_3 eq.	51.2
Ozone depletion potential	kg CFC-11 eq.	1.8E-04
Resource Use	**Unit**	**A1 to A3**
Total Primary Energy	MJ, HHV	2373.4
Non-renewable (fossil, nuclear)	MJ, HHV	2327.4
Renewable (solar, wind, biomass, hydroelectric, geothermal)	MJ, HHV	46.0
Total Material Resource Consumption	kg	1030.3
Non-renewable materials	kg	1029.6
Renewable materials	kg	0.7
Fresh water	L	1352.7
Waste	**Unit**	**A1 to A3**
Non-hazardous	kg	65.1
Hazardous	kg	10.0

Table A-8 Results of LCA for 1 ton of underground precast concrete

Environmental Impacts	**Unit**	**A1 to A3**
Global warming potential	lb CO_2 eq.	518.2
Acidification potential	lb SO_2 eq.	8.8
Eutrophication potential	lb N eq.	0.4
Smog creation potential	lb O_3 eq.	102.4
Ozone depletion potential	lb CFC-11 eq.	0.00036
Resource Use	**Unit**	**A1 to A3**
Total Primary Energy	10^6 BTU	1.56
Non-renewable (fossil, nuclear)	10^6 BTU	1.53
Renewable (solar, wind, biomass, hydroelectric, geothermal)	10^3 BTU	30.2
Total Material Resource Consumption	lb	2060.6
Non-renewable materials	lb	2059.2
Renewable materials	lb	1.4
Fresh water	gal.	325
Waste	**Unit**	**A1 to A3**
Non-hazardous	lb	130.2
Hazardous	lb	20.0

A.2 Norway

Four EPDs were created in Norway for precast concrete product manufactured by a single manufacturer. The first product was a lightweight concrete block[14].

A.2-1 Description of product: Lightweight concrete block (88 mm)

Programme operator	Norwegian EPD Foundation
PCR	EN 15804: 2012 + A1: 2013[15]
Declaration date	2014-10-20
Standard	EN 15804: 2012 + A1: 2013[16]
Scope (information modules)	A1 to A4 (cradle to gate with options)
Declared unit	1 m^3 of lightweight concrete block (88 mm)

Table A-9 Results of LCA for 1 m^3 of lightweight concrete block (88 mm)

Environmental Impacts	**Unit**	**A1**	**A2**	**A3**	**A4**
Global warming potential	kg CO_2 -eq	1.02E+02	3.05E+00	1.31E+01	3.69E+00
Depletion potential of the stratospheric ozone layer	kg CFC11 -eq	1.18E-06	0.00E+00	1.97E-06	0.00E+00
Formation potential of tropospheric photochemical oxidants	kg C_2H_4-eq	1.19E-01	3.23E-03	3.15E-02	9.75E-03
Acidification potential of land and water	kg SO_2 -eq	3.05E-01	1.02E-02	5.13E-03	2.25E-03
Eutrophication potential	kg PO_4^{3-}-eq	3.04E-02	1.54E-03	2.65E-03	1.50E-03
Abiotic depletion potential for non fossil resources	kg Sb -eq	1.45E-04	0.00E+00	5.16E-05	0.00E+00
Abiotic depletion potential for fossil resources	MJ	5.68E+02	4.03E+01	1.68E+02	4.84E+01
Resource Use	**Unit**	**A1**	**A2**	**A3**	**A4**
Renewable primary energy resources used as energy carrier	MJ	2.80E+02	5.45E-02	1.07E+02	8.33E-02
Renewable primary energy resources used as raw materials	MJ	2.17E-01	1.88E-02	1.43E-01	0.00E+00
Total use of renewable primary energy resources	MJ	2.81E+02	7.33E-02	1.08E+02	8.33E-02
Non renewable primary energy resources used as energy carrier	MJ	6.58E+02	4.02E+01	1.78E+02	4.82E+01
Non renewable primary energy resources used as materials	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total use of virgin, non-renewable resources with energy content	MJ	6.58E+02	4.02E+01	1.78E+02	4.82E+01
Use of secondary materials	kg	1.81E+01	0.00E+00	0.00E+00	0.00E+00
Use of renewable secondary fuels	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Use of non renewable secondary fuels	MJ	3.06E+02	0.00E+00	0.00E+00	0.00E+00
Use of net fresh water	m^3	1.27E+02	3.76E-01	2.44E+01	4.31E-01
Waste	**Unit**	**A1**	**A2**	**A3**	**A4**
Hazardous waste disposed	kg	3.95E-03	0.00E+00	2.22E-02	0.00E+00
Non-hazardous waste disposed	kg	1.58E+01	8.66E-03	2.20E+00	9.00E-03
Radioactive waste disposed	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Output flows	**Unit**	**A1**	**A2**	**A3**	**A4**
Components for re-use	kg	0.00E+00	0.00E+00	2.00E-03	0.00E+00
Materials for recycling	kg	5.80E-02	0.00E+00	4.22E-01	0.00E+00
Materials for energy recovery	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Exported electric energy	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Exported thermal energy	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00

The second product was a 35 cm (13 in.) lightweight concrete block with PUR-insulation[17].

A.2-2 Description of product: Lightweight concrete block with PUR-insulation (35 cm)

Programme operator	Norwegian EPD Foundation
PCR	EN 15804: 2012 + A1: 2013[18]
Declaration date	2014-02-07
Standard	EN 15804: 2012 + A1: 2013[19]
Scope (information modules)	A1 to A4 (cradle to gate with options)
Declared unit	1 m^3 of lightweight concrete block with PUR-insulation (35 cm)

Table A-10 Results of LCA for 1 m^3 of Lightweight concrete block with PUR-insulation (35 cm)

Environmental Impacts	Unit	A1	A2	**A3**	**A4**
Global warming potential	kg CO_2 -eq	1.29E+02	2.66E+00	1.29E+01	2.02E+00
Depletion potential of the stratospheric ozone layer	kg CFC11 -eq	1.02E-04	0.00E+00	1.99E-06	0.00E+00
Formation potential of tropospheric photochemical oxidants	kg C_2H_4-eq	1.98E-01	2.84E-03	3.33E-02	5.34E-03
Acidification potential of land and water	kg SO_2 -eq	2.63E-01	9.71E-03	6.74E-03	1.23E-03
Eutrophication potential	kg PO_4^{3-}-eq	3.11E-01	1.51E-03	3.52E-03	8.22E-04
Abiotic depletion potential for non fossil resources	kg Sb -eq	5.27E-01	0.00E+00	8.34E-05	0.00E+00
Abiotic depletion potential for fossil resources	MJ	1.80E+03	3.51E+01	1.62E+02	2.65E+01
Resource Use	**Unit**	**A1**	**A2**	**A3**	**A4**
Renewable primary energy resources used as energy carrier	MJ	3.13E+02	4.72E-02	1.83E+02	4.56E-02
Renewable primary energy resources used as raw materials	MJ	1.60E-01	1.61E-02	1.00E-01	0.00E+00
Total use of renewable primary energy resources	MJ	3.13E+02	6.33E-02	1.84E+02	4.56E-02
Non renewable primary energy resources used as energy carrier	MJ	1.67E+03	3.50E+01	1.77E+02	2.64E+01
Non renewable primary energy resources used as materials	MJ	3.92E+02	0.00E+00	0.00E+00	0.00E+00
Total use of virgin, non-renewable resources with energy content	MJ	2.06E+03	3.50E+01	1.77E+02	2.64E+01
Use of secondary materials	kg	1.28E+01	0.00E+00	0.00E+00	0.00E+00
Use of renewable secondary fuels	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Use of non renewable secondary fuels	MJ	2.37E+02	0.00E+00	0.00E+00	0.00E+00
Use of net fresh water	m^3	9.12E+01	3.25E-01	3.70E+01	2.36E-01

Waste	**Unit**	**A1**	**A2**	**A3**	**A4**
Hazardous waste disposed	kg	1.52E-02	0.00E+00	2.22E-02	0.00E+00
Non-hazardous waste disposed	kg	1.23E+01	7.40E-03	3.23E+00	4.93E-03
Radioactive waste disposed	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Output flows	**Unit**	**A1**	**A2**	**A3**	**A4**
Components for re-use	kg	0.00E+00	0.00E+00	2.00E-03	0.0E+000
Materials for recycling	kg	4.69E-02	0.00E+00	3.39E+00	0.0E+000
Materials for energy recovery	kg	0.00E+00	0.00E+00	0.00E+00	0.0E+000
Exported electric energy	MJ	0.00E+00	0.00E+00	0.00E+00	0.0E+000
Exported thermal energy	MJ	0.00E+00	0.00E+00	0.00E+00	0.0E+000

The third product was a 20 cm (7.9 in.) lightweight concrete block[20].

A.2-3 Description of product: Lightweight concrete block (20 cm)

Programme operator	Norwegian EPD Foundation
PCR	EN 15804: 2012 + A1: 2013[21]
Declaration date	2014-02-07
Standard	EN 15804: 2012 + A1: 2013[22]
Scope (information modules)	A1 to A4 (cradle to gate with options)
Declared unit	1 m^3 of lightweight concrete block (20 cm)

Table A-11 Results of LCA for 1 m^3 of Lightweight concrete block (20 cm)

Environmental Impacts	**Unit**	**A1**	**A2**	**A3**	**A4**
Global warming potential	kg CO_2 -eq	1.01E+02	2.98E+00	1.31E+01	2.84E+00
Depletion potential of the stratospheric ozone layer	kg CFC11 -eq	1.23E-06	0.00E+00	1.96E-06	0.00E+00
Formation potential of tropospheric photochemical oxidants	kg C_2H_4-eq	1.05E-01	2.94E-03	3.15E-02	7.51E-03
Acidification potential of land and water	kg SO_2 -eq	3.46E-01	9.71E-03	5.13E-03	1.73E-03
Eutrophication potential	kg PO_4^{3-}-eq	3.13E-02	1.49E-03	2.64E-03	1.16E-03
Abiotic depletion potential for non fossil resources	kg Sb -eq	1.27E-04	0.00E+00	5.16E-05	0.00E+00
Abiotic depletion potential for fossil resources	MJ	5.62E+02	3.93E+01	1.68E+02	3.73E+01
Resource Use	**Unit**	**A1**	**A2**	**A3**	**A4**
Renewable primary energy resources used as energy carrier	MJ	3.09E+02	5.28E-02	1.07E+02	6.41E-02
Renewable primary energy resources used as raw materials	MJ	1.75E-01	1.81E-02	1.43E-01	0.00E+00
Total use of renewable primary energy resources	MJ	3.10E+02	7.09E-02	1.08E+02	6.41E-02
Non renewable primary energy resources used as energy carrier	MJ	6.79E+02	3.91E+01	1.77E+02	3.71E+01
Non renewable primary energy resources used as materials	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total use of virgin, non-renewable resources with energy content	MJ	6.79E+02	3.91E+01	1.77E+02	3.71E+01
Use of secondary materials	kg	1.53E+01	0.00E+00	0.00E+00	0.00E+00
Use of renewable secondary fuels	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Use of non renewable secondary fuels	MJ	3.24E+02	0.00E+00	0.00E+00	0.00E+00
Use of net fresh water	m^3	1.12E+02	3.64E-01	2.44E+01	3.31E-01
Waste	**Unit**	**A1**	**A2**	**A3**	**A4**
Hazardous waste disposed	kg	3.29E-03	0.00E+00	2.22E-02	0.00E+00
Non-hazardous waste disposed	kg	1.66E+01	8.31E-03	2.20E+00	6.93E-03
Radioactive waste disposed	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Output flows	**Unit**	**A1**	**A2**	**A3**	**A4**
Components for re-use	kg	0.00E+00	0.00E+00	2.00E-03	0.00E+00
Materials for recycling	kg	6.82E-02	0.00E+00	4.22E-01	0.00E+00
Materials for energy recovery	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Exported electric energy	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Exported thermal energy	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00

The fourth product was a 15 cm lightweight concrete block[23].

A.2-4 Description of product: Lightweight concrete block (15 cm)

Programme operator	Norwegian EPD Foundation
PCR	EN 15804: 2012 + A1: 2013[24]
Declaration date	2014-10-20
Standard	EN 15804: 2012 + A1: 2013[25]
Scope (information modules)	A1 to A4 (cradle to gate with options)
Declared unit	1 m^3 of lightweight concrete block (15 cm)

Table A-12 Results of LCA for 1 m^3 of Lightweight concrete block (15 cm)

Environmental Impacts	**Unit**	**A1**	**A2**	**A3**	**A4**
Global warming potential	kg CO_2 -eq	1.89E+02	5.44E+00	1.31E+01	2.84E+00
Depletion potential of the stratospheric ozone layer	kg CFC11 -eq	1.91E-06	0.00E+00	1.96E-06	0.00E+00
Formation potential of tropospheric photochemical oxidants	kg C_2H_4-eq	2.41E-01	6.50E-03	3.15E-02	7.51E-03
Acidification potential of land and water	kg SO_2 -eq	4.55E-01	1.91E-02	5.13E-03	1.73E-03
Eutrophication potential	kg PO_4^{3-}-eq	4.59E-02	2.81E-03	2.64E-03	1.16E-03
Abiotic depletion potential for non fossil resources	kg Sb -eq	1.70E-04	0.00E+00	5.16E-05	0.00E+00
Abiotic depletion potential for fossil resources	MJ	9.47E+02	7.19E+01	1.68E+02	3.73E+01
Resource Use	**Unit**	**A1**	**A2**	**A3**	**A4**
Renewable primary energy resources used as energy carrier	MJ	4.52E+02	9.83E-02	1.07E+02	6.41E-02
Renewable primary energy resources used as raw materials	MJ	1.75E-01	3.45E-02	1.43E-01	0.00E+00
Total use of renewable primary energy resources	MJ	4.52E+02	1.33E-01	1.08E+02	6.41E-02
Non renewable primary energy resources used as energy carrier	MJ	1.10E+03	7.18E+01	1.77E+02	3.71E+01
Non renewable primary energy resources used as materials	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total use of virgin, non-renewable resources with energy content	MJ	1.10E+03	7.18E+01	1.77E+02	3.71E+01

Use of secondary materials	kg	4.11E+01	0.00E+00	0.00E+00	0.00E+00
Use of renewable secondary fuels	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Use of non renewable secondary fuels	MJ	5.32E+02	0.00E+00	0.00E+00	0.00E+00
Use of net fresh water	m^3	2.51E+02	6.80E-01	2.44E+01	3.31E-01
Waste	**Unit**	**A1**	**A2**	**A3**	**A4**
Hazardous waste disposed	kg	3.85E-03	0.00E+00	2.22E-02	0.00E+00
Non-hazardous waste disposed	kg	2.69E+01	1.59E-02	2.20E+00	6.93E-03
Radioactive waste disposed	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Output flows	**Unit**	**A1**	**A2**	**A3**	**A4**
Components for re-use	kg	0.00E+00	0.00E+00	2.00E-03	0.00E+00
Materials for recycling	kg	8.36E-02	0.00E+00	4.22E-01	0.00E+00
Materials for energy recovery	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Exported electric energy	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Exported thermal energy	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00

A.3 United Kingdom

In the U.K., four EPDs were available. The first was a private company that produces a product called Ecokerb[26].

A.3-1 Description of product: silver grey EcoKerb

Programme operator	The International EPD System
PCR	UN CPC 375 Concrete 2013:02[27]
Declaration date	2015-02-21
Standard	EN 15804: 2012 + A1: 2013[28]
Scope (information modules)	A1 to A3 (cradle to gate)
Declared unit	1 m^3 of silver grey EcoKerb

Table A-13 Results of LCA for 1 m^3 of silver grey EcoKerb

Environmental Impacts	**Unit**	**A1 to A3**
Global warming potential	kg CO_2-eq	5.33E2
Depletion potential of the stratospheric ozone layer	kg R11-eq	3.65E-5
Acidification potential of land and water	kg SO_2-eq	1.50E0
Eutrophication potential	kg PO_4^{3}-eq	3.74E-1
Formation potential of tropospheric ozone photochemical oxidants	kg ethene-eq	8.70E-2
Abiotic depletion potential for non-fossil resources	kg Sb-eq	4.55E-4
Abiotic depletion potential for fossil resources	MJ	4.48E3
Resource Use	**Unit**	**A1 to A3**
Renewable primary energy as energy carrier	MJ	1.02E2
Renewable primary energy resources as material utilization [MJ]	MJ	0.00E0
Total use of renewable primary energy resources	MJ	1.02E2
Non-renewable primary energy as energy carrier	MJ	4.78E3
Non-renewable primary energy as material utilization	MJ	0.00E0
Total use of non-renewable primary energy resources	MJ	4.78E3
Use of secondary material [kg]	kg	4.68E2
Use of renewable secondary fuels [MJ]	MJ	1.96E2
Use of non-renewable secondary fuels [MJ]	MJ	3.37E2
Use of net fresh water	m^3	6.01E0

Waste	**Unit**	**A1 to A3**
Hazardous waste disposed	kg	0.00E0
Non-hazardous waste disposed	kg	1.40E-1
Radioactive waste disposed	kg	0.00E0
Output flows	**Unit**	**A1 to A3**
Components for re-use	kg	1.31E2
Materials for recycling	kg	1.74E0
Materials for energy recovery	kg	0.00E0
Exported energy	MJ	0.00E0

The second EPD out of the U.K. was created for a private company that produces a product called Countryside kerb[29].

A.3-2 Description of product: silver grey Countryside kerb

Programme operator	The International EPD System
PCR	UN CPC 375 Concrete 2013:02[30]
Declaration date	2015-02-21
Standard	EN 15804: 2012 + A1: 2013[31]
Scope (information modules)	A1 to A3 (cradle to gate)
Declared unit	1 m^3 of silver grey Countryside kerb

Table A-14 Results of LCA for 1 m^3 of silver grey Countryside kerb

Environmental Impacts	**Unit**	**A1 to A3**
Global warming potential	kg CO_2-eq	4.74E2
Depletion potential of the stratospheric ozone layer	kg R11-eq	3.65E-5
Acidification potential of land and water	kg SO_2-eq	1.36E0
Eutrophication potential	kg PO_4^{3-}-eq	3.39E-1
Formation potential of tropospheric ozone photochemical oxidants	kg ethene-eq	7.56E-2
Abiotic depletion potential for non-fossil resources	kg Sb-eq	4.85E-4
Abiotic depletion potential for fossil resources	MJ	4.30E3
Resource Use	**Unit**	**A1 to A3**
Renewable primary energy as energy carrier	MJ	9.58E1
Renewable primary energy resources as material utilization [MJ]	MJ	0.00E0
Total use of renewable primary energy resources	MJ	9.58E1
Non-renewable primary energy as energy carrier	MJ	4.63E3
Non-renewable primary energy as material utilization	MJ	0.00E0
Total use of non-renewable primary energy resources	MJ	4.63E3
Use of secondary material [kg]	kg	7.43E1
Use of renewable secondary fuels [MJ]	MJ	1.56E2
Use of non-renewable secondary fuels [MJ]	MJ	2.68E2
Use of net fresh water	m^3	6.30E0
Waste	**Unit**	**A1 to A3**
Hazardous waste disposed	kg	0.00E0
Non-hazardous waste disposed	kg	1.27E-1
Radioactive waste disposed	kg	0.00E0

Output flows	**Unit**	**A1 to A3**
Components for re-use	kg	1.27E2
Materials for recycling	kg	1.70E0
Materials for energy recovery	kg	0.00E0
Exported energy	MJ	0.00E0

The third EPD out of the U.K. was for lightweight precast concrete blocks[32].

A.3-3 Description of product: Enviroblock lightweight block

Programme operator	The International EPD System
PCR	UN CPC 375 Concrete 2013:02[33]
Declaration date	2015-02-21
Standard	EN 15804: 2012 + A1: 2013[34]
Scope (information modules)	A1 to A3 (cradle to gate)
Declared unit	1 m^3 of Enviroblock lightweight block

Table A-15 Results of LCA for 1 m^3 of Enviroblock lightweight block

Environmental Impacts	**Unit**	**A1 to A3**
Global warming potential	kg CO_2-eq	1.42E2
Depletion potential of the stratospheric ozone layer	kg R11-eq	8.83E-6
Acidification potential of land and water	kg SO_2-eq	5.47E-1
Eutrophication potential	kg PO_4^{3-}-eq	9.18E-2
Formation potential of tropospheric ozone photochemical oxidants	kg ethene-eq	2.95E-2
Abiotic depletion potential for non-fossil resources	kg Sb-eq	4.67E-5
Abiotic depletion potential for fossil resources	MJ	1.19E3
Resource Use	**Unit**	**A1 to A3**
Renewable primary energy as energy carrier	MJ	3.09E1
Renewable primary energy resources as material utilization [MJ]	MJ	0.00E0
Total use of renewable primary energy resources	MJ	3.09E1
Non-renewable primary energy as energy carrier	MJ	1.26E3
Non-renewable primary energy as material utilization	MJ	0.00E0
Total use of non-renewable primary energy resources	MJ	1.26E3
Use of secondary material [kg]	kg	1.25E3
Use of renewable secondary fuels [MJ]	MJ	5.05E1
Use of non-renewable secondary fuels [MJ]	MJ	8.71E1
Use of net fresh water	m^3	9.25E-1
Waste	**Unit**	**A1 to A3**
Hazardous waste disposed	kg	0.00E0
Non-hazardous waste disposed	kg	3.20E-2
Radioactive waste disposed	kg	0.00E0
Output flows	**Unit**	**A1 to A3**
Components for re-use	kg	8.56E0
Materials for recycling	kg	2.10E-2
Materials for energy recovery	kg	0.00E0
Exported energy	MJ	0.00E0

The final EPD out of the U.K. was for normal weight precast concrete blocks[35].

A.3-4 Description of product: Enviroblock dense block

Programme operator	The International EPD System
PCR	UN CPC 375 Concrete 2013:02[36]
Declaration date	2015-02-21
Standard	EN 15804: 2012 + A1: 2013[37]
Scope (information modules)	A1 to A3 (cradle to gate)
Declared unit	1 m^3 of Enviroblock dense block

Table A-16 Results of LCA for 1 m^3 of Enviroblock dense block

Environmental Impacts	**Unit**	**A1 to A3**
Global warming potential	kg CO_2-eq	9.88E1
Depletion potential of the stratospheric ozone layer	kg R11-eq	4.04E-6
Acidification potential of land and water	kg SO_2-eq	2.71E-1
Eutrophication potential	kg PO_4^{3}-eq	6.87E-2
Formation potential of tropospheric ozone photochemical oxidants	kg ethene-eq	1.73E-2
Abiotic depletion potential for non-fossil resources	kg Sb-eq	2.93E-5
Abiotic depletion potential for fossil resources	MJ	6.55E2
Resource Use	**Unit**	**A1 to A3**
Renewable primary energy as energy carrier	MJ	2.05E1
Renewable primary energy resources as material utilization [MJ]	MJ	0.00E0
Total use of renewable primary energy resources	MJ	2.05E1
Non-renewable primary energy as energy carrier	MJ	6.77E2
Non-renewable primary energy as material utilization	MJ	0.00E0
Total use of non-renewable primary energy resources	MJ	6.77E2
Use of secondary material [kg]	kg	1.50E3
Use of renewable secondary fuels [MJ]	MJ	4.66E1
Use of non-renewable secondary fuels [MJ]	MJ	8.03E1
Use of net fresh water	m^3	1.21E0
Waste	**Unit**	**A1 to A3**
Hazardous waste disposed	kg	0.00E0
Non-hazardous waste disposed	kg	3.81E-2
Radioactive waste disposed	kg	0.00E0
Output flows	**Unit**	**A1 to A3**
Components for re-use	kg	1.15E1
Materials for recycling	kg	2.80E-2
Materials for energy recovery	kg	0.00E0
Exported energy	MJ	0.00E0

References

Chapter 2

[1] Monografía Ache M-13 *Hormigón Autocompactante: Diseño y Aplicaciones*. Comisión 2. Grupo de Trabajo 2/2 "Hormigón Autocompactante". Ache. Septiembre de 2008. ISBN 978-84-89670-61-7.

[2] Alexander, Sven (1997) "Taking advantage of the environmental challenges facing the precasting industry". FTP symposium proceedings, *The concrete way to development*. Johannesburg.

[3] *fib* (2003) *Environmental issues in Prefabrication*. Bulletin 21.

[4] Alexander, Sven (1997) "Precast concrete manufacture seen from an ecological point of view". *Symposium proceedings, Prefabrication - facing the new century*. Helsinki.

[5] The Intergovernmental Panel on Climate Change (IPCC) http://www.ipcc.ch/report/ar5/

[6] Irastorza,Luis. Las Ciudades Del Siglo XXI. *Ensayo Sobre Sus Fundamentos Socioeconómicos, Tecnológicos, Energéticos Y Climáticos*, Fundación Esteyco, 2012

[7] A European Economic Recovery Plan by the European Commission Brussels, 26.11.2008 COM(2008) 800 final

[8] Viñolas B. "Applications and advances of MIVES methodology in multi-criteria assessments". PhD Thesis. UPC 2011. [In Spanish]. At: http://www.tesisenxarxa.net/

[9] Buildings Performance Institute Europe, Europe's Buildings Under the Microscope, in October 2011, and the Directive European energy efficiency the building.

[10] *Monitoring and Sustainability in Spain*, BP Chair of Energy and Sustainability, Universidad Pontificia Comillas, Edition 2011.

[11] European Directive 2010/31/EU on energy efficiency in the building.

[12] BPIE, 2011, Buildings Performance Institute Europe: BPIE. *Europe's Buildings Under The Microscope*, 2011.

Chapter 3

[1] ACI318-14: Building Code requirements for Structural Concrete, ACI, 2014.

[2] Sakai, Koji, "Sustainability in *fib* Model Code 2010 and its future perspectives", *Structural Concrete* 14 (2013), No. 4, pp. 301-308.

[3] CEN/TC 350: Framework.

[4] Sakai, Koji; Shibata Toshio, Kasuga Akio and Nakamura Hikaru: "Sustainability design of concrete structures", *Structural Concrete* 17(2016), No.6.

[5] López Vidal, A. & Yepes Piqueras, V., *Towards sustainable civil engineering works using precast concrete solutions*. *CPI* 5/2015.

[6] EN 16757:2017.

[7] *fib*: Model Code 2010.

[8] JSCE: Standard Specifications for Concrete Structures, Design, 2012

[9] Sakai, Koji, "Sustainability in *fib* Model Code 2010 and its future perspectives", *Structural Concrete* 14 (2013), No. 4, pp. 301-308

[10] ACI318-14: Building Code requirements for Structural Concrete, ACI, 2014

[11] American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). 2009. Standard for the Design of High-Performance Green Buildings, ANSI/ASHRAE/USGBC/IES Standard 189.1-2009, Atlanta, GA

[12] *ibid*.

[13] *ibid*.

[14] *ibid*.

[15] ISO 14044, Environmental management – Life cycle assessment – Requirements and guidelines.

[16] *ibid*.

[17] *ibid*.

[18] International Code Council (ICC). 2012. International Green Construction Code.

[19] International Code Council (ICC). 2015. International Green Construction Code.

[20] ISO 14044, Environmental management – Life cycle assessment – Requirements and guidelines.

[21] ASTM. 2013. Standard Practice for Minimum Criteria for Comparing Whole Building Life Cycle Assessments for Use with Building Codes and Rating Systems. ASTM E2921.

Chapter 4

[1] Hendriks, Ch. F. (2000) *Durable and sustainable construction materials*, Aeneas.

[2] *fib* (2003) *Environmental issues in Prefabrication*. Bulletin 21.

[3] Aretz, Martijn, *Milieuvergelijkingen van draagconstructies*. Delft University of Technology, Faculty of Civil Engineering, 2001.

[4] *fib* (2013) *Integrated life Cycle assessment of concrete structures*. Bulletin 71.

[5] Sarja, A. (2002), *Integrated Life Cycle Design of Structures*. 1st ed. London: Spon Press, ISBN 0-415-25235-0.

[6] *fib* Bulletin 67 (2012), *Guidelines for green concrete structures*. ISSN 1562-3610.

Chapter 5

[1] Paus, Kjeld: *Platsbygge - prefabbygge inom Sticklingshöyden - Lidingö. Byggforskningsrådet*, Stockholm, 1996.

[2] Carbonation along service life. General principle of rebinding of CO_2 by carbonation of concrete. (Annex BB EN 16757)

[3] T. De Marco, G. Fava, G.L. Guerrini, G. Manganelli, G. Moriconi, L. Riderelli. *Use of photocatalytic products for sustainable construction development*. 2009.

[4] The Concrete Centre. *Thermal Mass. A Concrete Solution For The Changing Climate*. Ref. TCC/05/05 ISBN 1-904818-13-7 First published 2005.

[5] Hietamäki J, Kuoppala M, Kalema T and Taivalantti K (2003). *Thermal mass of buildings – Central researches and their results*. Tampere University of Technology, Institute of Energy and Process Engineering. Report 2003:174. Tampere, Finland, 43 pp and Annex.

[6] Airaksinen, Miimu & Vuolle, Mika, "Heating Energy and Peak-Power Demand in a Standard and Low Energy Building". *Energies* 6/2013. ss. 235–250. 17 s.

[7] Servando Álvarez, Luisa F. Cabeza, Alvaro Ruiz-Pardo, Albert Castell, José Antonio Tenorio. *Building integration of PCM for natural cooling of buildings*.

[8] British Precast Targets 2014.

[9] Arets, Martijn, *Milieuvergelijkingen van draagconstructies*. Delft University of Technology, Faculty of Civil Engineering, 2001.

Chapter 6

[1] Valdivieso Fernández, Raquel, PhD thesis, "Sostenibilidad en el sector de la construcción. Sostenibilidad en estructuras y puentes ferroviarios". Escuela Técnica Superior de Ingeniería Civil, Universidad Politécnica de Madrid, Spain (2016).

[2] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - *Mainstreaming sustainable development into EU policies: Review of the European Union Strategy for Sustainable Development*, 2009.

[3] The European Parliament and The Council of the European Union. Directive 2010/31/EU *On the energy performance of buildings (recast)*, 2010.

[4] The EU Commission. *Analysis of options to move beyond 20% greenhouse gas emission reductions and assessing the risk of carbon leakage*. Commission Staff working document, 2010.

[5] The European Union. Communication from the Commission to the European Parliament and the Council: *Strategy for the sustainable competitiveness of the construction sector and its enterprises*, 2012.

[6] The EU Commission - Directorate-General Research and Innovation. *Energy-efficient buildings – Multi-annual roadmap for the contractual PPP under Horizon 2020*; Publications Office of the EU, 2013.

[7] The European Parliament and The Council of the European Union. *Proposal for a Directive amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments*, 2015.

[8] Framework Convention on Climate Change (UNFCC). *Adoption of the Paris Agreement. Technical Report FCCC/CP/2015/L.9/Rev.1*, United Nations, 2015.

[9] Caverzan, A.; Lamperti Tornaghi, M.; Negro, P., Eds. *Proceedings of SAFESUST Workshop*. Publications Office of the European Union, 2016.

[10] Tsimplokoukou, K.; Lamperti Tornaghi, M.; Negro, P. *Building design for safety and sustainability*; in Scientific and Technical Research Series, Publications Office of the European Union: Luxembourg, 2014.

[11] Caruso, MC.; Lamperti Tornaghi, M.; Negro, P. *Applicability of the Sustainable Structural Design (SSD) method at urban/regional/national level*; in Scientific and Technical Research Series, Publications Office of the European Union: Luxembourg. [in publishing].

[12] ISO. Environmental management – Life cycle assessment – Principles and framework (ISO14040:2006). Standard 14040, International Organization for Standardization, 2006.

[13] ISO. Environmental management – Life cycle assessment – Requirements and guidelines (ISO14044:2006). Standard 14044, International Organization for Standardization, 2006.

[14] Wolf, M.A.; Pant, R.; Chomkhamsri, K.; Sala, S.; Pennington, D. *The International Reference Life Cycle Data System (ILCD) Handbook* - JRC Reference Reports. European Commission JRC, Ispra, Italy, 2012.

[15] Fragiadakis, M.; Vamvatsikos, D.; Karlaftis, M.; Lagaros, N.; Papadrakakis, M. "Seismic assessment of structures and lifelines". *Journal of Sound and Vibration* 2015, 334, 29–56.

[16] Negro, P.; Mola, E. "Performance-based engineering concepts: past, present and future". *First European Conference on Earthquake Engineering and Seismology*. Geneva, 2006.

[17] Olmati, P.; Petrini, F.; Gkoumas, K. "Fragility analysis for the Performance-Based Design of cladding wall panels subjected to blast load". *Engineering Structures* 2014, 78, 112 – 120.

[18] Mueller, H.S.; Haist, M.; Moffatt, J.S.; Vogel, M. "Assessment of the sustainability potential of concrete and concrete structures considering their environmental impact, performance and lifetime". *Construction and Building Materials* 2014, 67, 321 – 337.

[19] Spence, S.M.; Gioffré, M. "Large scale reliability-based design optimization of wind excited tall buildings". *Probabilistic Engineering Mechanics* 2012, 28, 206 – 215.

[20] Deierlein, G.; Krawinkler, H.; Cornell, C. "A framework for performance-based earthquake engineering". *Pacific conference on earthquake engineering*, 2003, pp. 1–8.

[21] Negro, P.; Mola, E. "A performance based approach for the seismic assessment and rehabilitation of existing RC buildings". *Bulletin of Earthquake Engineering* 2017, 15, 3349–3364.

[22] Romano, E.; Negro, P.; Taucer, F. "Seismic performance assessment addressing sustainability and energy efficiency"; *EUR 26432 EN in JRC Scientific and Policy Reports*, Publications Office of the European Union: Luxembourg, 2014.

[23] U.S. Federal Emergency Management Agency. *Recommended Seismic Design Criteria for New Steel Moment-Frame Buildings* (FEMA 350). 2000.

[24] European Comittee for Standardization (CEN). Eurocode 8: Design of structures for earthquake resistance-General rules, seismic actions and rules for buildings (EN 1998–1), 2005.

[25] Ministero delle Infrastrutture. D.M. 14 gennaio 2008: Approvazione delle nuove norme tecniche per le costruzioni. Gazzetta Ufficiale della Repubblica Italiana - Serie Generale n.29 – Suppl. Ord. n. 30), 2008.

[26] Biswas, W.K. "Carbon footprint and embodied energy consumption assessment of building construction works in Western Australia". *International Journal of Sust. Built Environment* 2014, 3, 179–186.

[27] Statistical Office of the European Union (Eurostat). Energy price statistics, 2017.

[28] European Energy Exchange (EEX). European Emission Allowances, current.

[29] Loli, A.; Lamperti Tornaghi, M; Negro, "A method to include Life-Cycle Analysis in Earthquake Design". *16th World Conference on Earthquake Engineering (16WCEE)*. Santiago - Chile, 2017.

[30] Lamperti Tornaghi, M.; Loli, A.; Negro, P. "Balanced Improvement of Safety and Environmental Performances of Buildings". *Buildings*. [in publishing].

[31] B. Alarcón, A. Aguado, R. Manga y A. Josa, A. Value "Function for Assessing Sustainability: Application to Industrial Buildings". *Sustainability*, vol. 3, pp. 35-50, 2011. doi:10.3390/su3010035

[32] T. Saaty. "How to make a decision: The analytic hierarchy process". *Eur J Oper Res*, vol. 48, pp. 9-26, 1990.

[33] T. Saaty. *Fundamentals of decision making and priority theory with the Analytic Hierarchy Process*. Vol. VI, Pittsburgh: RWS Publications, 2006.

[34] E. Kazimieras, J. Antucheviciene, Z. Turskis y H. Adeli. "Hybrid multiple-criteria decision-making methods: A review of applications in engineering". *Sci Iran*, vol. 23, nº 1, pp. 1-20, 2016.

[35] J. San-Jose y I. Garrucho. "A system approach to the environmental analysis industry of buildings". *Build Environ*, vol. 45, nº 3, pp. 673-683, 2010. doi: 10.1016/j.buildenv.2009.08.012

[36] J. San-Jose y J. Cuadrado. "Industrial building design stage based on a system approach to their environmental sustainability". *Constr Build Mater*, vol. 24, nº 4, pp. 438-447, 2010. doi: 10.1016/j.conbuildmat.2009.10. 019

[37] J. Reyes, J. San-Jose, J. Cuadrado y R. Sancibrian. "Health & Safety criteria for determining the value of sustainable construction projects". *Safety Sci*, nº 62, pp. 221-232, 2014. doi: 10.1016/j.ssci.2013.08.023.

[38] J. San-José, R. Losada, J. Cuadrado y I. Garrucho. "Approach to the quantification of the sustainable value in industrial buildings". *Build Environ*, vol. 42, nº 11, pp. 3916-3923, 2007. doi: 10.1016/j.buildenv.2006.11.013.

[39] G. Ormazabal, B. Viñolas y A. Aguado. "Enhancing value in crucial decisions: Line 9 of the Barcelona Subway". *Manage Eng J*, vol. 24, nº 4, p. 265–272, 2008. 2008.. Doi.: 10.1061/(ASCE) 0742-597X(2008) 24:4(265).

[40] F. Pardo y A. Aguado. "Investment priorities for the management of hydraulic structures". *Struct Infrastruct E: Maint Manag Life-Cycl Design and Perform*, vol. 11, pp. 1338-1351, 2014. Doi: 10.1080/15732479.2014.964267.

[41] F. Pardo y A. Aguado. "Sustainability as the key to prioritise investments in public infrastructures". *Environ Impact Asses.* Review. Vol. 60, September 2016, 40-51. Doi: 10.1016/j.eiar. 2016.03.007.

[42] A. de la Fuente, J. Armengou, O. Pons y A. Aguado. "Multi-criteria decision-making model for assessing the sustainability index of wind-turbine support systems. Application to a new precast concrete alternative". *J Civ Eng Manag*, doi: 10.3846/13923730.2015.1023347

[43] A. de la Fuente, O. Pons, A. Josa y A. Aguado. "Multi-Criteria Decision Making in the sustainability assessment of sewerage pipe systems". *J Clean Prod*, vol. 112, nº 5, pp. 4762-4770, 2016. doi: 10.1016 / j.jclepro.2015.07.002

[44] S. Hosseini, A. de la Fuente y O. Pons. "Multi-criteria decision-making method for sustainable site location of post-disaster temporary housing in urban areas". *J Constr Eng M ASCE*, In Press. doi: 10.1061/(ASCE)CO.1943-7862.0001137

[45] S. Hosseini y A. de la Fuente. "Multi-criteria decision-making method for assessing the sustainability of post-disaster temporary housing units' technologies: A case study in Bam". *Sustainable Cities and Society*, vol. 20, pp. 38-51, 2016. doi:10.1016/j.scs.2015.09.012

[46] O. Pons y A. Aguado. "Integrated value model for sustainable assessment applied to technologies used to build schools in Catalonia. Spain". *Build Environ*, vol. 53, pp. 49-58, 2012. doi:10.1016/ j.buildenv.2012.01.007

[47] O. Pons y A. de la Fuente. "Integrated sustainability assessment method applied to structural concrete columns". *Constr Build Mater*, vol. 49, p. 882–893, 2013. doi: 10.1016/j.conbuildmat. 2013.09.009

[48] CPH 2008. Spanish Structural Concrete Standard. Annex 14: Recommendations for the use of fiber reinforced concrete, Madrid, 2008.

[49] Aguado, A. del Caño, P. de la Cruz, P. de la Cruz, P. Gómez y A. Josa. "Sustainability assessment of concrete structures. The EHE approach Rev.", *J Constr Eng* M ASCE, vol. 138, nº 2, pp. 268-276, 2012. Doi: 10.1061/(ASCE)CO.1943-7862.0000419

[50] A. Caño, D. Gómez y M. de la Cruz. "Uncertainty analysis in the sustainable design of concrete structures: A probabilistic method". *Constr Build Mater*, vol. 37, p. 865–873, 2012. doi: 10.1016/ j.conbuildmat.2012.04.020

[51] *MIVES I Project: Integrated Model for a Sustainable Constructive Design. Application to Industrial and Service Buildings;* Ministerio de Ciencia y Educacion: Madrid, Spain, 2002.

[52] *MIVES II Project: Sustainability through Value Analysis Applied to Several Fields*; Ministerio de Ciencia y Educacion: Madrid, Spain, 2005.

[53] *MIVES III Project: Towards Sustainability in Construction through Value Analysis with and without Uncertainty*; Ministerio de Ciencia y Educacion: Madrid, Spain, 2009.

[54] *MIVES IV Project: Quantification of Sustainability in Construction Engineering with and without Uncertainty*; Ministerio de Ciencia y Educacion: Madrid, Spain, 2010.

[55] O. Pons, A. de la Fuente, A. Aguado. "The use of MIVES as a sustainability assessment MCDM method for architecture and civil engineering applications". *Sustainability*, vol. 8, pp. 460-475, 2016. doi: 10.3390/su8050460

Chapter 7

[1] Colliers International, UAE construction cost benchmarking, October 2015.

[2] DEWA Tariff calculator. Dubai Electricity and Water Authority. https://www.dewa.gov.ae/

[3] MEHTA, P. Kumar; MONTEIRO, Paulo J. M. Concreto: *Microestrutura, Propriedades e Materiais*. 2. ed. São Paulo: IBRACON, 2014. Cap. 14. p. 729-742.

[4] CIB - INTERNATIONAL COUNCIL FOR RESEARCH AND INNOVATION IN BUILDING AND CONSTRUCTION - United Nations Environment Programme International Environmental Technology Centre UNEP-IETC. Agenda 21 for Sustainable Construction in Developing Countries: A discussion document. Boutek Report N. Bou/E0204, Pretória, CIB/UNEP-IETC. 2002.

[5] ELKINGTON, J. "Towards the sustainable corporation: Win-win-win business strategies for sustainable development". *California Management Review* 36, 2, 90-100, 1994.

[6] VALDÉS, Adriana. "De cara al siglo XXI: la arquitectura y el concreto". *Construcción y Tecnología En Concreto*, Col. Flórida, v. 4, n. 10, p.16-23, 2015.

[7] COMITÉ EUROPÉEN DE NORMALISATION. EN 15804: Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. Brussels: CEN, 2012.

[8] Pacheco J., Doniak, M., Carvalho, P., Helene, P., (2016), "The paradox of high performance concrete used for reducing environmental impact and sustainability increase", *Proceedings of the Second International Conference on Concrete Sustainability (ICCS 16)*, Madrid, Spain.

[9] EN 15804:2012.

[10] NATIONAL READY MIXED CONCRETE ASSOCIATION. Concrete FL Fact Sheet. Silver Spring, 2012.

[11] ISAIA, G.; GASTALDINI A. "Concreto "verde" com teores muito elevados de adições minerais: um estudo de sustentabilidade". In: I *Conferência Latino-Americana de Construção Sustentável X Encontro Nacional de Tecnologia do Ambiente construído*, 2004, São Paulo, SP. Anais... CD-ROM.

[12] LEVY, S. "Sustentabilidade na Construção Civil: A Contribuição do Concreto". In: ISAIA, G. *Concreto: ensino, pesquisa e realizações. São Paulo: Instituto Brasileiro do Concreto* IBRACON, 2005. Volume 2, Capítulo 50, p. 1551-1579.

[13] KLEIN, C. H. *Concreto e sustentabilidade*. São Paulo, SP. 2008. Disponível em: http://www.instituto5dejunho.blogspot.com. Acesso em: 01 de maio 2009.

[14] LARANJEIRAS, A.C.R.; "Palestra: Estruturas de Concreto Duráveis: Uma chave para o sucesso do Desenvolvimento Sustentável", *Simpósio Comemorativo IBRACON 30 anos*, 2002.

[15] EN 15804:2012

[16] ALLIED CONCRETE LIMITED. Environmental Product Declaration: Ready Mixed Concrete Using Holcim Manufactured Cement. Registration N. S-P-00555. Invercargill, 2014.

[17] ALLIED CONCRETE LIMITED. Environmental Product Declaration: Ready Mixed Concrete Using Holcim Manufactured Cement. Registration N. S-P-00555. Invercargill, 2014.

[18] HELENE, Paulo; HARTMANN, Carine T. "Edifício e-Tower: Record mundial en el uso de hormigón coloreado de altas prestaciones". *Ingenieria Estructural*. 2003. v.11, p.11 - 18.

[19] HELENE, P. R. L. *Corrosão em armaduras para concreto armado*. 1.ed. São Paulo: PINI: Instituto de Pesquisas Tecnológicas, 1986 – Publicação IPT nº 1636. 47p.

[20] The value of the carbonation coefficient was estimated based on literature: Prática recomendada IBRACON – Comentários Técnicos NB-1, produced in 2003. The adopted model has been simplified based on the structure deterioration mechanism of carbonation, through the formula: $e = kCO_2 \cdot \sqrt{t}$, where *e* is the concrete cover in cm, kCO_2 is the carbonation constant in cm/year1/2 and t is the time, in years.

[21] COUTO, Douglas de Andreza. "Projeto de estruturas de edifícios altos com utilização de concreto de alto desempenho". 2009. 58 f. TCC (Graduação) - Curso de Engenharia Civil, Escola de Engenharia de Piracicaba, Piracicaba, 2009.

[22] BENTO, R. C.; ROSSIGNOLO, J. A.. "Avaliação ambiental comparativa de estruturas de concreto armado com a variação da classe de resistência do concreto". In: CONPAT - *XIII Congresso Latino-Americano de Patologia da Construção - XV Congresso de Controle de Qualidade na Construção - Congresso Luso-Africano da Construção*, 2015, Lisboa. Anais. Lisboa: ALCONPAT, 2015.

[23] SCHMIDT; Michael; TEICHMANN, Thomas. "Ultra-high-performance concrete: Basis for sustainable structures". 2007. *Trabalho apresentado ao Central Europe towards Sustainable Building Prague*, Alemanha, 2007.

[24] NATIONAL READY MIXED CONCRETE ASSOCIATION. Concrete FL Fact Sheet. Silver Spring, 2012.

[25] SCHMIDT; Michael; TEICHMANN, Thomas. "Ultra-high-performance concrete: Basis for sustainable structures". 2007. *Trabalho apresentado ao Central Europe towards Sustainable Building Prague*, Alemanha, 2007.

[26] HELENE, P.; TUTIKIAN, B. F. "Concreto de Alto e Ultra Alto Desempenho". In: ISAIA, G. C. *Concreto: Ciência e Tecnologia*. São Paulo: IBRACON, Cap 36, 2011.

[27] SCHMIDT; Michael; TEICHMANN, Thomas. "Ultra-high-performance concrete: Basis for sustainable structures". 2007. *Trabalho apresentado ao Central Europe towards Sustainable Building Prague*, Alemanha, 2007.

[28] BOGGIO, Aldo J.. "Estudo comparativo de métodos de dosagem de concreto de cimento Portland". 2000. 182 f. Dissertação (Mestrado) - Escola de Engenharia, Universidade Federal do Rio Grande do Sul, Porto Alegre, 2000.

[29] HAJEK, P.; FIALA, C.; NOVOTNA, M. "Sustainable Concrete: on the way towards sustainable building". Trabalho apresentado ao *World SB 14*, Barcelona, 2014.

[30] O. Pons, A. de la Fuente, A. Aguado. "The use of MIVES as a sustainability assessment MCDM method for architecture and civil engineering applications". *Sustainability*, vol. 8, pp. 460-475, 2016. doi: 10.3390/su8050460

[31] de la Fuente, A., Blanco, A., Armengou, A., Aguado, A., "Sustainability assessment of different reinforcement alternatives for precast concrete segmental linings", *Proceedings of the Second International Conference on Concrete Sustainability (ICCS 16)*, Madrid, Spain.

[32] de la Fuente, A., Gómez del Pulgar, F., Pardo, F., Aguado, A., *Proceedings of the Second International Conference on Concrete Sustainability (ICCS 16)*, Madrid, Spain.

Annex

[1] EPD Structural Doc_Lowres_Jan2016.pdf, EPD Wall Panel Doc_Lowres_Jan2016.pdf, EPD Underground Doc_Lowres_Jan2016.pdf

[2] ASTM International, Product Category Rules For Preparing an Environmental Product Declaration For Precast Concrete, March 2015.

[3] ISO 14025: 2006 Environmental labelling and declarations - Type III environmental declarations - Principles and procedures

[4] ISO 21930: 2007 Building construction – Sustainability in building construction – Environmental declaration of building products

[5] ASTM International, Product Category Rules For Preparing an Environmental Product Declaration For Precast Concrete, March 2015.

[6] ISO 14025: 2006 Environmental labelling and declarations - Type III environmental declarations - Principles and procedures

[7] ISO 21930: 2007 Building construction – Sustainability in building construction – Environmental declaration of building products

[8] ASTM International, Product Category Rules For Preparing an Environmental Product Declaration For Precast Concrete, March 2015.

[9] ISO 14025: 2006 Environmental labelling and declarations - Type III environmental declarations - Principles and procedures

[10] ISO 21930: 2007 Building construction – Sustainability in building construction – Environmental declaration of building products

[11] ASTM International, Product Category Rules For Preparing an Environmental Product Declaration For Precast Concrete, March 2015.

[12] ISO 14025: 2006 Environmental labelling and declarations - Type III environmental declarations - Principles and procedures

[13] ISO 21930: 2007 Building construction – Sustainability in building construction – Environmental declaration of building products

[14] EPD – Lightweight Concrete Block (Weber Saint-Gobain – 88mm)- Norway.pdf

[15] EN 15804: 2012 + A1: 2013 Sustainability of construction works –Environmental product declarations –Core rules for the product category of construction products

[16] EN 15804: 2012 + A1: 2013 Sustainability of construction works –Environmental product declarations –Core rules for the product category of construction products

[17] EPD – Lightweight Concrete Block (Weber Saint-Gobain – 35 cm)- Norway.pdf

[18] EN 15804: 2012 + A1: 2013 Sustainability of construction works –Environmental product declarations –Core rules for the product category of construction products

[19] EN 15804: 2012 + A1: 2013 Sustainability of construction works –Environmental product declarations –Core rules for the product category of construction products

[20] EPD – Lightweight Concrete Block (Weber Saint-Gobain – 20 cm)- Norway.pdf

[21] EN 15804: 2012 + A1: 2013 Sustainability of construction works –Environmental product declarations –Core rules for the product category of construction products

[22] EN 15804: 2012 + A1: 2013 Sustainability of construction works –Environmental product declarations –Core rules for the product category of construction products

[23] EPD – Lightweight Concrete Block (Weber Saint-Gobain – 15 cm) II- Norway.pdf

[24] EN 15804: 2012 + A1: 2013 Sustainability of construction works –Environmental product declarations – Core rules for the product category of construction products

[25] EN 15804: 2012 + A1: 2013 Sustainability of construction works –Environmental product declarations –Core rules for the product category of construction products

[26] EPD –Concrete – Precast Concrete Kerbs (EcoKerbs)- United Kindom.pdf

[27] The International EPD System: UN CPC 375 Concrete 2013:02 Version 1.01. The LCA was performed using the World Business Council for Sustainable Development (WBCSD) – Cement Sustainability Initiative (CSI) LCA tool (developed by Quantis).

[28] EN 15804: 2012 + A1: 2013 Sustainability of construction works –Environmental product declarations –Core rules for the product category of construction products

[29] EPD –Concrete – Precast Concrete Kerbs (Countryside kerb)- United Kindom.pdf

[30] The International EPD System: UN CPC 375 Concrete 2013:02 Version 1.01. The LCA was performed using the World Business Council for Sustainable Development (WBCSD) – Cement Sustainability Initiative (CSI) LCA tool (developed by Quantis).

[31] EN 15804: 2012 + A1: 2013 Sustainability of construction works –Environmental product declarations –Core rules for the product category of construction products

[32] EPD –Concrete – Precast Concrete Blocks (Lightweight)- United Kindom.pdf

[33] The International EPD System: UN CPC 375 Concrete 2013:02 Version 1.01. The LCA was performed using the World Business Council for Sustainable Development (WBCSD) – Cement Sustainability Initiative (CSI) LCA tool (developed by Quantis).

[34] EN 15804: 2012 + A1: 2013 Sustainability of construction works –Environmental product declarations –Core rules for the product category of construction products

[35] EPD –Concrete – Precast Concrete Blocks (Dense)- United Kindom.pdf

[36] The International EPD System: UN CPC 375 Concrete 2013:02 Version 1.01. The LCA was performed using the World Business Council for Sustainable Development (WBCSD) – Cement Sustainability Initiative (CSI) LCA tool (developed by Quantis).

[37] EN 15804: 2012 + A1: 2013 Sustainability of construction works –Environmental product declarations –Core rules for the product category of construction products

Background Bibliography

Aguado, A., Manga, M., and Ormazábal, G. (2006). “Los aspectos conceptuales del proyecto MIVES.” *La medida de la sostenibilidad en edificación industrial*, R. Losada, E. Rojí, and J. Cuadrado, eds., UPV, UPC, Labein-Tecnalia, Bilbao, Spain, 113-134 (in Spanish).

Alanne, K. (2004). “Selection of renovation actions using multicriteria “knapsack” model” *Autom. Constr*., 13(3), 377–391.

Alarcón, B. (2006). "Modelo integrado de valor para estructuras sostenibles. E.T.S. Ingenieros de Caminos", Canales y Puertos. U.P.C. Doctoral thesis. [in Spanish].

Alexander, Sven (1995) "Can Lightweight Aggregate be used with Advantage in Precasting?" *Symposium proceedings, Structural Lightweight Aggregate Concrete*. Sandefjord.

Asunmaa, Otto-Ville Anttoni (1999) *Optimizing Environmental Effects of Prefabricated Concrete Building Frames*. Helsinki University of Technology

ClMbéton (2002) *Bétons & environnement. Analyses de cycle de vie de bétons*. Paris.

Commission, (1987), Our Common Future, report.

Concrete for energy efficient buildings The benefits of thermal mass. Published by the European Concrete Platform ASBL Editor, Belgium

Cuadrado, J. (2008). "Establecimiento de una metodología general para la medida de la sostenibilidad en el ciclo de vida de los edificios industriales." Ph.D. thesis, Departamento de Ingeniería Mecánica, Escuela Técnica Superior de Ingeniería de Bilbao, Universidad del País Vasco, Bilbao, Spain (in Spanish).

Elizabeth Fry Building, University of East Anglia (1998) The Feedback for designers and clients. New Practice Final Report 106. The Department of the Environment, Transport and the Region's Energy Efficiency, London.

Elizabeth Fry Building. Building Services Journal April 1998

Energy Storage In Concrete Slabs Reduce Energy Consumption And Peak Cooling Loads At No Increase In Capital Costs. A. Engström, L-O. Andersson. Termodeck International Ltd

fib (2004) *Environmental Design*. Bulletin 28. *fib*

fib (2008) *Environmental Design of Concrete Structures*. Bulletin 47. *fib*

Fluitman, A; deLange, V.P.A. (1996) Comparison of the environmental effects of three concrete story floors. CREM Report no. 95.107Amsterdam.

Han, C. H. (2004). "Tools for establishing dominance with linear partial information and attribute hierarchy" Int. J. Syst. Sci., 35(2), 123–132.

Information on buildings and systems in English http://www.nollaenergia.fi

ISO 15686-1:2011, Buildings and constructed assets - Service life planning - Part 1: General principles and framework

Jacobs, F.; Hunkeler, F. (1999) "Design of self-compacting concrete for durable concrete structures". RILEM symposium proceedings, *Self-compacting concrete*. Stockholm.

Kuopion opiskelija-asunnot KUOPAS Oy http://www.kuopas.fi

Losada, R., Rojí, E., and Cuadrado, J. (2006). La medida de la sostenibilidad en edificación industrial, R. Losada, E. Rojí and J. Cuadrado, eds., UPV, UPC, Labein-Tecnalia, Bilbao, Spain.

Mestariasunnot Oy http://www.mestariasunnot.fi

Monografía Ache "Sostenibilidad y Construcción". Ache. Comisión 2. Grupo de Trabajo 2/6 "Sostenibilidad". Junio de 2012. ISBN 978-84-89670-75-4

NEW PRACTICE FINAL REPORT 106. The Elizabeth Fry Building, University of East Anglia – feedback for designers and clients.

Óberg, Mats (2000) *The optimal concrete building*. Lund Technical University. Division of Building Materials. Lund.

Paus, Kjeld (1996) *Platsbygge - prefabbygge inom Sticklingshyden* idingi. Byggforskningsrádet, Stockholm.

Planning and Design Handbook on Precast Building Structures. *fib* Bulletin 76. *fib* Commission 6 Prefabrication.

Punkki, Jouni (2001) "Sustainable Prefabrication". *fib Symposium proceedings, Concrete and Environment*. Berlin.

Ríos, S., Ríos-Insua, M. J., and Ríos-Insua, S. (1989). *Procesos de decision multicriterio*, EUDEMA Universidad Complutense de Madrid, Madrid, Spain.

Saaty, T. L. (1980). *The analytic hierarchy process*, McGraw-Hill, New York.

Saaty, T. L. (2006). *Fundamentals of decision making and priority theory with the Analytic Hierarchy Process*, Vol. VI, RWS Publications, Pittsburgh.

San José, J. T., and Josa, A. (2008). "Planteamiento MIVES para la evaluación. El caso de la EHE" *Cem.-Hormigon*, (913), 26–34 (in Spanish).

Steen, B; Ryding, S-O. (1991) *EPS, The Enviro-Accounting Method, An application of environmental principles for evaluation and valuation of environmental impact in product design*. The Swedish Environmental Research Institute, (IYL), Gothenburg,

Straatman, Remco (2000) *Environmental Related Issues in Precast Demountable Construction*. Delft University of Technology, Faculty of Civil Engineering.

Swiss Society of Engineers and Architects (1998) *Environmental Aspects of Concrete. Information on environmental compatibility*, Zurich.

Tellus Institute The (1992) *The Tellus packaging study. Assessing the impacts of production and disposal of packaging and public policy measures to alter its mix*. Boston.

World Commission on Environment and Development – WECD (Brundtland).

Chris A Clear & Tom De Saulles. *BCA Recarbonation Scoping Study*. 2007.

The *fib* (International Federation for Structural Concrete - Fédération internationale du béton) is grateful for the invaluable support of the following national member groups and sponsoring members, which contributes to the publication of *fib* technical bulletins, the *Structural Concrete* journal and *fib*-news.

National member groups

AAHES - Asociación Argentina del Hormigón Estructural, Argentina
CIA - Concrete Institute of Australia
ÖBV - Österreichische Bautechnik Vereinigung, Austria
GBB-BBG - Groupement Belge du Béton, Belgium
ABCIC - Associação Brasileira da Construção Industrializada de Concreto, Brazil
ABECE - Associação Brasileira de Engenharia e Consultoria Estrutural, Brazil
IBRACON – Instituto Brasileiro do Concreto, Brazil
fib Group of CANADA
CCES - China Civil Engineering Society
Cyprus University of Technology
Cyprus Association of Civil Engineers
Česká Betonářská Společnost, Czech Republic
DBF - Dansk Betonforening, Denmark
SB - Suomen Betoniyhdistys, Finland
AFGC - Association Française de Génie Civil, France
DAfStb - Deutscher Ausschuss für Stahlbeton, Germany
Technical Chamber of Greece
University of Patras, Department of Civil Engineering, Greece
Hungarian Group of the *fib*
The Institution of Engineers, India
fib-Indonesia
University of Amirkabir, Iran
IACIE - Israeli Association of Construction and Infrastructure Engineers
AICAP - Associazione Italiana Calcestruzzo, Armato e Precompresso, Italy
CTE - Collegio dei tecnici della industrializzazione edilizia, Italy
ITC - CNR, Istituto per le Tecnologie della Costruzione, Italy
ReLUIS, Italy
JCI - Japan Concrete Institute
JPCI - Japan Prestressed Concrete Institute
LCS - Lebanese Concrete Society
Administration des Ponts et Chaussées, Luxemburg
fib Netherlands
NZCS - New Zealand Concrete Society
NB - Norsk Betongforening / Norwegian Concrete Association
Polish Academy of Sciences, Committee for Civil Engineering, Poland
GPBE - Grupo Portugês de Betão Estrutural, Portugal
Polytechnic University of Timisoara, Romania
Technical University of Civil Engineering, Romania
University of Transylvania Brasov, Faculty of Civil Engineering, Romania
Association for Structural Concrete, Russia
Association of Structural Engineers, Serbia
SNK *fib*, Slovakia

Slovenian Society of Structural Engineers, Slovenia
University of Cape Town, Department of Civil Engineering, South Africa
KCI - Korean Concrete Institute, South Korea
ACHE - Asociación Cientifico-Técnica del Hormigon Estructural, Spain
SB - Svenska Betongföreningen, Sweden
Délégation nationale suisse de la *fib*, Switzerland
TCA - Thailand Concrete Association
Laboratoire de Génie Civil (LGC), Université de Tunis El Manar, Tunisia
ITU - Istanbul Technical University, Turkey
NIISK - Research Institute of Building Constructions, Ukraine
Society of Engineers, United Arab Emirates
fib UK, United Kingdom
ASBI - American Segmental Bridge Institute, United States of America
PCI - Precast/Prestressed Concrete Institute, United States of America
PTI - Post-Tensioning Institute, United States of America

Sponsoring members

Liuzhou OVM Machinery Company, China
Peikko Group Corp., Finland
Consolis, France
ECS - European Engineered Construction Systems Association (formerly VBBF), Germany
FBF - Betondienst, Germany
ISB - Institut für Stahlbetonbewehrung, Germany
MKT - Metall-Kunststoff-Technik, Germany
Progress Group GmbH, Germany
Larsen & Toubro Ltd, ECC Division, India
KEF Infrastructure India, India
FUJI P. S. Corporation, Japan
IHI Construction Service Company, Japan
Oriental Shiraishi Corporation, Japan
P. S. Mitsubishi Construction Company, Japan
SE Corporation, Japan
Sumitomo Mitsui Construction Company, Civil Engineering Division, Japan
Hilti, Liechtenstein
BBR VT International, Switzerland
Sika Schweiz, Switzerland
VSL International, Switzerland
PBL Group, Thailand
CCL Stressing Systems, United Kingdom
CEG – The Consulting Engineers Group, United States of America

fib Bulletins published since 1998

1 *Structural Concrete – Textbook on Behaviour, Design and Performance*; Vol. 1: *Introduction, Design Process, Materials*
Manual - textbook (244 pages, ISBN 978-2-88394-041-3, July 1999)

2 *Structural Concrete – Textbook on Behaviour, Design and Performance*; Vol. 2: *Basis of Design*
Manual - textbook (324 pages, ISBN 978-2-88394-042-0, July 1999)

3 *Structural Concrete – Textbook on Behaviour, Design and Performance*; Vol. 3: *Durability, Design for Fire Resistance; Member Design, Maintenance; Assessment and Repair, Practical aspects*
Manual - textbook (292 pages, ISBN 978-2-88394-043-7, December 1999)

4 *Lightweight aggregate concrete: Extracts from codes and standards*
State-of-the-art report (46 pages, ISBN 978-2-88394-044-4, August 1999)

5 *Protective systems against hazards: Nature and extent of the problem*
Technical report (64 pages, ISBN 978-2-88394-045-1, October 1999)

6 *Special design considerations for precast prestressed hollow core floors*
Guide to good practice (180 pages, ISBN 978-2-88394-046-8, January 2000)

7 *Corrugated plastic ducts for internal bonded post-tensioning*
Technical report (50 pages, ISBN 978-2-88394-047-5, January 2000)

8 *Lightweight aggregate concrete*: Part 1 (guide) – *Recommended extensions to Model Code 90*; Part 2 (technical report) – *Identification of research needs*; Part 3 (state-of-art report) – *Application of lightweight aggregate concrete* (118 pages, ISBN 978-2-88394-048-2, May 2000)

9 *Guidance for good bridge design*: Part 1 – Introduction, Part 2 – *Design and construction aspects*
Guide to good practice (190 pages, ISBN 978-2-88394-049-9, July 2000)

10 *Bond of reinforcement in concrete*
State-of-art report (434 pages, ISBN 978-2-88394-050-5, August 2000)

11 *Factory applied corrosion protection of prestressing steel*
State-of-art report (20 pages, ISBN 978-2-88394-051-2, January 2001)

12 *Punching of structural concrete slabs*
Technical report (314 pages, ISBN 978-2-88394-052-9, August 2001)

13 *Nuclear containments*
State-of-art report (130 pages, 1 CD, ISBN 978-2-88394-053-6, September 2001)

14 *Externally bonded FRP reinforcement for RC structures*
Technical report (138 pages, ISBN 978-2-88394-054-3, October 2001)

15 *Durability of post-tensioning tendons*
Technical report (284 pages, ISBN 978-2-88394-055-0, November 2001)

16 *Design Examples for the 1996 FIP recommendations Practical design of structural concrete*
Technical report (198 pages, ISBN 978-2-88394-056-7, January 2002)

17 *Management, maintenance and strengthening of concrete structures*
Technical report (180 pages, ISBN 978-2-88394-057-4, April 2002)

18 *Recycling of offshore concrete structures*
State-of-art report (33 pages, ISBN 978-2-88394-058-1, April 2002)

19 *Precast concrete in mixed construction*
State-of-art report (68 pages, ISBN 978-2-88394-059-8, April 2002)

20 *Grouting of tendons in prestressed concrete*
Guide to good practice (52 pages, ISBN 978-2-88394-060-4, July 2002)

21 *Environmental issues in prefabrication*
State-of-art report (56 pages, ISBN 978-2-88394-061-1, March 2003)

22 *Monitoring and safety evaluation of existing concrete structures*
State-of-art report (304 pages, ISBN 978-2-88394-062-8, May 2003)

23 *Environmental effects of concrete*
State-of-art report (68 pages, ISBN 978-2-88394-063-5, June 2003)

24 *Seismic assessment and retrofit of reinforced concrete buildings*
State-of-art report (312 pages, ISBN 978-2-88394-064-2, August 2003)

25 *Displacement-based seismic design of reinforced concrete buildings*
State-of-art report (196 pages, ISBN 978-2-88394-065-9, August 2003)

26 *Influence of material and processing on stress corrosion cracking of prestressing steel – case studies*
Technical report (44 pages, ISBN 978-2-88394-066-6, October 2003)

27 *Seismic design of precast concrete building structures*
State-of-art report (262 pages, ISBN 978-2-88394-067-3, October 2003)

28 *Environmental design*
State-of-art report (86 pages, ISBN 978-2-88394-068-0, February 2004)

29 *Precast concrete bridges*
State-of-art report (83 pages, ISBN 978-2-88394-069-7, November 2004)

30 *Acceptance of stay cable systems using prestressing steels*
Recommendation (80 pages, ISBN 978-2-88394-070-3, January 2005)

31 *Post-tensioning in buildings*
Technical report (116 pages, ISBN 978-2-88394-071-0, February 2005)

32 *Guidelines for the design of footbridges*
Guide to good practice (160 pages, ISBN 978-2-88394-072-7, November 2005)

33 *Durability of post-tensioning tendons*
Recommendation (74 pages, ISBN 978-2-88394-073-4, December 2005)

34 *Model Code for Service Life Design*
Model Code (116 pages, ISBN 978-2-88394-074-1, February 2006)

35 *Retrofitting of concrete structures by externally bonded FRPs*
Technical Report (224 pages, ISBN 978-2-88394-075-8, April 2006)

36 *2006 fib Awards for Outstanding Concrete Structures*
Bulletin (40 pages, ISBN 978-2-88394-076-5, May 2006)

37 *Precast concrete railway track systems*
State-of-art report (38 pages, ISBN 978-2-88394-077-2, September 2006)

38 *Fire design of concrete structures – materials, structures and modelling*
State-of-art report (106 pages, ISBN 978-2-88394-078-9, April 2007)

39 *Seismic bridge design and retrofit – structural solutions*
State-of-art report (300 pages, ISBN 978-2-88394-079-6, May 2007)

40 *FRP reinforcement in RC structures*
Technical report (160 pages, ISBN 978-2-88394-080-2, September 2007)

41 *Treatment of imperfections in precast structural elements*
State-of-art report (74 pages, ISBN 978-2-88394-081-9, November 2007)

42 *Constitutive modelling of high strength / high performance concrete*
State-of-art report (130 pages, ISBN 978-2-88394-082-6, January 2008)

43 *Structural connections for precast concrete buildings*
Guide to good practice (370 pages, ISBN 978-2-88394-083-3, February 2008)

44 *Concrete structure management: Guide to ownership and good practice*
Guide to good practice (208 pages, ISBN 978-2-88394-084-0, February 2008)

45 *Practitioners' guide to finite element modelling of reinforced concrete structures*
State-of-art report (344 pages, ISBN 978-2-88394-085-7, June 2008)

46 *Fire design of concrete structures —structural behaviour and assessment*
State-of-art report (214 pages, ISBN 978-2-88394-086-4, July 2008)

47 *Environmental design of concrete structures – general principles*
Technical report (48 pages, ISBN 978-2-88394-087-1, August 2008)

48 *Formwork and falsework for heavy construction*
Guide to good practice (96 pages, ISBN 978-2-88394-088-8, January 2009)

49 *Corrosion protection for reinforcing steels*
Technical report (122 pages, ISBN 978-2-88394-089-5, February 2009)

50 *Concrete structures for oil and gas fields in hostile marine environments*
State-of-art report (36 pages, IBSN 978-2-88394-090-1, October 2009)

51 *Structural Concrete – Textbook on behaviour, design and performance*, Vol. 1
Manual – textbook (304 pages, ISBN 978-2-88394-091-8, November 2009)

52 *Structural Concrete – Textbook on behaviour, design and performance*, Vol. 2
Manual – textbook (350 pages, ISBN 978-2-88394-092-5, January 2010)

53 *Structural Concrete – Textbook on behaviour, design and performance*, Vol. 3
Manual – textbook (390 pages, ISBN 978-2-88394-093-2, December 2009)

54 *Structural Concrete – Textbook on behaviour, design and performance*, Vol. 4
Manual – textbook (196 pages, ISBN 978-2-88394-094-9, October 2010)

55 *fib Model Code 2010, First complete draft* – Volume 1
Draft Model Code (318 pages, ISBN 978-2-88394-095-6, March 2010)

56 *fib Model Code 2010, First complete draft* – Volume 2
Draft Model Code (312 pages, ISBN 978-2-88394-096-3, April 2010)

57 *Shear and punching shear in RC and FRC elements - Workshop proceedings*
Technical report (268 pages, ISBN 978-2-88394-097-0, October 2010)

58 *Design of anchorages in concrete*
Guide to good practice (282 pages, ISBN 978-2-88394-098-7, July 2011)

59 *Condition control and assessment of reinforced concrete structures exposed to corrosive environments (carbonation/chlorides)*
State-of-art report (80 pages, ISBN 978-2-88394-099-4, May 2011)

60 *Prefabrication for affordable housing*
State-of-art report (130 pages, ISBN 978-2-88394-100-7, August 2011)

61 *Design examples for strut-and-tie models*
Technical report (220 pages, ISBN 978-2-88394-101-4, September 2011)

62 *Structural Concrete – Textbook on behaviour, design and performance*, Vol. 5
Manual – textbook (476 pages, ISBN 978-2-88394-102-1, January 2012)

63 *Design of precast concrete structures against accidental actions*
Guide to good practice (78 pages, ISBN 978-2-88394-103-8, January 2012)

64 *Effect of zinc on prestressing steel*
Technical report (22 pages, ISBN 978-2-88394-104-5, February 2012)

65 *fib Model Code 2010*, Final draft – Volume 1
Model Code (350 pages, ISBN 978-2-88394-105-2, March 2012)

66 *fib Model Code 2010*, Final draft – Volume 2
Model Code (370 pages, ISBN 978-2-88394-106-9, April 2012)

67 *Guidelines for green concrete structures*
Guide to good practice (56 pages, ISBN 978-2-88394-107-6, May 2012)

68 *Probabilistic performance-based seismic design*
Technical report (118 pages, ISBN 978-2-88394-108-3, July 2012)

69 *Critical comparison of major seismic codes for buildings*
Technical report (216 pages, ISBN 978-2-88394-109-0, August 2013)

70 *Code-type models for structural behaviour of concrete*
State-of-art report (196 pages, ISBN 978-2-88394-110-6, November 2013)

71 *Integrated life cycle assessment of concrete structures*
State-of-art report (62 pages, ISBN 978-2-88394-111-3, December 2013)

72 *Bond and anchorage of embedded reinforcement: Background to the fib Model Code for Concrete Structures 2010*
Technical report (170 pages, ISBN 978-2-88394-112-0, May 2014)

73 *Tall buildings: Structural design of concrete buildings up to 300m tall*
State-of-the-art report (158) pages, ISBN 978-2-88394-113-7, August 2014)

74 *Planning and design handbook on precast building structures*
Manual – textbook (313 pages, ISBN 978-2-88394-114-4, September 2014)

75 *Polymer-duct systems for internal bonded post-tensioning*
Recommendation (172 pages, ISBN 978-2-88394-115-1, December 2014)

76 *Benchmarking of deemed-to-satisfy provisions in standards: Durability of Reinforced Concrete Structures Exposed to Chlorides*
State-of-the-art-report (191 pages, ISBN 978-2-88394-116-8, May 2015)

77 *Corrugated-steel-web bridges*
State-of-the-art-report (110 pages, ISBN 978-2-88394-117-5, December 2015)

78 *Precast-concrete buildings in seismic areas*
State-of-the-art-report (273 pages, ISBN 978-2-88394-118-2, March 2016)

79 *Fibre-reinforced concrete - From design to structural applications*
ACI-*fib* workshop proceedings (480 pages, ISBN 978-2-88394-119-9, May 2016)

80 *Partial factor methods for existing concrete structures*
Recommendation (129 pages, ISBN 978-2-88394-120-5, December 2016)

81 *Punching of structural concrete slabs: Honoring Neil M. Hawkins*
ACI SP-315, ACI-*fib* symposium proceedings (378 pages, ISBN 978-2-88394-121-2, April 2017)

82 *Precast segmental bridges*
Guide to good practice (183 pages, ISBN 978-2-88394-122-9, August 2017)

83 *Precast Tunnel Segments in Fibre-Reinforced Concrete*
State-of-the-art report (162 pages, ISBN 978-2-88394-123-6, November 2017)

84 *Precast insulated sandwich panels*
State-of-the-art report (129 pages, ISBN 978-2-88394-124-3,

85 *Towards a rational understanding of shear in beams and slabs*
Technical Report (338 pages, ISBN 978-2-88394-125-0)

86 *Safety and performance concepts*
Guide to good practice (357 pages, ISBN 978-2-88394-126-7)

87 *2018 fib Awards for Outstanding Concrete Structures*
Bulletin (39 pages, ISBN 978-2-88394-127-4)

Abstracts for *fib* Bulletins and lists of available CEB Bulletins and FIP Reports are available on the *fib* website at https://www.fib-international.org/publications.html.

fib CEB-FIP

PCI
Precast/Prestressed Concrete Institute

Sustainability of precast structures

Contents

ISBN 978-2-88394-128-1

International Federation for Structural Concrete
Fédération internationale du béton
www.fib-international.org

ISSN: 1562-3610