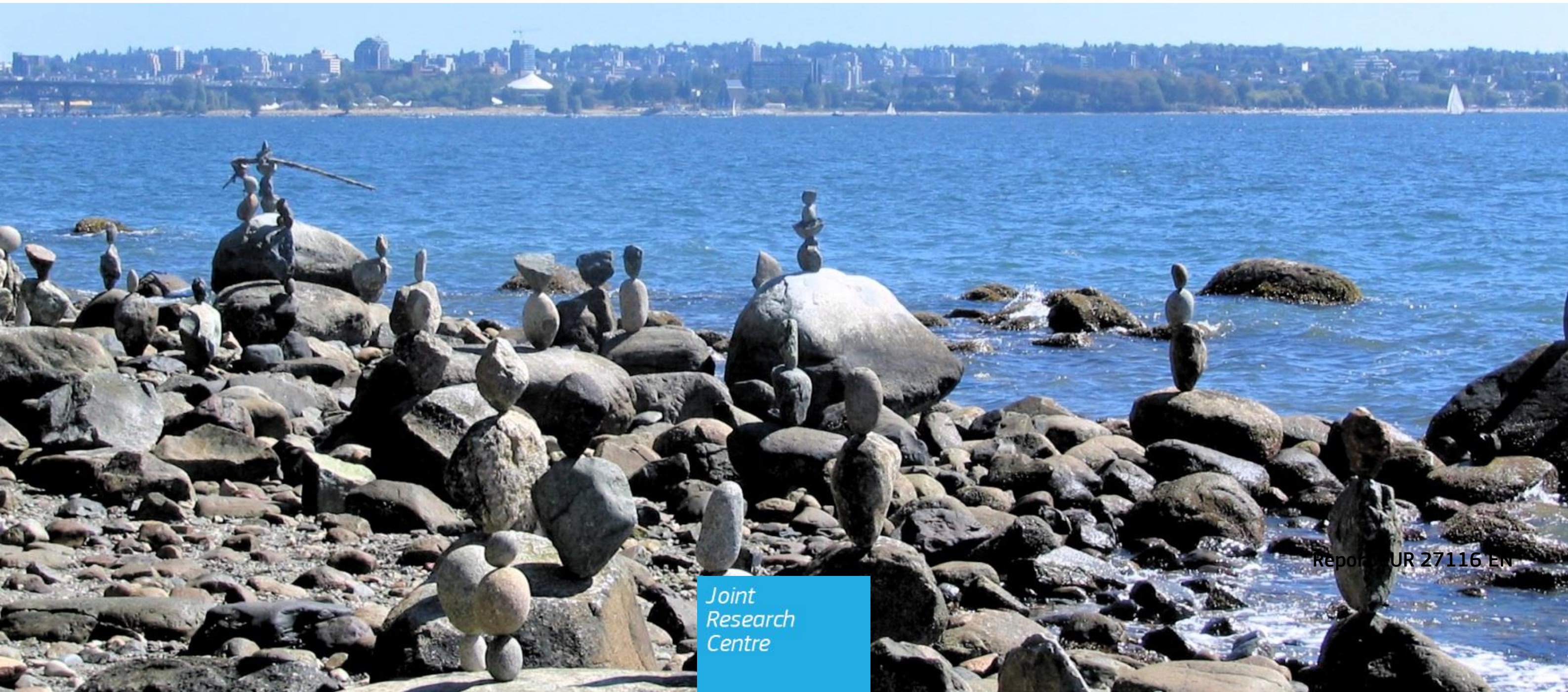
European Commission

JRC SCIENCE AND POLICY REPORTS

Building Design for Safety and Sustainability

Kassiani Tsimplokoukou
Marco Lamperti
Paolo Negro

2014



Report EUR 27116 EN

Joint Research Centre

European Commission
Joint Research Centre
Institute for the Protection and Security of the Citizen

Contact information
Paolo Negro
Address: Joint Research Centre, Via Enrico Fermi 2749, TP 480, 21027 Ispra (VA), Italy
E-mail: paolo.negro@jrc.ec..europa.eu
Tel.: +39 0332 78 5452

https://ec.europa.eu/jrc

JRC93115

EUR 27116 EN

ISBN 978-92-79-45682-4 (PDF)

ISSN 1831-9424 (online)

doi:10.2788/338223

Luxembourg: Publications Office of the European Union, 2014

Abstract
The issue of sustainability in the building industry is prominent, as this industry causes large impacts on the environment but also it contributes greatly in a socioeconomic perspective of growth. In line with sustainability the purpose of this report is twofold: to provide a comprehensive description of the current state-of-the-art building assessment methods and to contribute towards sustainability and building design optimisation through the introduction of a comprehensive design approach. In the first part of the report the role of the environmental methods and footprint schemes in ascertaining building sustainability is examined, with a deeper analysis of the Footprint methods introduced by the European Commission. Footprint schemes provide an environmental assessment on a product-level approach. However, a building is better described as a process than a product, while taking into account the interactions involved in the building life-cycle it seems insufficient to consider building components in isolation.
Current environmental assessment methods evaluate buildings over their life-cycle at a later design stage to provide an indication of their environmental performance. The sole aspect of the environmental performance cannot provide comparable building solutions, while at this stage the information cannot be effectively used in the general design process. A more effective way of achieving building sustainability is to consider the environmental issues in the early design stage, where the principles of durability, probabilistic reliability and safety of structures are involved. Since these parameters are parts of the same whole they need to be addressed together. To move towards sustainability, a new integrated-design approach is deemed essential that allows building assessment in a multi-performance perspective. In the second part, the Sustainable Structural Design (SSD) methodology is presented based on environmental and structural performance parameters in a life-cycle approach. Emphasis is put on integrating the environmental results in the structural performance, which is treated in a probabilistic manner through the introduction of a simplified Performance-Based Assessment method. A global assessment parameter as the result of environmental issues expressed as costs and structural repair and downtime losses is obtained, which allows different stakeholder categories to make decisions in a multi-dimensional perspective. The final part of the report is devoted to further research insights. Both the EU framework on resource efficiency and the communication on resource efficiency opportunities in the building sector are discussed.

Abstract

The issue of sustainability in the building industry is prominent, as this industry causes large impacts on the environment but also it contributes greatly in a socioeconomic perspective of growth. In line with sustainability the purpose of this report is twofold: to provide a comprehensive description of the current state-of-the-art building assessment methods and to contribute towards sustainability and building design optimisation through the introduction of a comprehensive design approach.

In the first part of the report the role of the environmental methods and footprint schemes is examined, with a deeper analysis of the Footprint methods introduced by the European Commission, in ascertaining building sustainability. Footprint schemes provide an environmental assessment on a product-level approach. This approach is questioned when applied to buildings. A building is better described as a process rather as a product, while taking into account the interactions involved in the building life-cycle it seems insufficient to consider building components in isolation.

Current environmental assessment methods evaluate buildings over their life-cycle at a later design stage to provide an indication of their environmental performance. The sole aspect of the environmental performance cannot provide comparable building solutions, while at this stage the information cannot be effectively used in the general design process. A more effective way of achieving building sustainability is to consider the environmental issues in the early design stage, where the principles of durability, probabilistic reliability and safety of structures are involved. Since these parameters are parts of the same whole they need to be addressed together. To move towards sustainability, a new integrated-design approach is deemed essential that will allow building assessment in a multi-performance perspective.

In the second part, the Sustainable Structural Design (SSD) methodology is presented based on environmental and structural performance parameters in a life-cycle approach. Emphasis is put on integrating environmental results in the structural performance, which is treated in a probabilistic manner through the introduction of a simplified Performance-Based Assessment method. A global assessment parameter as the result of ecological costs and structural repair and downtime losses is obtained, which allows different stakeholder categories to make decisions in a multi-dimensional perspective.

The final part of the report is devoted to further research insights. Both the EU framework on resource efficiency and the communication on resource efficiency opportunities in the building sector are discussed.

Keywords: Building design, Performance-Based Assessment, Safety, Sustainability, LCA, PEF method, Footprint, Sustainable Construction

Contents

List of Figures, Tables, Equations

Acronyms and Initialisms

BREEAM Building Research Establishment Method

C_{TOT} Total Cost

CEN European Committee for Standardisation

CEPMC Construction Products Europe

CPF Carbon Product Footprint

CPR Construction Products Regulation

CPWG Construction Products Working Group

DM Damage Measure

DV Decision Variable

E_C Energy used at site for building construction

E_E Embodied Energy

E_D Demolition Energy

E_{DIS} Dismantling Energy

E_O Operating Energy

E_{LC} Life Cycle Energy

E_{OA} Annual operating energy

E_T Energy for the transportation of materials

EDP Engineering Demand Parameter

EF Ecological Footprint

EMF Emission Footprint

ENF Energy Footprint

EPBD Energy Performance Building Directive

EPDs Environmental Product Declarations

EUA_S European Emissions Allowances

EU ETS European Union Emissions Trading System

GHG Protocol Greenhouse Gas Protocol

GPP Green Public Procurement

GWP Global Warming Potential

IDA Incremental Dynamic Analysis

IDR Inter-storey drift ratio

ILCD Handbook International Reference Life Cycle Data System Handbook

IM Intensity Measure

ISO International Organisation for Standardisation

L total expected Loss

L_b Life span of the building

LCA Life Cycle Assessment

LEED Leadership in Energy and Environmental Design

m_i Material quantity

M_i energy content of material per unit quantity

MAF Mean Annual Frequency

NF Nitrogen Footprint

OEF Organisational Environmental Footprint

OEFCRs Organisation Environmental Footprint Category Rules

P_{CO2} Carbon price

P_{ENERGY} Energy price

PAS 2050 Publicly Available Specifications

PBA Performance-Based Assessment

PBD Performance-Based Design

PEER Pacific Earthquake Engineering Research Center

PEER PBEE Pacific Earthquake Engineering Research Center Performance Based Earthquake Engineering

PEF Product Environmental Footprint

PEFCRs Product Environmental Footprint Category Rules

PGA Peak Ground Acceleration

PV Present Value

Q_{CO2} Quantity of carbon emissions

Q_{ENERGY} Quantity of energy consumption

R_N Probability of exceedance

R_{SSD} Global assessment parameter of the SSD methodology

SbTool Sustainable Building Tool

$_S$PBA Simplified Performance-Based Assessment

SSD Methodology Sustainable Structural Design Methodology

T_R return period

WBCSD World Business Council for Sustainable Development

WF Water Footprint

WRI World Resources Institute

Executive Summary

Part I: Environmental Methods and Footprint Schemes towards Sustainable Building Design

The aim of this report is to contribute towards sustainability and building design optimisation with the introduction of a new approach to design buildings both for safety and sustainability. EU policy initiatives aim at addressing sustainability in the building sector, while reduced energy consumption and carbon emissions are defined as crucial targets for this sector.

In the first part of the report, a comprehensive description of state-of-the-art for building assessment methods is provided. In addition a description of the general framework towards sustainable buildings is given. Those methods have been developed by the industry, research community and organisations as well as by the European Commission.

The analysis involves:

- the European framework towards environmental sustainable buildings;
- the Standardised framework developed by the International Organisation of Standardisation (ISO);
- the Sustainable construction framework developed by CEN;
- description of methods such as BREEAM, LEED, SbTool;
- footprint methods and schemes with a further analysis on the product environmental footprint method (PEF) developed by the European Commission. Further insights involve the relation of this method with the EN 15804 standard.

The central focus of these methods lies on the environmental aspect. More specifically, the sustainability assessment of a building is involved at a later design stage on the basis of the environmental impacts that are produced throughout its lifecycle. In addition, footprint methods provide the assessment on a product-level approach. This approach is questioned when is applied to buildings; taking into account the interactions involved in building life cycle it seems insufficient to consider building components in isolation.

A building is better described as a process rather than a product. This process involves correlating and complementary technical, environmental and economic parameters. To this regard, the environmental information could be better addressed and more effectively used in the general design process. In this early design stage the principles of structural response, durability and reliability of a structural system are also involved, while all these various parameters are closely related and significant in resolving cost, resource and environmental constraints.

A more fruitful way to design sustainable buildings considers these parameters as parts of the same whole and thus, allows them to be addressed together. To move towards sustainability and building design optimisation new holistic approaches to design structural systems are needed that provide building design and thus, assessment in a multi-performance perspective.

Part II: Introduction of the Sustainable Structural Design (SSD) Methodology

In the second part of the report, a new approach to design buildings is presented. The Sustainable Structural Design (SSD) methodology, based on a life cycle approach, incorporates the environmental results in the structural design (figure 1).

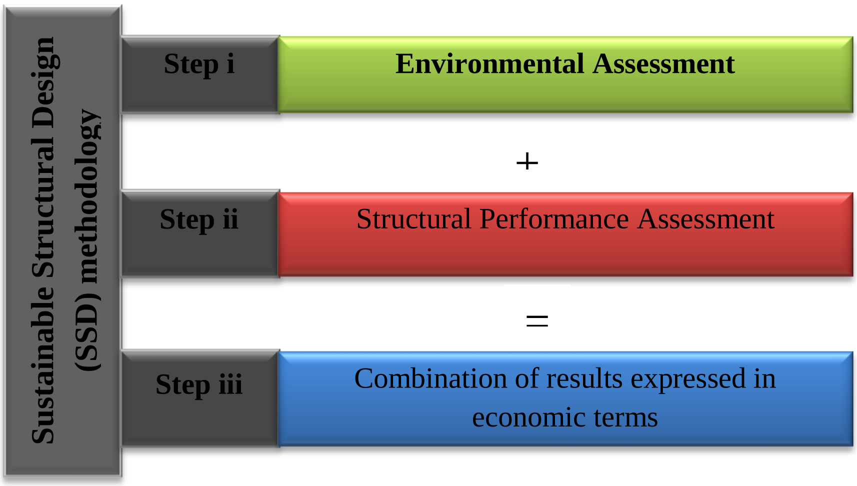


Figure 2: Framework of the Sustainable Structural Design (SSD) Methodology

The first step of this method follows the life cycle assessment (LCA) approach as it has been introduced by the ISO 14044 Standard. This method provides a framework to define and quantify the environmental impacts resulting throughout the building's life cycle: the production, construction, use-phase and demolition of a building, including considerations of recycling and reuse. The output is the environmental impacts in terms of air, water pollution and energy consumption, produced through constructing, using and disassembling.

The structural performance is treated in a probabilistic manner through the introduction of a simplified Performance-Based Assessment Method (figure 2). The Performance-Based Assessment (PBA) of structural systems involves the implementation of probabilistic scenarios for the evaluation of the response of the structures under uncertain and/or extreme events. Structures are designed in a way to meet predefined performance objectives as well as needs tailored to user/customer requirements. More specifically, in a structural aspect, such methods provide more reliable and predictable results in terms of safety and operability. In an economic perspective, those methods involve the estimation of the costs needed to repair damaged buildings as well as the calculation of the downtime losses. These costs are considered along with the initial construction cost.

The environmental impacts are converted into costs in the third step of the SSD method. Prices that are defined by the EU market, they are used both for the energy consumption and for the carbon emissions data. All the environmental impacts associated with the global warming potential (GWP) are converted into CO_2 equivalent and are multiplied by the carbon price defined under the European Union emissions trading system (EU ETS). A global assessment parameter, as the result of environmental (emissions, energy consumption) and structural costs (repair costs, downtime losses, initial construction cost) is obtained. Using this approach, stakeholders are able to evaluate, compare and make decisions between alternative building design solutions.

Part III: Resource Efficiency

The third part of the report provides a description of the European policy framework on resource efficiency and the Communication on ''*Resource Efficiency Opportunities in the Building Sector*''. This Communication aims at promoting a more efficient use of construction materials as well as to reduce the environmental impacts regarding the whole life-cycle of buildings. The development of transparent and comparable indicators for building assessment has been defined as the next step. These indicators are not available yet but they will be associated to total energy consumption, use of construction materials and their embodied environmental impacts, durability of construction products, design for deconstruction, construction management and demolition waste, recycling, water-use, intensity use of buildings and indoor comfort.

The SSD methodology, presented in this report, is capable of accounting for all components of sustainability in the design process. The design process is traditionally driven by costs (construction costs, expected maintenance and transformation costs, expected losses in the event of extreme actions etc.). Therefore, a method based on the conversion of all parameters that are associated to the environment (energy consumption, GHG emissions, depletion of resources) into costs is proposed. To this regard, different design options are sorted with respect to a total cost, so that the most efficient solution could be identified.

Part I: Environmental Methods and Footprint Schemes towards Sustainable Building Design

1. Sustainability and the Building Sector

1.1 Introduction

Sustainability involves the interactions and significant relationships among environmental, social and economic parameters. With reference to the building sector, sustainability is about ensuring that a building is environmentally friendly, economically feasible as well as that it provides a healthy and quality indoor environment to its users. Sustainable building construction refers to various methods applied for implementing construction projects that involve environmental preservation, increased reuse of waste for the production of construction materials, actions fruitful to the society, and profitable aspects for the company (1).

The improving social, economic and environmental indicators of sustainable development are drawing attention to the construction industry, which is a globally emerging sector, and a highly active industry in both developed and developing countries (2). In a socioeconomic perspective, according to Eurostat data, 13.4 million persons are employed in the construction sector, accounting for 7.5% of the total employment in the EU-27. In addition, the building sector is one of the largest sectors within the EU-27, operating 882 thousand enterprises and employing 3.9 million people, accounting for 29.4% of the total employment in construction. These enterprises generated 150.9 billion euro of value added which was 2.5 % of the non-financial business economy total and 30.4 % of the construction total (3). However, in an environmental perspective, the data indicate that buildings are responsible for approximately the 40% of the total energy consumption in the EU (4) and 30% of the total carbon dioxide emissions (5), apart from high resource-use and solid waste generation (2).

Improving the environmental performance of buildings is receiving increasing attention by researchers, policy-makers and the industry. The latter has resulted in EU regulations that focus on the environmental aspect of sustainability (6). Specifically, the European Commission introduced the "Resource efficiency opportunities in the building sector" proposal. This initiative covers the environmental dimension of sustainability considering materials, waste, water use and embedded energy aiming at efficiency resource use and reduced environmental impacts (7). Other existing EU Regulations are mainly directed to improve energy efficiency of buildings (Energy Performance Buildings Directive, Energy Efficiency Directive, the Energy Labelling Directive and the Eco-design directive). In addition, the revised Waste Framework Directive corresponds to the European policy towards recycling and waste demolition in construction (8).

However, while currently the focus is on energy saving and use of environmentally friendly materials, other aspects also affect the performance of buildings in terms of sustainability (6). A building project can be considered as sustainable only when all the three dimensions of sustainability – environmental, economic, social– are taken into account. The dimensions of sustainability are interlinked and influence each other, while the interrelationship of a building with its surroundings creates various effects. The use of renewable sources and water, waste generation and production of emissions are among the present common concerns. With reference to the building industry, preservation of the cultural heritage, natural conservation, use of eco-friendly materials, energy saving and more quality indoor conditions are addressed as main objectives. To achieve these objectives and to foster sustainable building construction, holistic approaches must be adopted. Building sustainability assessment methods could contribute in promoting a more sustainable built environment (9).

1.2 Review of Sustainable Methods and Tools for Buildings

Building Environmental and/or Sustainable Assessment methods are evidence of the importance of integrating a sustainability approach both in building design and construction (10). Those methods, which are based on a Life cycle approach, can provide both owners and occupants with long-term benefits, namely reduced environmental impacts, higher quality indoor conditions and lower operational buildings expenses (9).

During the last two decades a significant number of environmental and sustainability assessment tools for buildings have been developed by diverse organisations throughout the world (11, 12). The Building Research Establishment Method (BREEAM) was founded in the UK in 1990 and was the first commercial available environmental assessment tool for buildings (13). This method together with the Leadership in Energy and Environmental Design (LEED) method and the Sustainable Building Tool (SbTool) have provided the basis for the development of other tools used globally.

In general, these assessment methods evaluate a number of partial building characteristics with the use of indicators and communicate these results based on an environmental rating or sustainability score (9). These indicators provide information regarding the impacts resulted from the construction and operation of buildings and other built assets. However, these methods usually are not comparable (14), as it is evident that each method was developed in order to meet local demands (12).

Diverse attempts to format a list of generally accepted indicators have led to the creation of different elements and evaluating criteria in different countries. The latter, can be considered as a real response to meet actual demands of decision-making, as both the essential indicators and their weights are highly dependent on the environmental, social and economic contexts of their use (9).

1.3 Continuing Standardisation Work on ″Sustainable Construction″

In an attempt to define an objective definition of the '' Sustainable construction'' term and to provide a common framework to compare results, the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN) have worked actively to define standard requirements for the environmental and sustainability assessment of buildings. Specifically, as a result of the ISO Technical Committee (TC) 59, "Building construction", and its Subcommittee (SC) 17, "Sustainability in building construction", the following technical specifications and standards were published:

- ISO/TS 21929-1:2006, Sustainability in building construction – sustainability indicators – Part 1: Framework for the development of indicators for buildings
- ISO 21930:2007, Sustainability in building construction – environmental declaration of building products
- ISO 15392:2008, Sustainability in building construction – general principles
- ISO 21931-1:2010, Sustainability in building construction – framework for methods of assessment of the environmental performance of construction works – Part 1: Buildings (15)

In parallel, CEN has provided standardised methods towards achieving sustainability in construction. Specifically, the Technical Committees were set up in 2005 to carry out the CEN 350 work "Sustainability of construction works", that provides standardized methods for the assessment of the sustainability aspects of new and existing construction works as well as standards for the environmental product declarations (EPD) of construction products. As a result of the work carried out to date the following pre-standards and standards have been developed:

- CEN/TR 15941:2010, Sustainability of construction works – Environmental product declarations – Methodology for selection and use of generic data
- EN 15804: Sustainability of construction works – Environmental Product declarations –Core rules for the product category of construction products
- EN 15643-1:2010, Sustainability of construction works – Sustainability assessment of buildings – Part 1: General framework
- EN 15643-2:2009, Sustainability of construction works – Assessment of buildings – Part 2: Framework for the assessment of environmental performance
- EN 15643-3:2008, Sustainability of Construction Works – Assessment of buildings – Part 3: Framework for the assessment of social performance
- EN 15643-4:2008, Sustainability of Construction Works – Assessment of buildings – Part 4: Framework for the assessment of economic performance

- EN 15978:2010, Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method (16)

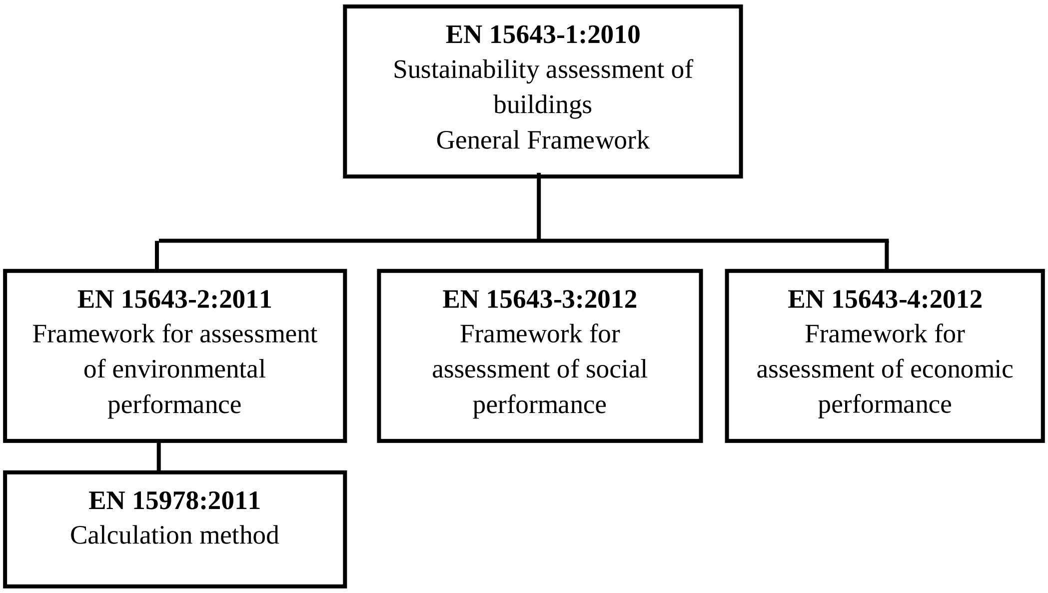


Figure 3: European Standardisation suite for the assessment of the sustainability of building (17)

Those standards aim to provide harmonised methodologies for the assessment of the environmental and the life cycle cost performance of buildings along with quantifiable social performance aspects e.g. health and comfort of buildings. Technical and functional requirements for buildings are also integrated in the sustainable assessment of buildings (15, 16).

1.4 European Framework on Sustainability for Buildings

In the same line, with reference to the term ''Sustainable buildings'' EU current actions cover the dimension of environmental sustainability focusing on the reduction of the environmental impacts associated with buildings. Therefore, existing EU policy initiatives and Regulations are mainly directed to improve the environmental performance of buildings including energy efficiency and eco-friendly materials. Some of the EU Regulations that have been published and reflect the work towards environmental sustainability are the following:

- Energy Performance Building Directive (EPBD)
- EcoDesign Directive (energy related products)
- Energy Labelling Directive (energy related products)

- EcoLabelling Regulation
- EcoLabel for Buildings (first priority office buildings)
- Energy Efficiency Action Plan (2007-2012, 2013-2020)
- Green Public Procurement (GPP)
- Construction and Demolition Waste (Waste Framework Directive)
- Lead Market Imitative (on Sustainable Construction)
- Resource Efficiency Roadmap–EC (DG/Env) communication on Sustainable buildings
- CPR →obligatory CE marking of CPs 1th July 2013–New: BRCW 7 Sustainable use of natural resources (18).

The "Resource Efficiency Opportunities in the Building Sector" report suggests that existing policies on buildings, which mainly referring to energy efficiency, should be combined and/or integrated within policies for resource efficiency taking into account environmental impacts and resource use throughout the building life cycle. In that way, except of resource efficiency and reduced environmental impacts, competition and thus improvement procedures could be enhanced in the construction sector (7).

In addition, the Communication on "Strategy for the Sustainable Competitiveness of the Construction Sector and its enterprises" indicates crucial challenges that the construction sector needs to face until 2020 in order to be more efficient in the future. These challenges include improving resource efficiency, environmental performance and respective business opportunities. Furthermore, it refers to the future Communication on Sustainable Buildings and proposes areas for future development, such as the need for "methods to assess the environmental performance of buildings" while the action plan refers to an EU wide life cycle costing methodology applied to buildings for green public procurement (19).

These regulations reflect the work towards sustainable buildings as well as towards achieving the EU targets on climate policy, which refer to a 20% reduction of the carbon emissions and energy use, both by 2020 (20).

2. Environmental Footprint Schemes for Products

2.1 Background of the Environmental Footprint Schemes

In line with environmental sustainability, diverse tools have emerged known as footprints, which are applied for the assessment of environmental as well as other financial and social issues (21, 22).

With reference to the environmental footprints, examples include the ecological footprint (EF), which was introduced in 1992 (23), the water footprint (WF) that was developed in 2002 (24) and the carbon footprint, which is interlinked with the global warming potential (21) and was introduced in the 1990's (25).

In recent years, attempts have been made to develop a unified footprint method for the evaluation of the environmental impacts of production and consumption (22). According to the latter, the European Commission has introduced two methods for addressing the environmental footprint of products and organisations, namely the Product and Organisation Environmental Footprint (PEF and OEF) methods. This work relates to one of the building blocks of the Europe 2020 Strategy – "Roadmap to a Resource Efficient Europe" and specifically refers to one of its aims, which is to "Establish a common methodological approach to enable Member States and the private sector to assess, display and benchmark the environmental performance of products, services and companies based on a comprehensive assessment of environmental impacts over the life cycle ('environmental footprint')" (26).

In general, environmental footprint schemes offer environmental-oriented information, such as energy and water consumption, carbon emissions and waste generation. The results are expressed as a single score in order to provide information about the environmental footprint of products. The framework of such methods usually follows the LCA approach by attributing potential environmental impacts to a specific product in a supply chain perspective (27).

Improving the environmental performance of products and communicating their environmental footprint is receiving considerable attention (28). The latter is also highlighted by the diverse attempts (29) to develop international standards on carbon footprint of products (PAS 2050, GHG Protocol and ISO 14067) (30), European guidelines for environmental footprint studies (PEF, OEF methods) (26) as well as other footprint schemes (30).

2.2 Overview of Environmental Footprint Methods

The term ''footprint'' is described as a quantitative value, which defines the degree in which humans affect the environment and the natural resources (21). Another explanation defines the footprint as the value that describes how human activities can cause different types of impacts on global sustainability (31).

Common methods available for calculating environmental footprints include ecological, materials, carbon, nitrogen, and water footprint analyses (21). Specifically, the Ecological Footprint (EF) Standard introduced by Global Footprint Network and measures the degree to which human activities surpass biocapacity (32). The Water Footprint (WF) method is similar to the concept of virtual water (33) and describes the total amount of direct and indirect fresh water consumed and/or polluted during an activity. It is a method used for estimating in a quantifiable perspective, the water usage for a specific product considering a wide group of consumers (individual, city, state, nation) or producers (public organizations, companies, sectors) (34). Other environmental footprints are the Energy Footprint (ENF), which includes other sub-footprints such as the fossil, nuclear and renewable energy footprint, the Emission footprint (EMF), which describes the emissions into the air resulted from a product or service, the Nitrogent Footprint (NF), the Land Footprint, the Biodiversity Footprint (BF) and others. However, apart from major categories of footprints, such as the carbon footprint, extensive application of other footprints is missing, and thus general conclusions about their effectiveness cannot be appropriately obtained yet (21).

With reference to the carbon footprint, this was first introduced in the 1990's and has its origin in the ecological footprint (*25*). It is described as the amount of CO_2 or equivalent greenhouse gas (GHG) emissions produced during an activity or process over a product's life cycle (*35*). Three internationally acknowledged GHG standards have been fundamental in addressing the carbon footprint of products, which are the Publicly Available Specifications (PAS) 2050, GHG Protocol Product Standard and the ISO 14067 Carbon Product Footprint (CPF).

The Publicly Available Specifications (PAS) 2050 were first introduced in 2008 by the British Standard Institution (BSI 2008) and follow the LCA approach as provided by the ISO 14040 and 14044 standards. PAS 2050 was revised in 2011 (BSI 2011), in line with the GHG Protocol Product Standard (WRI and WBCSD, 2011) regarding issues such as sector/product rules, biogenic carbon, recycling, land-use change, delayed emissions. This standard provides support on how to deal with several issues such as system boundary definition and allocation as well as carbon storage and delayed emissions. However, it does not specify guidelines for products or sectors, but in a similar way with the GHG Protocol, it supports the use and development of sector specific rules known as 'supplementary requirements'.

The GHG Protocol Product Standard is the result of the joint initiative of World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). It was published in 2011 and provides the requirements and the guidelines for the quantification of the GHG inventories for products as well as the communication of the results expressed in a carbon footprint value. The GHG Protocol is based on the LCA methodology provided by the ISO standards as well as on the first version of PAS 2050 published in 2008 (BSI, 2008). It recommends the development and use of sector specific rules, titled ''product rules'' in order to enhance transparent and accurate comparisons between products.

In parallel, the ISO 14067 is an under development standard for product carbon footprinting and communication including labelling (30). The CFP standard aims at addressing the impact category of climate change; therefore other social, economic and environmental impacts resulting from products are not evaluated. The CFP study measures the GHG emissions and removals during the life cycle of a product so as the potential contribution to the global warming, expressed as CO_2, could be calculated. The methodology followed for the CFP quantification includes all the four phases of the LCA methodology based on the 14044 Standard (ISO 14067). In line with the increasing interest in the use of carbon labelling schemes, ISO 14067 aims at providing guide and standardisation lines on carbon labels, which can further contribute to the development of reliable and comparable carbon schemes in the future (36).

2.3 The EU Environmental Footprint Methods

2.3.1 Policy Context

In the same vein, the European Commission published in April 2013 an official journal, titled ''Recommendations on the Use of Common Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations''. This Recommendation supports the use of environmental footprint methods in policies and schemes that measure or communicate the product's environmental performance in a life cycle perspective. In addition, two new methodologies for conducting Environmental Footprint studies, namely the Product and Organisational Environmental Footprint methods (PEF and OEF), were presented.

The PEF and OEF methods were initiated with the aim of developing a harmonised European methodology for Environmental Footprint (EF) studies that cover a wider group of environmental performance criteria following a life-cycle approach. These methods were developed under the co-operation of the JRC -IES and DG ENV and refer to the EU policies regarding sustainability and environmental performance of products. Specifically, this project lies on the following three actions (25):

1. "Integrated Product Policy - Building on Environmental Life-Cycle Thinking":

The importance of addressing the environmental impacts resulting throughout a product's life cycle in an integrated way was recognised (37).

2. "Sustainable Materials Management and Sustainable Production and Consumption":

The European Council invited the European Commission to develop a common methodology for addressing in a quantitative perspective, the environmental impacts incurring throughout a product's life cycle, in order to support the use of product labelling. The initial aim was described in the conclusions of the ''*Sustainable Consumption and Production Action Plan''*, where the Council invited the Commission to develop voluntary methodologies that facilitate the future establishment of carbon audits for organisations and the calculation of the carbon footprint of products (38).

3. *"Roadmap to a Resource Efficient Europe'':*

Included proposals regarding increased resource productivity and aimed to support growth in a life-cycle perspective. One of the aims was to "*establish a common methodological approach to enable Member States and the private sector to assess, display and benchmark the environmental performance of products, services and companies based on a comprehensive assessment of environmental impacts over their life cycle (environmental footprint)*". Furthermore another aim was to '' *ensure better understanding of consumer behaviour and provide better information on the environmental footprints of products, including preventing the use of misleading claims, and refining eco-labelling schemes* '' (23).

Apart from these three actions, the Communication on "*Single Market Act*" included also a specific objective regarding the environmental footprint of products, which describes the initial aim and acts as the starting point. This action specifically stated that ''*before 2012, the Commission will look into the feasibility of an initiative on the Ecological Footprint of Products to address the issue of the environmental impact of products, including carbon emissions. The initiative will explore possibilities for establishing a common European methodology to assess and label them''* (39).

Those three actions were implemented through the adoption of *the "Communication Building the Single Market for Green Products"* (40) and the "*Commission Recommendation on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations"*. The key element of these communications is the establishment of the product environmental footprint (PEF) and the organisation environmental footprint (OEF) methods that address the environmental performance of products and services in a life cycle perspective. Furthermore, this project supports international attempts considering cooperation in methodological development as well as in availability of data, while it provides the principles for communicating the environmental performance in a transparent, reliable, complete and comparable way. These methods are targeted to the member states including companies, private organisations and the financial community that follow similar procedures for the environmental assessment of their products and services (26).

2.3.2 Continuing Work on the PEF and OEF Method

As a result to the work carried out until today concerning the development of a unified Environmental Footprint method, which resulted in the development of the PEF and the OEF methods, some of the documents that have been published are the following:

- *Analysis of Existing Environmental Footprint Methodologies for Products and Organisations: Recommendations, Rationale and Alignment (2010).*

- *Product Environmental Footprint (PEF) Guide (2012): Deliverable 2 and 4A of the Administrative Arrangement between DG Environment and the Joint Research Centre No N070307/2009/552517, including Amendment No 1 from December 2010.*

- *Communication from the Commission to the European Parliament and the Council. Building the Single Market for Green Products: Facilitating better information on the environmental performance of products and organisations (2012).*

- *Commission staff working document executive summary of the impact assessment. Accompanying the document Communication from the Commission on Building the Single Market for Green Products: Facilitating better and credible information on environmental performance of products and organisations (2012).*

- *Study on different options for communicating environmental information for products. Final report. European Commission – DG Environment (2012).*

- *Commission Recommendation, 2013, on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations (2013/179/EU). The Final Product Environmental Footprint and Organisation Environmental Footprint methods were published as an annex (2013).*

- *Attitudes of Europeans towards building the single market for green products. Report (2013).*

- *Materials of the PEF training for piloters (January 2014).*

- *European Commission, 2014, Environmental Footprint Pilot Guidance document, - Guidance for the implementation of the EU Product Environmental Footprint (PEF) during the Environmental Footprint (EF) pilot phase, v. 4.0, May 2014.*

- *Summary EF construction product working group (CPWG) meeting 30/7/2014 .*

- *Draft Product Environmental Footprint Category Rules (PEFCRs) 1 and 2: PEFCRs are essential for more robust and consistent assessments, especially if results are indented to be used for comparisons in a policy context or for communication to consumers.*

- *Draft Organisation Environmental Footprint Category Rules (OEFCRs) 1: OEFCRs are essential for more robust and consistent assessments, especially if results are indented to be used for comparisons in a policy context or for communication to consumers.*

- *JRC Technical Report (September 2014): Normalisation method and data for Environmental Footprints, Deliverable 2 of the AA Environmental Footprint and Material Efficiency Support for Product Policy (No. 70307/2012/ENV.C.1/635340).*

The PEF and OEF methods were implemented and tested under a number of pilot studies that represent a variety of goods and services. The first phase started on the 1st of November 2013 and includes 14 pilot studies some of which were thermal insulation, metal sheets, photovoltaic electricity generation, stationery, IT equipment, household detergents, hot and cold water supply pipes. The second phase, which started on June 2014, includes 11 pilot studies and covers the categories of food, feed and drinks. Based on a further three - year testing period (2013-2016), the Product Environmental Footprint Category Rules (PEFCRs) as well as the Organisation Environmental Footprint Category Rules (OEFCRs) will be developed in order to provide further guidance on how to conduct an environmental footprint study for specific categories of products as well as to increase transparency in such studies (40).

2.3.3 The Product and Organisation Environmental Footprint (PEF- OEF) Methods

The product environmental footprint (PEF) is a multi-criteria measure of the environmental performance of a product or good / service over its life-cycle, while the organisation environmental footprint (OEF) method covers a range of products that an organisation produces. Those two methods were developed based on the life cycle assessment (LCA) methodology as well as on existing internationally recognised standards and methodologies as illustrated in figure 3 and 4.

With reference to the PEF method, an analysis of existing methodologies of product carbon footprint methods was initially conducted and the relation of these methods in future policies was examined. The latter, led to the conclusion that all environmental impacts of products should be taken into account, as GHG emissions do not represent the most crucial environmental aspect of some product categories. Therefore a Product Environmental Footprint project was initiated with the aim of developing a harmonized environmental footprint methodology that covers a broader variety of relevant environmental performance criteria.

Both the Product Environmental Footprint (PEF) and the Organisation Environmental Footprint (OEF) methods follow a life cycle approach to calculate the environmental impacts and to evaluate the environmental performance. The PEF method applies specifically to individual products or services, whereas the OEF method covers organisational activities as a whole and thus all activities associated with the products and/or services of the organisation considering a supply-chain perspective (from extraction of raw materials, through use, to final waste management).

Although the adoption of the OEF and PEF methods is not mandatory, it is suggested that companies and sector unions should choose them and promote their use, as these methods could be useful for the assessment of the environmental performance of their products and organisations. In addition, the organisation and product environmental Footprint methods could be used as supplementary tools, each applied to support specific purposes. In a long term view it will be evaluated if these methods could be extended so as to take into account both economic and social performance indicators (26).

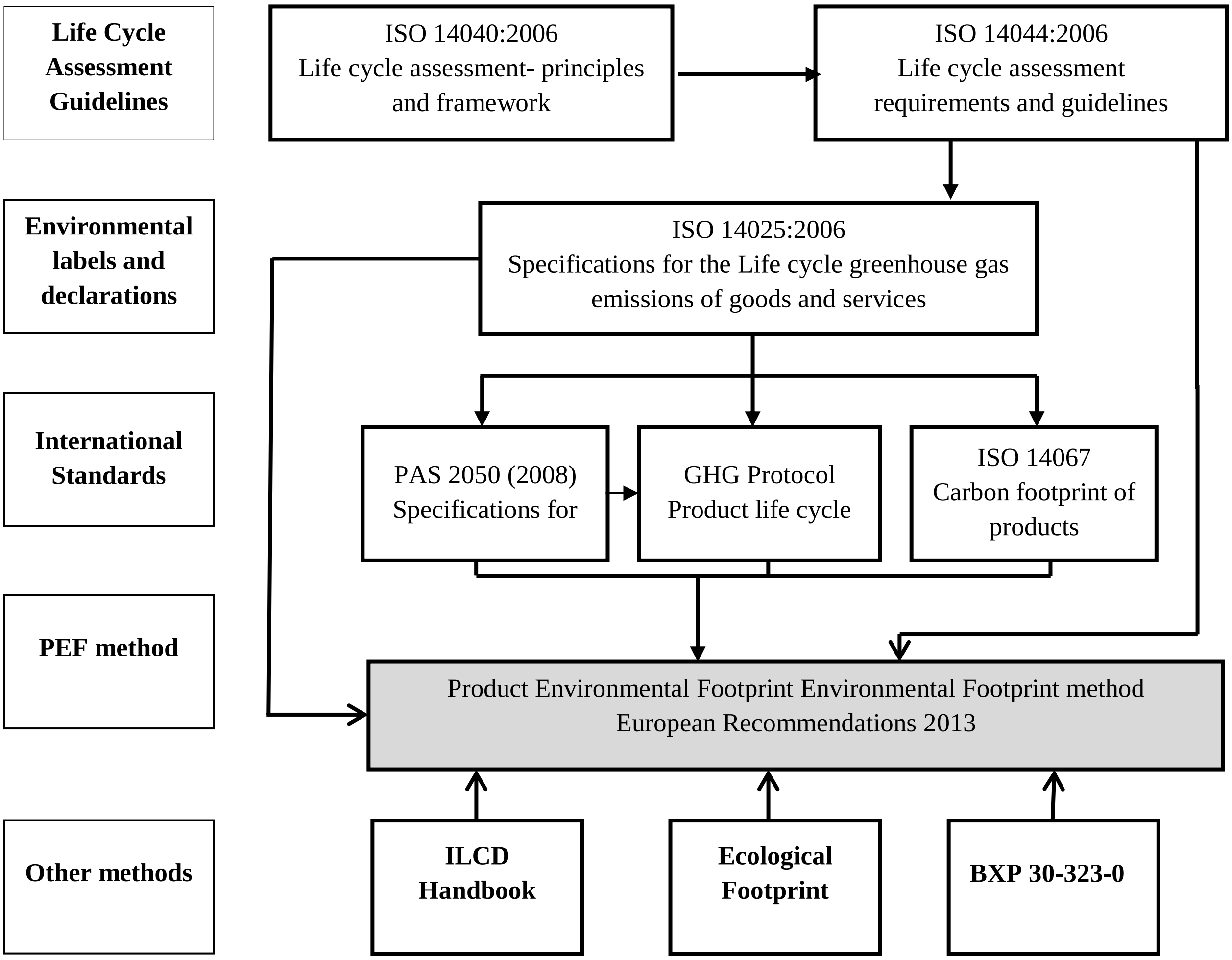


Figure 4: Relationship between LCA, GHG Standards and PEF method (26)

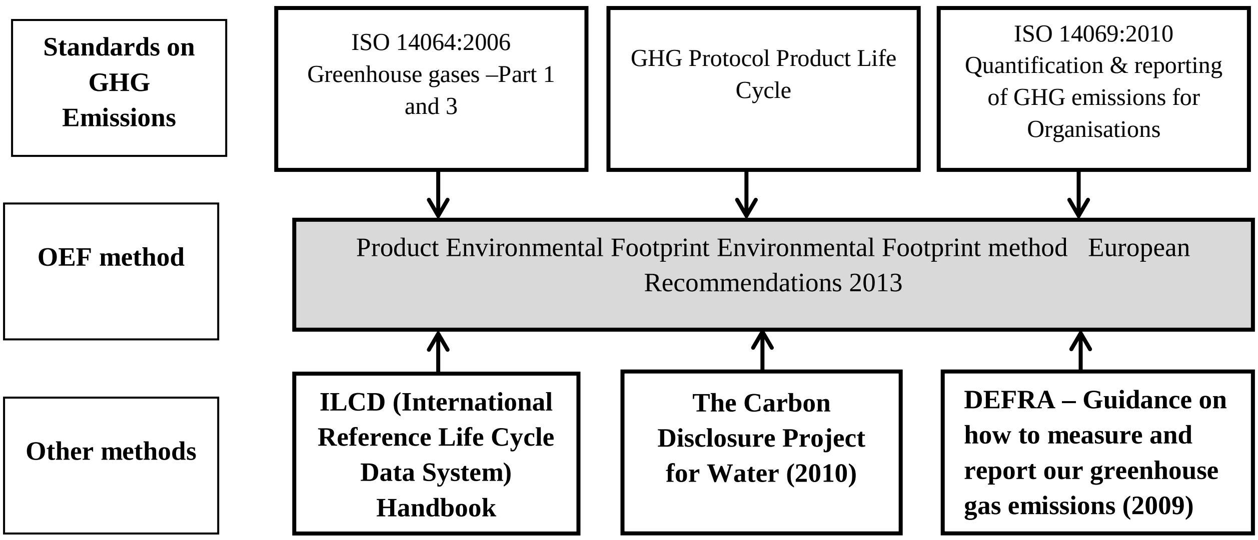


Figure 5: Development of the OEF method based on International methodologies (26)

2.3.4 Additions – New Elements in the PEF and OEF Methods

The PEF and OEF methods are closely related to the ISO 14025 as well as other environmental footprint standards. Similar to the product category rules (PCRs) for type III EPDs described in ISO 14025 Standard, the PEF and OEF guides suggest that product category rules should be developed and associated with each product group including specific requirements named product environmental footprint category rules (PEFCR) and organization environmental footprint sector rules (OEFSR).

In addition, in the PEF/OEF guidelines, 14 impact categories have been defined which derived from an evaluation of the best impact assessment methods published in 2010. The default impact categories that the environmental footprint (EF) impact assessment methods cover are the climate change, ozone depletion, eco toxicity (fresh water), human toxicity (cancer effects and non-cancer effects), particulate matter, ionising radiation, photochemical ozone formation, acidification, eutrophication (terrestrial and aquatic), resource depletion (water, mineral, fossil) and land transformation. For those categories, respective impact category indicators, assessment methods and further instructions on how to calculate the impacts are given in the guidelines (26).

The suggested list of the environmental impacts in ISO 14025 Standard includes the category of climate change (carbon footprint), the depletion of the stratospheric ozone layer, acidification of land and water sources, eutrophication, formation of photochemical oxidants, depletion of fossil energy resources, and depletion of mineral resources. The ISO 14025 Standard follows the LCA methodology provided by the ISO 14040 Standard series and thus, it provides the evaluation of the environmental impacts of products and services categorised into four phases, namely materials, production, transport and end of life. Thus, a product is characterised through the environmental product declaration (EPDs) (ISO 14025). EPDs aim at communicating to the target market the environmental performance of a product while limiting the potential impacts resulting over its life cycle (6).

Finally, an innovative addition to the PEF and OEF guidelines is a reference product in each product group, which displays median impact scores of the product group. This practically means that 50% of the products in the product category should have impacts worse than the reference product, and 50% of the products in the same product category should have a better impact than the reference product (26).

2.3.5 Future Work Regarding the Footprint of Construction Products and Buildings. Link between the PEF method and the EN 15804.

A document providing further explanations on the use of the PEF and OEF method was published by the European Commission. One answer refers to the link between the PEF method and the EN 15804 Standard. It is stated that the PEF method, as a general method could be applied to various product categories, while the EN 15804 Standard covers the category of construction products. In that line, the EN 15804 standard could be used so as the product specific category rules could be developed, so that more specific requirements for the category of construction products could be defined.

Therefore, the EN 15804 standard could be used as a supporting tool for the creation of the product environmental footprint category rules for construction products (42).

Furthermore, considering the differences between the PEF method and the EN15804 standard, a first meeting of the "*Environmental Footprint Construction Products Working Group*" (CPWG) was held on July 2014 by representatives from the DG Environment, the DG JRC, DG Enterprise, CEN and the Construction Products Europe. The aim of the CPWG work is to bridge the differences between EN 15804 and the PEF method, based on the findings that will derive from the five pilot studies that are currently taking place regarding the category of construction products (pipes, thermal insulation, metal sheets, paints, and photovoltaic panels). Specifically, the work of the CPWG is expected to cover issues such as the differences in impact assessment categories/indicators, data quality, end of life issues and potential benchmarks. In addition, a key issue is the interest for defining an environmental assessment method at the building level, including addressing possible ways to shift from construction products to the whole building assessment. In addition to the latter, the CPWG will also evaluate potential links between the Basic Working Requirement 7 described in the construction products regulation and the PEF method/EN15804 Standard (43).

In addition, regarding the possible link between the PEF and the CEN/TC 350 methodologies, the Construction Product Europe (CEPMC) has published a document providing some considerations regarding the building environmental assessment. Specifically, it is indicated that the PEF method provides the guideline to calculate the environmental footprint of a product, while the final product of the building sector is the building rather its individual components; thus, a building should be assessed as a whole and not partially. Furthermore, it is proposed that the CEN/TC 350 environmental assessment methodology should be considered as the reference document for the assessment of the Product Environmental Footprint of Buildings as well as for the development of the PEFCRs for buildings. The document concludes that it is important to define and use the same indicators as well as one methodology for the assessment of buildings and construction products across Europe (44).

2.3.6 Conclusions: To What Extent Do Environmental Footprint Schemes Address Sustainability in the Building Sector?

Improving the environmental performance of products and communicating their environmental footprint is receiving increasing attention (28). The latter is supported by the various attempts to initiate eco-labelling schemes, footprint methods, standards and guidelines that provide information about the environmental footprint of products (91). In the same vein, the newly developed Environmental Footprint methods (PEF and OEF) aim at serving as harmonised European methodologies for addressing and communicating the environmental footprint of products through setting general guide lines that could be applied to diverse product categories (26).

With reference to the construction sector, a common belief is that the environmental impact of engineering works should be addressed and evaluated starting from their ''birthplace''; thus, the construction materials (45). On the other hand, buildings are considered as multidimensional products, which are comprised from various components, have long life expectancy and multiple functions. In addition, the construction process is not a standardised method and therefore each building is considered as a unique product (46). In that line, the ″product″ of the construction industry seems too complex to satisfactorily give eco-labels to buildings. Furthermore, the building when considered as a product is never finalised, but is continuously evolving and changing as it does go through diverse cycles of occupancy.

A building is better expressed as a process than a product. Considering the variety and nature of the influences and interactions on building design it seems malapropos to consider buildings and/or its components in isolation, rather a holistic approach to design is required. Therefore, an emerging question is, to what extent do environmental standards and product footprint schemes address sustainability in the building sector? (29)

In extension to the latter, when referring to sustainable buildings apart from all three aspects of sustainability, the principle of quality and durability of structures should also be taken into account (47). Enhancing the durability of structures contributes in achieving sustainability since the service life of a building is extended (48) and thus annualized environmental impacts are reduced respectively (47).

Furthermore, buildings are often subjected to earthquakes, wind disturbances as well as other loads with high potential risk parameters. While almost all design constraints are taken into account in the structural design, some actual responses to seismic, wind and other loads occurring over the working life of a building may violate such constraints (49). In that line, it is necessary to account for uncertainty and probabilistic response in the analysis of structures (50).However, the safety design aspect is disregarded in the current life-cycle building assessment methods, leading to a unilateral focus on reducing the environmental impact while downgrading the aspect of durability and therefore the sustainability of the designed structures.

Given that the environmental impact, the technical performance and the service life are three correlating and complementary parameters, focusing solely on reducing the environmental impact will not ensure environmental improvement and, thus sustainable buildings (51).

Sustainable Approaches in the Building Sector

Sustainability is built on three pillars, namely the environmental, social and the economic one. Sustainability in the construction sector refers to all practices that should be adopted in order to ensure that a building is environmentally friendly, economically feasible as well as healthy and comfortable to its users.

In the direction of sustainable construction, a number of attempts to develop building assessment methods as well as Footprint methods have been initiated by standardisation bodies and diverse organisations globally. In addition, the European Union has provided a policy framework towards sustainable buildings, which currently covers the environmental aspect including energy efficiency.

Footprint schemes provide an environmental assessment on a product-level approach. This approach is often questioned when is applied to buildings. A building is better described as a process rather as a product. Taking into account the interactions involved in the building life-cycle it seems insufficient to consider building components in isolation.

Current environmental assessment methods and tools evaluate buildings over their life-cycle at a later stage to provide an indication of their environmental performance. This stage does not provide the space for changes, while the sole aspect of environmental performance cannot provide comparable options for building solutions. Therefore, the information cannot be used in a fruitful way nor can be effectively embedded in the general design process.

A more effective way of achieving building sustainability is to consider and incorporate environmental issues in the early design stage, where the principles of durability, probabilistic reliability and safety of structures are also involved. Since these parameters are parts of the same whole they need to be considered together.

Part II: Introduction of the Sustainable Structural Design (SSD) Methodology

3. The Framework of the SSD Methodology

In line with the previous remarks, the sustainability of building structures is therefore interlinked with a reduction of the environmental impacts resulting from construction, maintenance and operation processes along with an increase of the durability of the structure based on an equivalent technical performance (51). In that line, the Sustainable Structural Design Methodology (SSD) is presented as a supporting tool for the general design process of buildings. This methodology considers the technical - structural aspect along with the environmental one formatting a design method for safety and sustainability. It is comprised by three steps, namely the environmental, the structural which refers to the structural engineering and the economic one (figure 5).

With reference to the environmental dimension, the Life Cycle Assessment approach has gained great recognition as an objective method to address environmental impacts (52). It has been used extensively for evaluating environmental issues in both manufacturing and construction sector (27). In parallel, it has also served as the basis for the development of international standards on carbon footprint of products (PAS 2050, GHG Protocol and ISO 14067), European Guidelines for environmental footprint studies (PEF and OEF methods) as well as for other environmental assessment schemes and methods (30). The LCA methodology follows a holistic approach to environmental evaluation; therefore, it could be fruitful integrating the LCA approach into building construction decision making for selection of environmentally preferable products, as well as for evaluation and optimization of construction processes (52).Therefore, the first step of the SSD methodology covers the environmental aspect and evaluates the environmental performance of alternative structural design solutions with the use of the LCA methodology.

As far as the structural aspect is concerned, the performance based design of buildings involves uncertainty and probabilistic response in the analysis of structures. To achieve a performance based approach built on sustainability and building design optimisation, the expression of performance targets in a quantitative economic perspective is deemed a proper way (50). A new simplified performance-based assessment method (s PBA) is presented that aims at reducing the complexity and the amount of data needed as well as at facilitating the procedure of estimating losses due to uncertainties. The output of this method is a total cost C_{TOT}, which is the sum of costs needed to repair damaged buildings, of the downtime losses and of the initial construction cost.

The third step of the methodology is a combination of the environmental and the structural results expressed as an economic value. A method that converts the environmental results in economic terms id presented. In addition, the structural and environmental costs are presented into monetary unit and summed, so that a global sustainable parameter results.

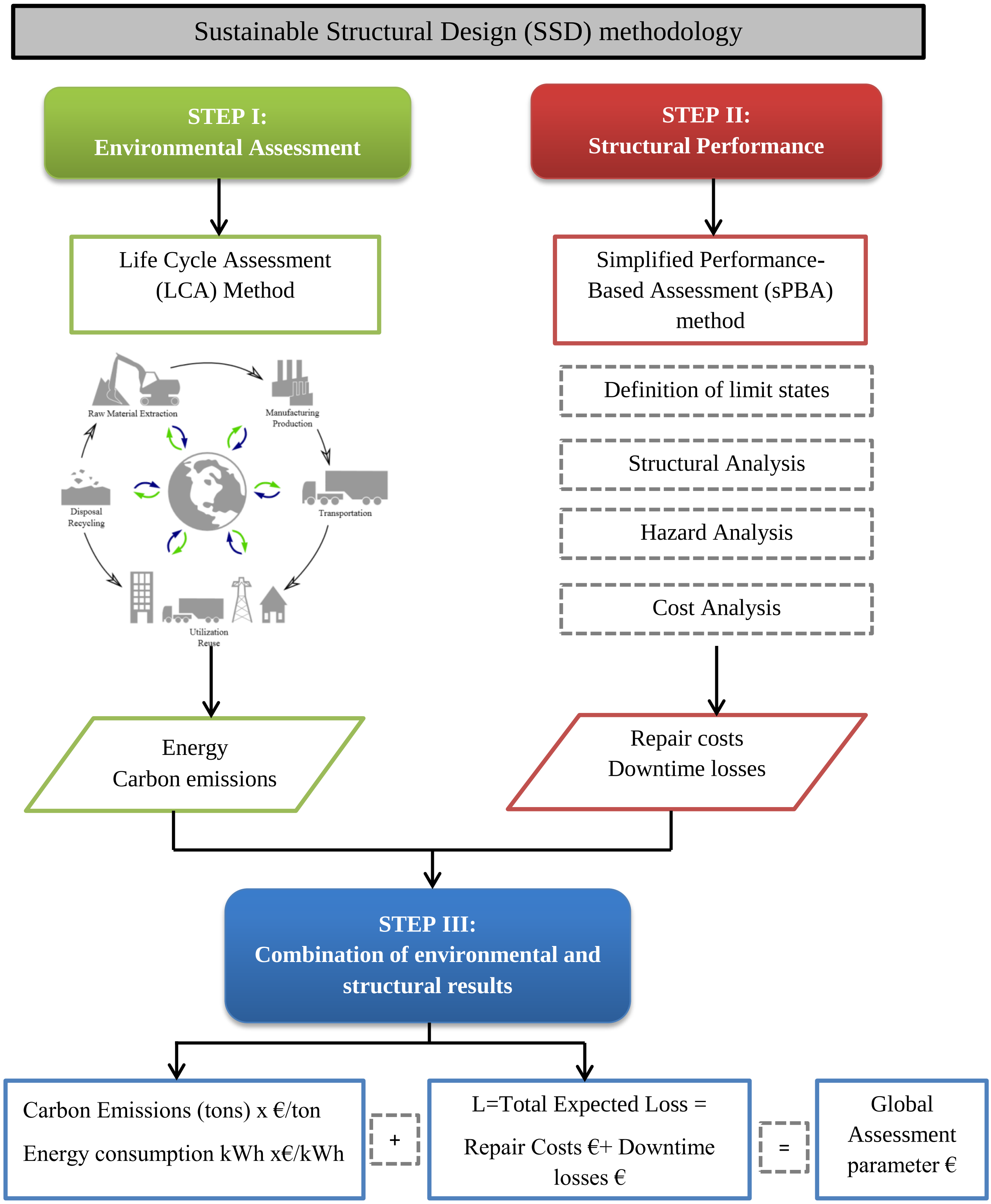


Figure 6: Steps of the SSD methodology - flowchart

The overall aim of the SSD methodology is to contribute towards the development of a methodology that optimizes building design in terms of environmental and structural performance for safety and sustainability.

3.1 Step 1: Environmental Assessment

3.1.1 Environmental Impact Assessment Using the Life Cycle Assessment (LCA) Approach

Life Cycle Assessment (LCA) is a methodology for addressing the potential impacts of goods and services over their life cycle in an environmental perspective; from raw material and production, to the use and the end-of life phase (*6*). Hence, a common interpretation that usually follows the LCA methodology is the ''cradle to grave'' approach (*52*).

The International standards of series ISO 14040 have provided the description of the LCA methodology in four steps (figure 6), including the principles and the criteria for conducting and reporting such a study. The first step is the *Definition of goal and scope*, which defines the objectives, quality criteria and system boundaries. Secondly, the *Inventory Analysis* involves the collection of information, energy demands and emission data regarding every stage of the product's life cycle (*ISO 14040*). With regard to the building sector, the inventory analysis phase includes material quantities and properties as well as energy consumption data. In the *Impact Assessment* phase, the potential environmental impacts and the resource acquisition are evaluated based on the data provided in the second phase. Finally, at the *Interpretation of results*, recommendations are proposed and are indicated on the final report based on the conclusions derived from the findings of the study (*6*).

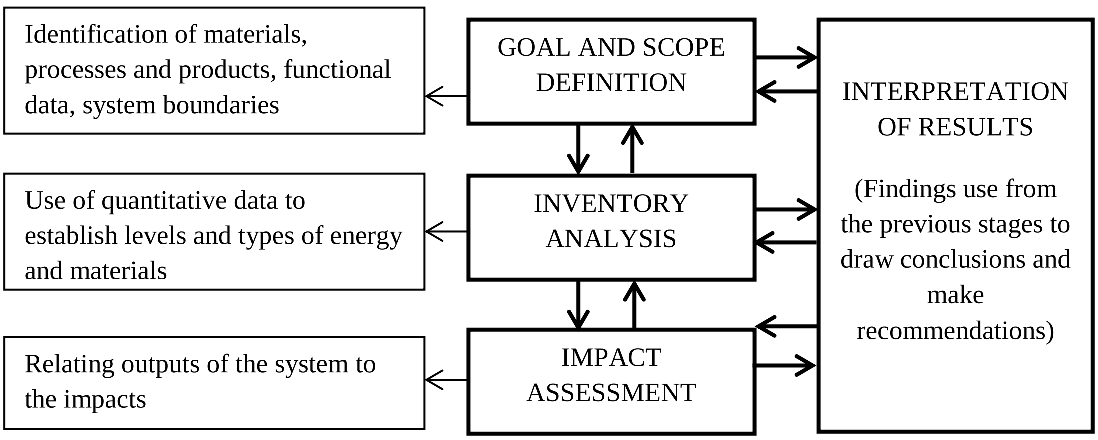


Figure 7: Steps of the LCA methodology as described by ISO 14044 Standard

Even though LCA-studies were already conducted since 1960s, SETAC (Society of Environmental Toxicology and Chemistry) contributed to the harmonisation of life cycle assessment in 1990 which led to the standardization process and finally to the development of the ISO 14040 Standard series (54). The importance of LCA methodology has long been recognized by the European Commission as the most proper method for evaluating the potential environmental impacts of products (17). It has been used extensively to assess product development processes from cradle to grave for many years; however the application in the building sector began to rise the last decade (52), and therefore diverse building LCA tools have been initiated in different countries (17).With the current push toward sustainable construction, LCA has gained great recognition as an objective method to evaluate the environmental impact of construction practices (52).

In general, LCA is used to estimate and quantify the environmental impacts resulting over all phases of product's life cycle, namely the production, use, disposal, and recycling, including the materials from which the products are made of. More specifically, the use of resources and environmental emissions as well as the corresponding potential impacts are calculated and therefore indicated as quantities. The potential impacts result from gas emissions in the atmosphere, contaminated substances in the rivers as well as other harmful substances, which are calculated over a specified period of time (17).

With reference to the construction and building sector, life-cycle analysis takes into consideration all the inputs and outputs of constructing, operating, and disposing of a building system (9). There are three types of LCA application related to buildings. The ″Building Materials″ (BM) type deals with individual construction products and compares alternative material options, e.g. roofing (ceramic tiles vs. concrete tiles), insulation (mineral wool vs. polystyrene). The ″Component Combination″ (CC) type evaluates specific parts or subcategories of a building under a specific technology option, e.g. roof, façade, flooring, insulation, window systems. The third type is the ″Whole construction and Whole Process of Construction″ (WPC), which includes the evaluation of the whole construction, categorised as residential, non-residential and civil engineering constructions. The first two types (BM/CC) belong to the bottom – up approach, where the focus is on material selection whereas the third is described as a top –down approach, where the whole building and its entire life cycle become the objects of consideration and the area for environmental improvements (55). The environmental impacts commonly addressed when LCA is applied to the building sector, are the fossil fuel consumption, global warming potential, acidification, eutrophication, ozone depletion, smog formation and primary energy (56).

3.1.2 Energy Efficiency Using the Life Cycle Energy Analysis (LCEA) Approach

Life Cycle Energy Analysis (LCEA) is an approach that considers all energy inputs to a building over its life cycle (57). The subject of activity of this analysis involves the energy consumption from raw material and construction (manufacture phase) to the operation (use phase) and dismantling (demolition phase) of a building (58). Manufacture phase deals with the manufacturing and transportation of construction materials and technical installations used both in building construction and renovation (52). The use phase involves all activities related to the use of the buildings, throughout its service life, including maintenance and material replacement (59). The demolition phase includes disassembling of the building and transportation of materials to land sites and recycling plants (58). Energy in buildings is present in all phases of their life cycle and is categorised in Embodied, Operation and Demolition Energy (45). Therefore, Life cycle energy includes:

- Embodied energy

Embodied energy is the energy required for producing and constructing a building across the entire supply chain. Embodied energy is expressed as:

$$E_E = \sum m_i M_i + Ec$$

Equation 1: Embodied energy

where m_i = material quantity; M_i = energy content of material per unit quantity; Ec = energy used at site for building construction (57);

- Operating energy

Operating energy expresses the energy demands for the ordinary use of the building. It is the energy for heating, ventilation, air conditioning, domestic hot water, lighting, and for running appliances (52). Operational energy consumption depends on geographical elements and climate conditions as well as on quality requirements. It is expressed as:

$$E_O = E_{OA} L_b$$

Equation 2: Operating energy

where E_O=operating energy throughout the life span of the building; E_{OA} = annual operating energy; L_b = Life span of the building (57);

- Demolition energy

Energy required at the end of the building's service life to dismantle the building and dispose of its materials to landfill or to recycling plants (52). It is expressed as:

$$E_D = E_{DIS} + E_T$$

Equation 3: Demolition energy

where: E_D= demolition energy; E_{DIS} = energy required for the dismantling of the building; E_T = energy consumption for the transportation of the materials.

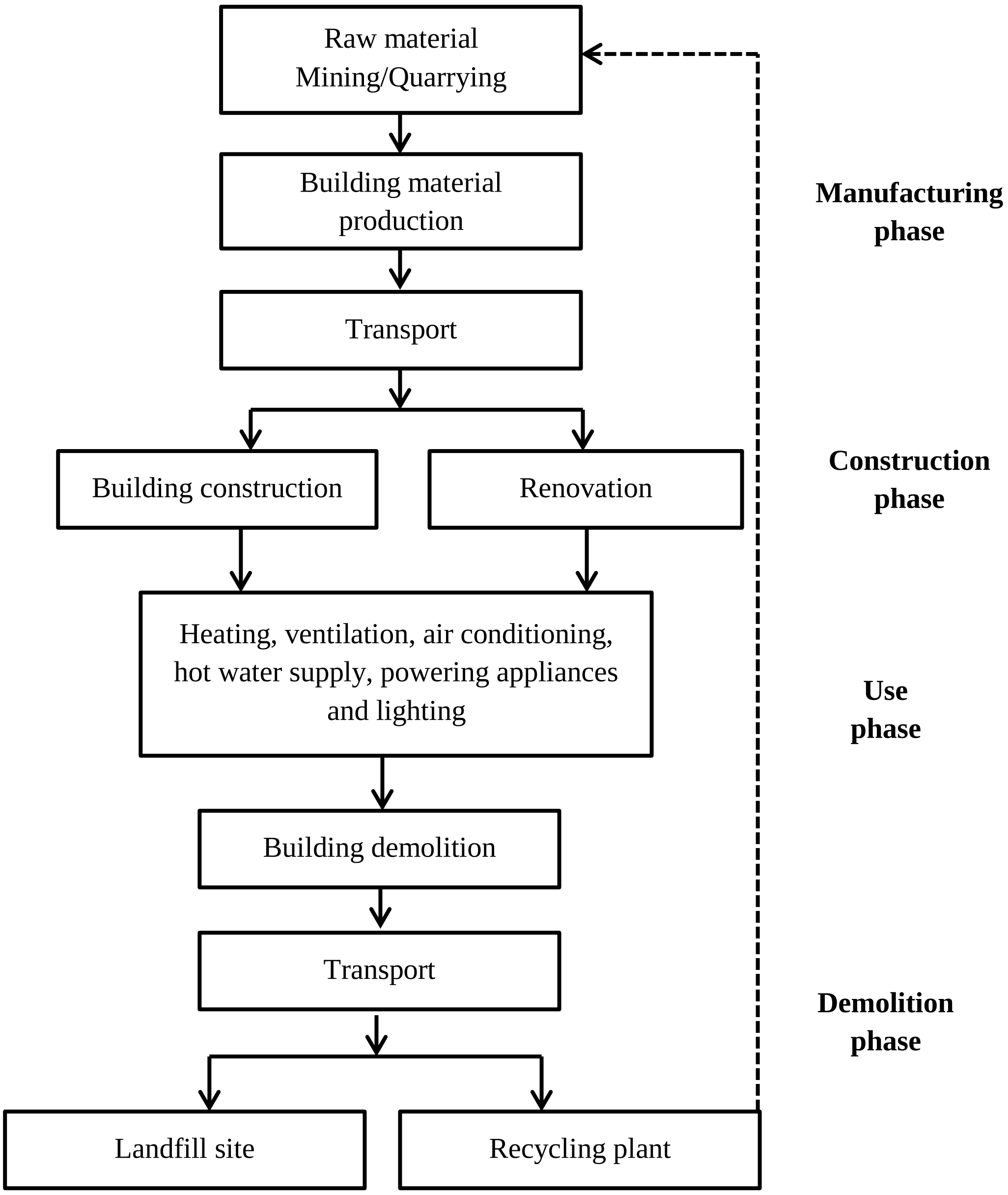


Figure 8: Energy Analysis of Building Life Cycle

Therefore, the energy over the lifespan of the building is the sum of the all the energies incurred in its life cycle. It is thus expressed as:

$$E_{LC} = E_E + E_O + E_D$$

Equation 4: Life cycle energy

Life cycle energy analysis can contribute to address practices for energy reduction in energy efficiency performance of buildings. By performing a life cycle energy analysis, the phases that demand highest energy amounts can be determined and improved (57).

Environmental Assessment

The first step of the SSD methodology deals with the environmental assessment of a building. The methodology used is the Life Cycle Assessment, which is considered as the best framework provided to address the environmental impacts in a life-cycle perspective.

LCA methodology has gained great recognition as an objective method to address the environmental impacts. It has been used extensively for evaluating environmental issues, including the impact category of climate change, in both the manufacturing and the construction sector. In parallel, it has also served as the basis for the development of international standards on carbon footprint of products (PAS 2050, GHG Protocol and ISO 14067), European Guidelines for environmental footprint studies (PEF and OEF methods) as well as for other environmental schemes.

The LCA methodology follows a holistic approach to environmental evaluation; therefore, it could be fruitful integrating the LCA approach into building design for the selection of environmentally preferable products, as well as for evaluation and optimization of construction processes.

3.2 Step II: Structural Performance Assessment

3.2.1 Structural Design in a Performance-Based Approach

The design of a structure is satisfactory if structural analysis indicates that actions imposed on structural components as well as deformations, which occur due to diverse loads do not exceed limit states (53). However, recent developments highlight that focus should not be placed in the sole aspect of structural response but also in the aspect of structural performance (59). Performance is expressed in terms of predefined targets that the structure is required to meet rather than how it should be built (60). In this respect, Performance-Based Design (PBD) has been widely acknowledged as a robust methodology for verifying that structural systems meet design performance objectives over their design life (61).

Generally the most appropriate and efficient design of structures is based on deterministic methods that focus on satisfying respective deterministic constraints. To move towards building design optimisation it is essential to consider those uncertain parameters that might have a negative effect in the performance of the structural system as well as to account for reliability constraints (60).

The Performance-Based Assessment (PBA) of structural systems involves the implementation of probabilistic scenarios for the evaluation of structures in terms of uncertainties (61), in order that increased levels of safety can be achieved (62). In a structural aspect, the aim is at bringing about more predictable, reliable and increased levels of safety and operability (62). In fact, while almost all design constraints are taken into account in the structural design, some actual responses to seismic, wind and other natural hazards that act as loads over the working life of a building may violate such constraints (49). It is therefore inevitable to account for uncertainty and probabilistic response in the analysis of structures (50).

Uncertainties fall into three main categories, namely hazard uncertainties (61) (e.g. earthquakes, winds) (62), structural uncertainties (e.g. stiffness, material properties, structural capacity) and interaction mechanism uncertainties (e.g. pressure duration) (61). To this regard, performance-based assessment allows structural systems to be designed in a way to meet performance targets in terms of capacity, safety and quality. The focus is on determining those targets in a quantitative perspective, which allows a more reliable performance assessment and thus, structural design (60). Performance is built on three main criteria, namely the definition of targets in the design process, the examination of alternative solutions that are able to meet predefined targets and reliability and risk assessment of alternative solutions so that the most efficient one to be selected (62).

In an economic perspective, a key element of PBA methods is that they involve the evaluation of the costs associated with a structural solution and/or rehabilitation measures as well as the expected losses that may occur over the life-span of the building for all the defined limit states (63). In this respect, diverse stakeholder categories could evaluate if the amount needed to repair a highly damaged building could be economically feasible; thus, one could evaluate, compare and make decisions between alternative structural design solutions (64).

Performance-based design allows the evaluation of structures over their life-span. In addition, structural systems are designed in a way to meet predefined performance objectives both in an economic and structural (safety, capacity etc) aspect as well as to meet needs that are tailored to user/customer requirements (60).

3.2.2 Performance-Based Engineering Methods. Review on the PEER PBEE Methodology

Following the former considerations, the development of Performance-Based Engineering methods is gaining considerable interest in the field of structural engineering. Examples of such methods include the Performance-Based Fire Engineering, the Performance-Based Tsunami Engineering, the Performance-Based Wind Engineering (PBWE), the Performance-Based Hurricane Engineering (PBHE) and other methods (65).

The interest in those methods was originated from the successful implementation of the Performance-Based Earthquake Engineering (PBEE) approach in the field of earthquake engineering (66). Performance in PBEE is expressed in economic terms (e.g., expected annual losses), or in terms of operability and safety performance (e.g., expected downtime due to safety tagging and/or repair) (67).

One primary development in the PBEE frameworks is the Pacific Earthquake Engineering Research (PEER) Centre’s probability approach (68).The PEER PBEE method could be used as a reference methodology in order to define a global approach for sustainable structural design (64).

The PEER PBEE (Pacific Earthquake Engineering Research Center Performance Based Earthquake Engineering) framework incorporates loss modelling and provides results of uncertain future repair costs resulting from probabilistic scenarios in order to evaluate future performance (53,69). More specifically, this framework estimates the mean annual frequency (MAF) of exceeding predefined limit states in order to assess the performance of the whole building based on an economic (future repair costs), life safety (casualties), post-earthquake operability (economic value, deaths, downtime) dimension along with structural response (53, 70).

The framework of the PEER PBEE follows four main phases: the *hazard analysis* that indicates the seismicity at the site; the *structural analysis* that provides the necessary force and deformation measures; the *damage analysis* that allows the transformation of response measures into states of damage; the *loss analysis*, where the damage is related to a performance measure (69). The framework of the PEER PBEE method is illustrated in figure 8.

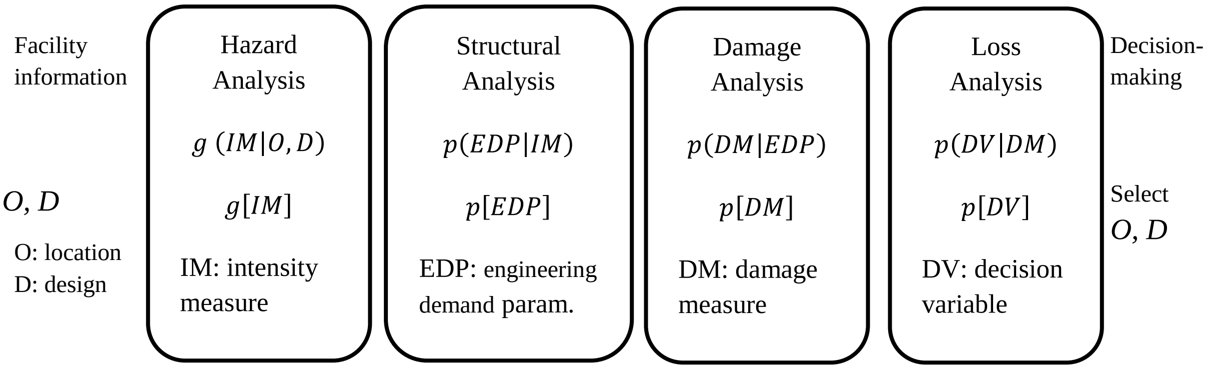


Figure 9: Framework of the PEER performance-based evaluation

The *Hazard Analysis* involves the evaluation of the seismic hazard based on the facility location and its design characteristics considering a specific seismic environment and thus, nearby faults, site distance, source-to-site conditions, facility location, facility design, etc. . Therefore, the seismic hazard is produced g[IM]. The hazard curve indicates the annual frequency with which seismic excitation is estimated to exceed various levels. Excitation is parameterised through an Intensity Measure (IM) (53), which could be the peak ground acceleration or the spectral acceleration (69).

In the *Structural Analysis* phase, a nonlinear structural analysis is performed to estimate the uncertain structural response of the structure under a ground motion of given IMs. The response is measured in terms of engineering demand parameters (EDP) based on seismic excitation and design $p(EDP|IM)$.

In the Damage Analysis phase, the EDPs are used as input to fragility functions to define the damage levels through damage measures (DM). Specifically, through using the fragility functions, the probability that a facility component (beam, column, wall etc.), exceeds or not a particular damage state is defined (53). Damage in PEER PBEE is expressed as a fragility function for different response measures. DMs refer to the conversion of response measures to quantifiable damage states. The outcome of a damage analysis provides the $p(DM|EDP)$ (69).

The Loss Analysis phase, involves the probabilistic estimation of performance parameterised through decision variables (DV). DVs are related to DMs that were selected in the previous phase and the $p(DV|DM)$ is calculated. Performance is defined in terms of DVs, and is expressed in monetary unit, downtime or other metric. That information is then used by diverse stakeholder categories to make decisions considering repair costs, risks etc. (53).

The combination of all equations results to the triple integral:

$$G\,(DV) = \iiint\limits_{0}^{\infty} G(DV|DM)\,\left|\frac{dG(DM|EDP)}{dDM}\right|\,\left|\frac{dG(EDP|IM)}{dEDP}\right|\,dIM\,dEDP\,dDM$$

Equation 5: PEER PBEE triple integral

In the PEER framework, a probabilistic occurrence model, such as the Poisson process, is employed to describe the probability of occurrence of earthquakes of varying intensity. At each intensity level, this process is defined by the mean rate of occurrence (λ). The mean rate λ, as a function of IM is interpreted as a seismic hazard curve produced by a probabilistic seismic hazard analysis. Therefore, the equation is given as follows (69) (equation 6):

$$\lambda\,(DV) = \iiint\limits_{0}^{\infty} G\,(DV|DM)\;|dG(DM|EDP)|\,|dG(EDP|IM)|\,|d\lambda\,(IM)|$$

Equation 6: PEER PBEE - mean rate of occurrence (λ)

3.2.3 Introduction of a Simplified Performance-Based Assessment (sPBA) Method

The PEER PBEE methodology has been fundamental in addressing the importance of integrating a loss assessment approach in the structural design. However, such a methodology seems too complicated to be applied to ordinary projects. Considering the latter, a simplified Performance-Based Assessment (sPBA) has been introduced by the ELSA of the IPSC (Institute for the Protection and Security of the Citizen) of the JRC (Joint Research Centre). The framework of the sPBA method provided by ELSA, aims at reducing the complexity and the amount of data needed as well as at facilitating the procedure of estimating losses due to uncertainties. This framework takes into account the location and building characteristics in order to generate the mean information in the hazard, structural and loss domain.

The sPBA method aims at contributing to the sustainable structural design of buildings. This method involves the evaluation of costs as well as the expected losses for each limit state to which different peak ground accelerations and inter-storey drifts correspond. The output of this analysis is the total expected loss (L) calculated with the use of the total probability theorem. The simplified performance-based assessment consists into the evaluation of the costs associated to each design solution and the expected losses that may occur over the life-span of the building for all the defined limit states (64). The steps of the sPBA methodology are the following:

- ***Definition of Limit States***

In this step a number of limit states are defined and the associated costs for each limit state are calculated. The limit states are defined in terms of damageability. Therefore, the limit states that could be defined are the low-damage, heavy-damage, severe structural damage and loss of the building/collapse. With the use of the fragility curves, which express the probability of structural damage due to earthquakes for each limit state the EPDs in terms of inter-storey drift ratios (IDR) are obtained. The engineering measure defining damage is the inter-storey drift. Usually the maximum inter-story drift ratio is related to the damage measure and each damage level is expressed as a probabilistic function of the inter-story drift ratio.

- ***Structural Analysis***

In the structural analysis step, since the EDP has been calculated in the previous step, a peak ground acceleration that cause that EDP in the building can be defined for each limit state through the skeleton curves. Skeleton curves are obtained from the Incremental Dynamic Analysis (IDA) (64). IDA has been adopted by FEMA-350 guidelines and established as a state-of-the-art method to determine global collapse capacity. This method is used for assessing the behavior of structures under seismic loads with the use of the results of probabilistic seismic hazard analysis in order to estimate the seismic risk faced by a given structure.

IDA performs multiple nonlinear dynamic analyses of a structural system under a range of ground motions, each associated to several levels of seismic intensity. Those levels are selected in a way to force the structure to move from elastic to inelastic phase and finally to global dynamic instability, where the structure experiences collapse. The results are presented in terms of IDA curves, one for each ground motion record of the seismic intensity, which are represented by an Intensity Measure (IM), versus the structural response, as measured by an Engineering Demand Parameter (EDP) (71).The peak ground acceleration could be used as the intensity measure and the maximum inter story drift as the EDP. Therefore, the IDA (skeleton) curves provide the peak ground acceleration versus the maximum inter-storey drift in each configuration. From the inter-storey drift thresholds defined for each limit state, the peak ground acceleration is obtained.

- ***Hazard Analysis***

In the Hazard analysis, the output of the structural analysis is used in order that the probability of exceedance to be estimated. Seismic codes provide the relation between the return periods (TR) and the peak ground accelerations (PGA).

For instance, the Italian seismic map provides a set of values of the peak ground acceleration for a discrete set of return periods, starting from a return period of 30 years, along with an interpolation formula for those values. Thus, the peak ground acceleration can be obtained for any return period.

The interpolation equation provided is as follows:

$$\log (a_g) = \log(a_{g1)} + \log\left(\frac{a_{g2}}{a_{g1}}\right) x \log\left(\frac{T_R}{T_{R1}}\right)\ x\ \left[\log\left(\frac{T_{R2}}{T_{R1}}\right)\right]$$

Equation 7: Interpolation equation

where: a_g is the generic PGA value for which the corresponding return period is calculated and a_{gi} and T_{Ri} are the two closest tabulated values of the parameters.

By solving the formula for the return period (TR), with the determined a_g values, the corresponding return periods can be defined. Therefore, the probability of exceedance in N years RN is then obtained from the following equation (72):

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

Equation 8: Probability of exceedance

- ***Cost Analysis. Expected Total Loss***

This step involves diverse stakeholder categories. Firstly, for each limit state the level of the damage has been defined. In that line, the contractor can estimate the time needed to repair the corresponding damages. Therefore, a graph indicating the repair time needed to repair the damages that have been caused to each subsystem for each limit state is obtained. Moreover, since the limit states with the corresponding damages have been defined, the engineer could estimate the costs to repair the damaged building components. Therefore, the amount of the cost needed for the corresponding building repairs could be calculated.

Then, using the information about the repair time needed for each limit state, this can be associated also with the downtime loss. Downtime refers to a period of time that a system fails to provide or perform its primary function. Therefore, a second graph, indicating the economic loss that the client is going to have due to the time needed to repair the damaged building is obtained. These graphs are essential as they provide information to the client about the economic loss that occurs over the time needed to repair a damaged building, which is described as a downtime loss. The downtime loss describes the amount of money that results while the building is not used.

In that line, this final step is the total expected loss calculation, which is expressed as the sum of the monetary loss and the downtime loss calculated previously. In this respect, both the amount of money needed to repair the damaged building (monetary loss) and the amount of money that are lost during the repair actions taking place at the building are considered. The latter is indicated in the following equation:

$$C_i = E\left(Loss_{repair}\middle|IM\right) + E(Loss_{downtime}|IM)$$

Equation 9: Costs associated to each limit state

Therefore, once the costs C_i associated to the attainment of each limit state and the respective probability of exceedance R_i have been calculated, the total expected loss (L) in each configuration could be estimated via the total probability theorem as follows:

$$L = \sum C_i \, (R_{Ni} - R_{Ni+1})$$

Equation 10: Total Loss (L)

One could consider that the costs should be expressed in terms of their present value (PV), also known as present discounted value, which is a future amount of money that has been discounted to reflect its current value. However, there is no change in the result if the costs are converted in their present value or not. This method evaluates and defines the most effective design solution among alternatives. Therefore, the amount of money needed for one alternative compared to another will be higher or lower than the other alternative even if total costs are discounted in their present value. In a financial perspective the costs could be expressed in their present value in each limit state and then summed as it was indicated in equation 10.

Therefore the total cost (C_{TOT}) is the sum of the expected total loss (L) as calculated via the equation 9 and the initial construction cost. This is indicated in the following equation:

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

Equation 11: Total Cost

where: L is the expected economic loss needed to repair a damaged structure, including the downtime losses and I is the initial construction cost.

When comparing two structural design solutions, given that both of them in order to be acceptable should meet specific response acceptance criteria, the evaluation could be performed based on economic criteria. This practically means that the most effective structural design solution is the one that demands less initial construction cost and/or repair costs and/or downtime losses that are also associated with the structural response. The total repair cost is the one needed to repair building damages that may occur due to natural hazards or other risk parameters, which are estimated through probabilistic scenarios.

In general, with the use of the sPBA method one could evaluate if the amount needed for a refurbishment of a highly damaged building is feasible in economic terms. Moreover, this evaluation is also essential when applied to alternative structural solutions, since the most effective one, in both economic and structural terms, could be defined. In addition, a comparison between alternative structural solutions could be performed in terms of reduction of the total expected loss taking into account also the initial construction cost of the structure (64).

Structural Performance Assessment

The second step of the methodology deals with the structural performance assessment. Emphasis is put on probabilistic performance estimation frameworks and the rational treatment of uncertainty.

A review is conducted on the Performance-Based approach, with a further analysis on the PEER PBEE method, which has been fundamental in addressing the importance of integrating a loss assessment approach in the structural design. A new simplified Performance-Based Assessment method is presented that aims at reducing the complexity and the amount of data needed as well as at facilitating the procedure of estimating losses due to uncertainties. The structural design is treated in a probabilistic manner, with one or more objectives that represent the cost of future repair measures and downtime losses that may occur over the service life of a structural system to be calculated and expressed as the expected total loss (L).

The expected total loss (L) is summed to the initial construction cost formatting the total cost C_{TOT}*, which allows diverse stakeholder categories to make decisions in a multi-dimensional perspective.*

3.3 Step III: Combination of Environmental and Structural Results. Working Towards a Global Assessment Parameter

The third step of the SSD methodology aims at addressing a global sustainability parameter that allows considering both the environmental and the structural aspect. This parameter is the sum of the environmental (i.e. energy and CO_2 emissions) and structural performance results expressed in economic terms. The construction cost as well as the Total Expected Loss (L), which represents the expected costs to repair seismic damaged buildings and the downtown losses it has been addressed at the second step and expressed in economic terms. In addition, the environmental impacts have been estimated at the first step of the methodology. Therefore, in the third step the environmental impacts are converted into monetary unit and the equation of the global parameter of the SSD methodology is provided.

3.3.1 Environmental Impacts into Monetary Unit: The European Union Emissions Trading System and the Market Prices

The building sector is recognised as a major energy consumer (27) and thus a significant contributor to environmental impacts (13) including the impact of climate change (30). Global climate change results from the concentrations of greenhouse gases (GHGs) such as carbon dioxide, methane and nitrous oxide (36).

Indicative data show that the building sector accounts for the 33% of the global CO2 emissions with the concrete being a main contributor accounting for 1kg of CO2 for each Kg of cement produced (45). Furthermore, other construction products commonly used in buildings, such as steel and aluminium, follow a process of raw material extraction, melting, manufacturing and material distribution to the construction sites. Each phase demands energy which results in carbon emissions. The production processes of all building materials used along with the construction activity describe the building's embodied carbon, which according to data represents approximately 20% of the total carbon emissions caused by the building sector (73). In addition, studies on buildings indicate that the greatest impacts on human health and toxic releases occur during the manufacturing and construction phase, while the greatest amounts of energy consumption (70-90%) and GHG emissions result during the operation phase (74).

Considering these data, the 2012/31/EU directive of 2012 stated that the main focus of the building and construction sector should be in energy efficiency (75). Following the latter, improving the energy performance of buildings is an essential measure in order to achieve the ambitions of Europe, specifically the EU Climate & Energy targets, which refer to the reduction of Greenhouse gas emissions by 20% and energy savings of 20%, both by 2020 (20).

To achieve energy efficiency in buildings the EU has introduced respective Directives, which specifically are the Energy Performance of Buildings Directive (2010/31/EU, 2010, EPBD) and the Directive 2010/30/EU. With reference to the carbon emissions, the European Union introduced the European Union Emissions Trading System (EU

ETS), which was the first trading scheme globally and it remains the biggest one until today. It was launched in 2005 in order to help mitigate the global impact of climate change and it is essential regarding the EU climate policy.

The cost of CO2 is linked with the European Union Emissions Trading System (EU ETS). The first phase of the EU ETS was developed to act as an individual treaty, such as the United Nations Framework Convention on Climate Change (UNFCCC, 1992) or the Kyoto Protocol (1997). However, the EU agreed to incorporate the Kyoto mechanism certificates as compliance tools within the EU ETS. Following the latter, the "Linking Directive" allowed operators to use a certain amount of Kyoto certificates from flexible mechanism projects in order to cover their emissions. Those mechanisms are the Joint Implementation projects, the Clean Development Mechanism (CDM) and the International Emissions Trading (IET). In that line, a Certified Emission Reduction unit (CER) that is based on one of the three mechanisms is considered as EU equivalent.

Under the EU ETS, the EU Member States agree on maximum national emission limits, which should be approved by the European Commission. Those countries allocate allowances to their industrial operators, who are able to buy or sell such allowances named '' European Emissions Allowances'' or EUAs while they track and validate the actual emissions according to the relevant assigned amount. The total number of permits issued either auctioned or allocated defines the price for carbon. Therefore, the actual carbon price is determined by the market based on the relationship of demand and supply (76).

3.3.2 Carbon Emissions Converted into Monetary Unit

The carbon price per tonne derives from the carbon emissions evaluated through the EU ETS. The EU ETS is comprised from three phases. The first phase was from 2005 to 2007, the second from 2008 until 2012 and the third is from 2013 until 2020. Regarding the carbon price, until April 2006 the price of allowances increased steadily where finally reached a peak of around €30 per tonne CO2. However, in late April 2006, the Netherlands, the Czech Republic, Belgium, France, and Spain announced that their verified emissions were less than the number of allowances allocated to installations. Thus, the price for EU allowances dropped 54% from €29.20 to €13.35 in the last week of April 2006. Moreover, in May 2006, the price fell under €10/tonne, while in 2007 carbon prices were near zero for the most of the year. The fall of the price is attributed firstly to the fact that EU Member States had allocated many EU allowances and secondly the market had reduced emissions in the first two years of the phase, so there was no need for many allowances in 2007.

With reference to the second phase, in the first half of 2008 the carbon price increased to approximately €20/tCO2. In the second half of 2008 the average price was €22/tCO2, €13/tCO2 in the first half of 2009 and €12.40/ tCO2 in December 2010. In March 2012, the permit price was continuously under €10 per tonne compared to nearly €30 per tonne in 2008 and therefore was too low to provide incentives for the industry to reduce carbon emissions. The closing price for an EU allowance in December 2013 was at 6.67 euro a metric tonne while in January 2013, the EU allowance price fell to 2.81 euro per tonne (figure 8).

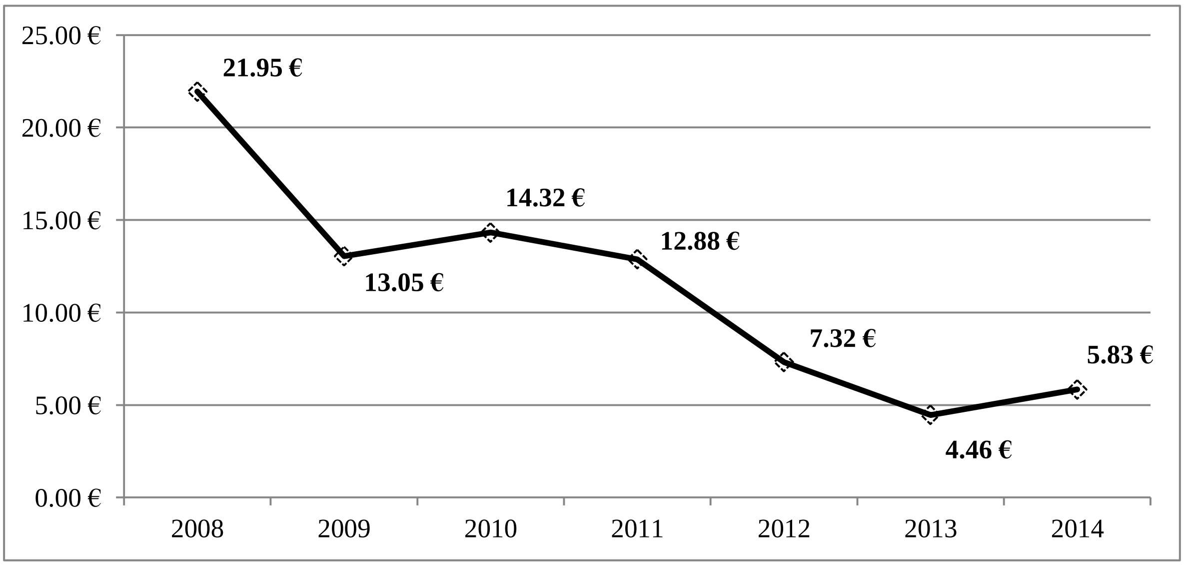


Figure 10: Average carbon prices from 2008 to 2014

For the third phase, the projections for the 2020 indicate a price of around 22 Euro/tCO_2.During 2014 the average carbon price is formatted at 5.48 euros per tonne, while in November 2014 the average carbon price was 6.19 euros per tonne. Most market commentators estimate a price around or below 30 Euro/tCO_2. These carbon price projections are subject to great uncertainty, as they depend on future fossil fuel prices, and on predicting accurately business emissions (77).

Considering the carbon prices formatted by the EU ETS, the cost of the environmental impact of global climate change could be calculated based on the following equation:

$$R_{SSD(CO_2)} = P_{CO_2} * Q_{CO_2}$$

Equation 12: Carbon emissions converted into costs

where: $R_{SSD(CO_2)}$ *is the global result for the sustainable structural design methodology expressing the financial value of environmental impacts;*

P_{CO_2} *is the carbon price of one tonne of* CO_2 *emissions, expressed in euro/tonne;*

Q_{CO_2} *is the amount of the equivalent* CO_2 *emissions resulted from the LCA analysis, expressed in tonnes.*

3.3.3 Energy Consumption Converted into Monetary Unit

Energy in Buildings is present in all phases of their life cycle and is categorised in Embodied, Operation and Demolition Energy (45). While the energy consumption during the use- phase (operating energy) of a building, seems to account the greater percentage of the total energy, embodied and demolition energy are also considerable (4). At a global view, the building industry consumes 30-40% of the total energy and produces 30% of the total carbon dioxide emissions (5).

As it is indicated by the following charts, buildings (residential and non-residential) represent approximately the 40% of the total energy consumption in Europe. With reference to the diverse energy sources, buildings consume the 63% of the total natural gas and 59, 1% of the total electricity consumption. Furthermore, figure 8 indicates that natural gas and electricity are the most used sources for power generation regarding all regions of Europe, with gas representing an average of approximately 35% and electricity an average of 23,7% .

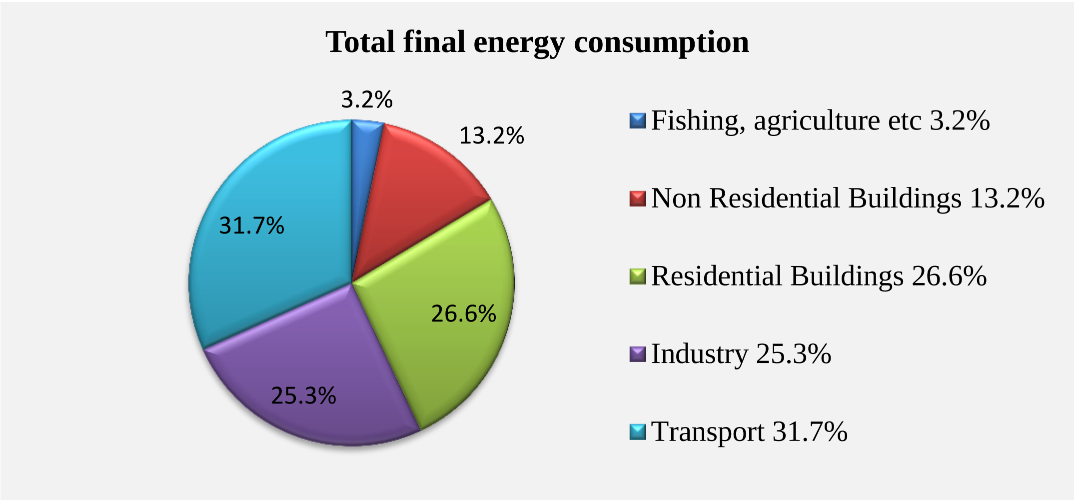


Figure 11: Total final energy consumption by sector (Eurostat 2010)

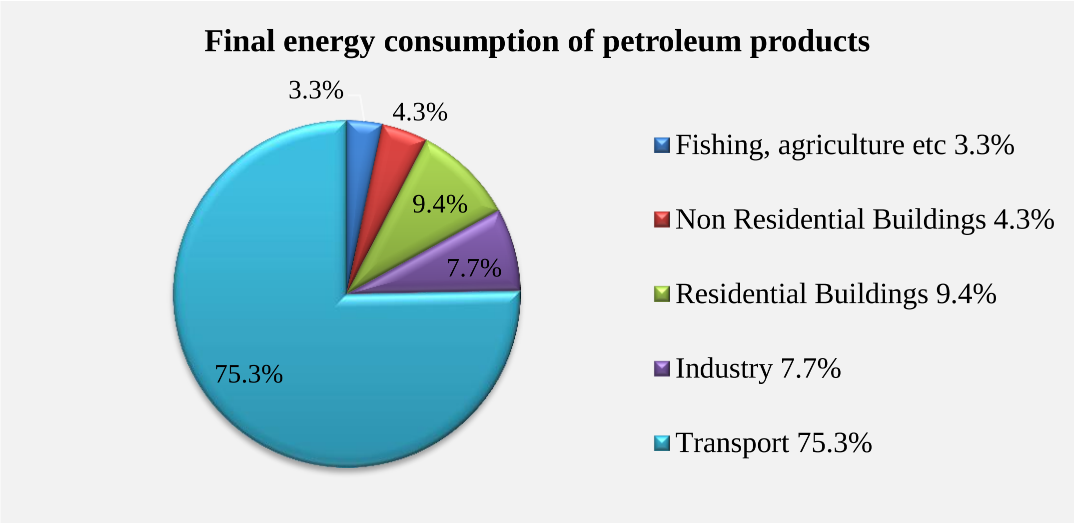


Figure 12: Final energy consumption of petroleum products by sector (Eurostat 2010)

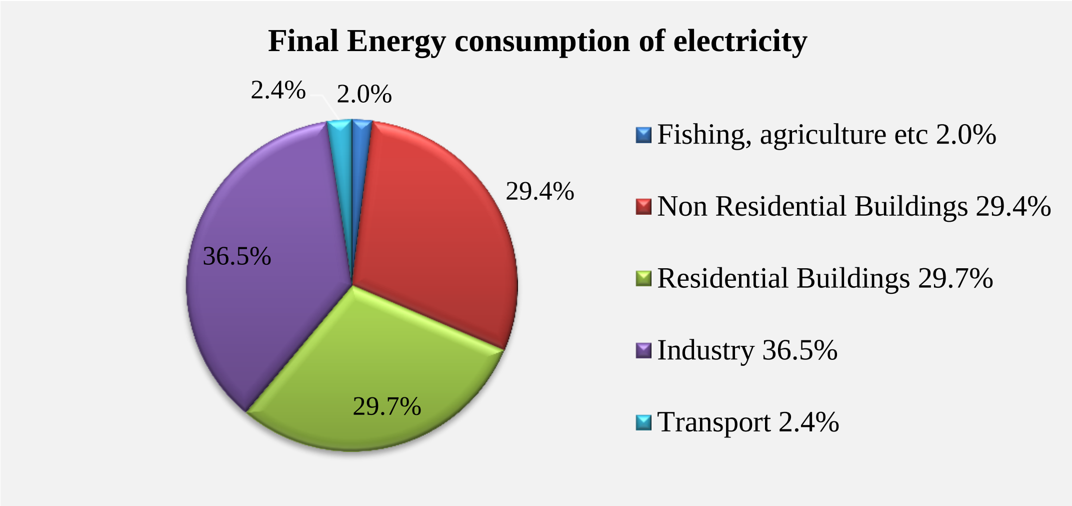


Figure 13: Final energy consumption of electricity by sector (Eurostat 2010)

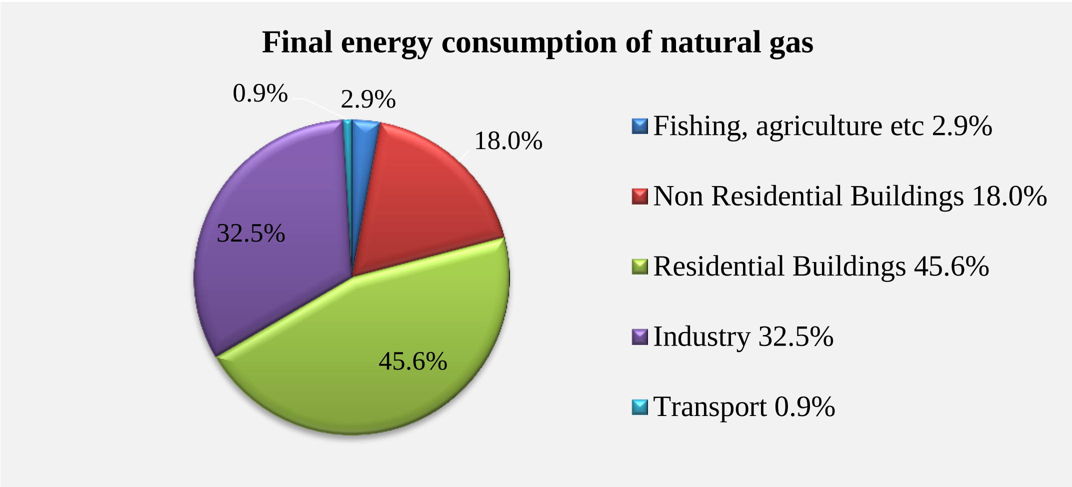


Figure 14: Final energy consumption of natural gas by sector (Eurostat 2010)

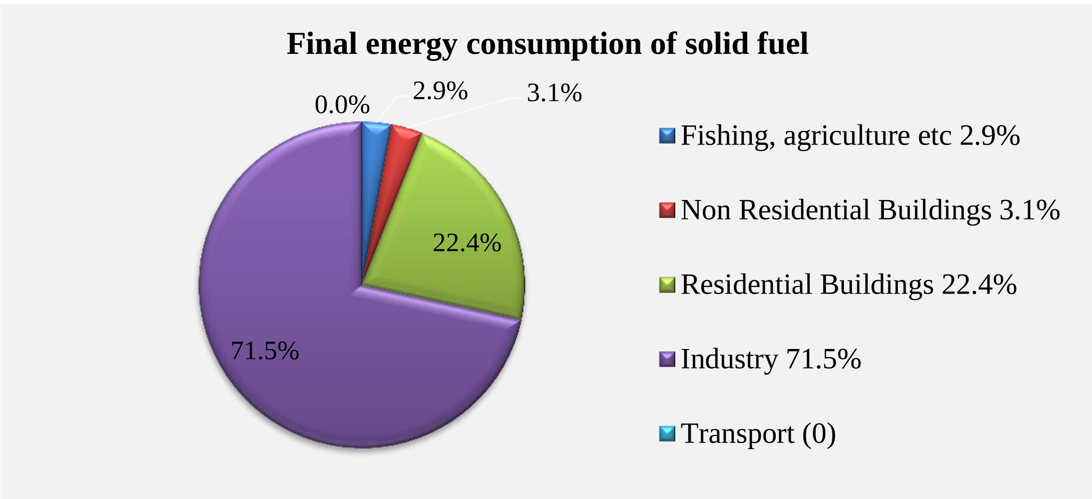


Figure 15: Final energy consumption of solid fuel by sector (Eurostat 2010)

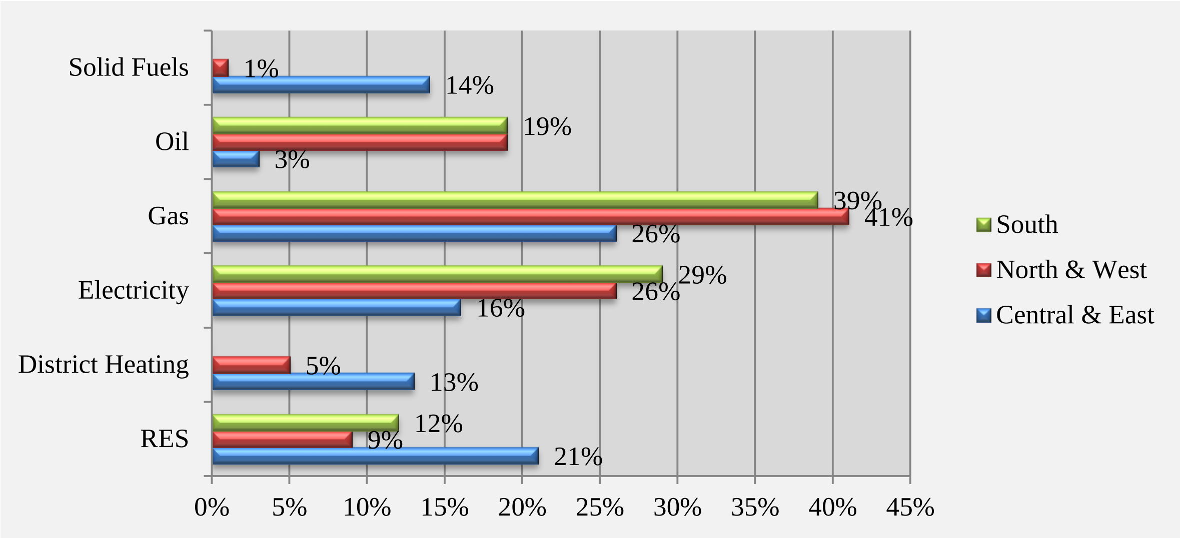


Figure 16: Final energy mix in residential buildings by region (BPIE 2011)

	Electricity prices						Gas prices					
	Households ([1])			Industry ([2])			Households ([3])			Industry ([4])		
	2011	2012	2013	2011	2012	2013	2011	2012	2013	2011	2012	2013
EU-28	0.179	0.188	0.199	0.110	0.115	0.120	0.056	0.063	0.065	0.035	0.040	0.041
Euro area (EA-17)	0.190	0.198	0.211	0.116	0.121	0.127	0.062	0.069	0.073	0.037	0.042	0.043
Belgium	0.214	0.233	0.217	0.110	0.108	0.108	0.063	0.069	0.066	0.033	0.035	0.040
Bulgaria	0.083	0.085	0.092	0.065	0.069	0.081	0.043	0.049	0.051	0.029	0.036	0.036
Czech Republic	0.150	0.150	0.153	0.111	0.104	0.102	0.054	0.066	0.064	0.031	0.034	0.034
Denmark	0.291	0.300	0.300	0.099	0.097	0.103	0.116	0.111	0.113	0.045	0.048	0.049
Germany	0.253	0.260	0.292	0.125	0.128	0.143	0.059	0.064	0.066	0.046	0.047	0.048
Estonia	0.097	0.110	0.135	0.072	0.078	0.097	0.042	0.050	0.052	0.028	0.037	0.038
Ireland	0.190	0.216	0.230	0.116	0.132	0.136	0.051	0.061	0.065	0.038	0.038	0.042
Greece	0.125	0.139	0.156	0.105	0.118	0.125	:	:	0.077	:	:	0.053
Spain	0.198	0.219	0.223	0.114	0.121	0.122	0.054	0.066	0.073	0.029	0.036	0.039
France	0.138	0.139	0.147	0.085	0.095	0.096	0.058	0.064	0.068	0.037	0.039	0.041
Croatia	0.114	0.121	0.137	0.091	0.090	0.095	0.038	0.038	0.047	0.041	0.043	0.046
Italy	0.199	0.213	0.229	0.152	0.165	0.168	0.069	0.077	0.083	0.031	0.042	0.042
Cyprus	0.205	0.278	0.276	0.167	0.224	0.208	-	-	-	-	-	-
Latvia	0.117	0.138	0.138	0.098	0.110	0.113	0.039	0.051	0.051	0.029	0.037	0.038
Lithuania	0.121	0.126	0.137	0.105	0.114	0.123	0.044	0.051	0.060	0.035	0.045	0.044
Luxembourg	0.168	0.170	0.167	0.100	0.105	0.098	0.051	0.058	0.062	0.042	0.051	0.051
Hungary	0.168	0.155	0.140	0.100	0.095	0.096	0.056	0.048	0.043	0.031	0.044	0.041
Malta	0.170	0.170	0.170	0.180	0.180	0.180	-	-	-	-	-	-
Netherlands	0.174	0.186	0.192	0.098	0.097	0.096	0.064	0.076	0.081	0.034	0.037	0.040
Austria	0.199	0.198	0.208	0.113	0.110	0.111	0.069	0.076	0.077	0.035	0.045	0.045
Poland	0.147	0.142	0.148	0.101	0.092	0.093	0.046	0.047	0.047	0.033	0.034	0.036
Portugal	0.165	0.199	0.208	0.099	0.114	0.115	0.061	0.074	0.084	0.034	0.040	0.042
Romania	0.108	0.105	0.132	0.080	0.083	0.090	0.028	0.027	0.029	0.023	0.026	0.028
Slovenia	0.144	0.154	0.161	0.099	0.095	0.097	0.067	0.080	0.067	0.045	0.058	0.049
Slovakia	0.168	0.172	0.170	0.128	0.132	0.129	0.047	0.052	0.050	0.035	0.040	0.037
Finland	0.154	0.155	0.158	0.076	0.076	0.075	:	:	:	0.042	0.047	0.049
Sweden	0.209	0.203	0.210	0.089	0.081	0.080	0.119	0.117	0.123	0.051	0.054	0.055
United Kingdom	0.143	0.168	0.174	0.098	0.115	0.118	0.043	0.052	0.053	0.025	0.032	0.035
Iceland	:	0.111	0.105	:	:	:	:	:	:	:	:	:
Norway	0.213	0.188	0.191	0.111	0.092	0.097	:	:	:	:	:	:
Montenegro	0.087	0.091	0.102	0.061	0.065	0.073	:	:	:	:	:	:
FYR of Macedonia	:	:	0.081	:	:	0.080	:	:	:	0.038	0.047	0.041
Serbia	:	:	0.056	:	:	0.057	:	:	0.041	:	:	0.038
Turkey	0.122	0.131	0.150	0.079	0.086	0.093	0.029	0.032	0.041	0.022	0.025	0.031
Albania	0.115	0.116	0.116	:	:	:	:	:	:	:	:	:
Bosnia and Herzegovina	0.075	0.080	0.080	0.061	0.065	0.065	0.045	0.056	0.056	0.048	0.057	0.057

([1]) Annual consumption: 2 500 kWh < consumption < 5 000 kWh.
([2]) Annual consumption: 500 MWh < consumption < 2 000 MWh; excluding VAT
([3]) Annual consumption: 20 GJ < consumption < 200 GJ.
([4]) Annual consumption: 10 000 GJ < consumption < 100 000 GJ; excluding VAT.

Figure 17: Electricity and natural gas prices in Europe (Eurostat)

With reference to gas and electricity prices Eurostat provides data from 2011 to 2013 for each member state both for the residential and the industry sector as well as average prices for the EU 28 (Figure 9,10,11). The average price for the electricity regarding the year 2013 was 0.199€/kWh for residential buildings and 0.12€/kWh for the industry. The electricity price for residential buildings has been increased around 11% since 2011 while regarding the industry the difference is about 0.09% (from 0.11 increased to 0.12). In addition the average price for the natural gas in 2013 was 0.065€/kWh for residential buildings and 0.043€/kWh for the industry.

Furthermore, taking into account the local characteristics of each member state the price of natural gas as well as the electricity price varies in a great degree. As an example the lowest electricity price for residential buildings is recorded in Belgium, while the highest in Denmark. However, with regard to the industry prices the highest electricity price is found in Cyprus and the lowest in Finland. Respective data for the natural gas prices indicate that the highest price for both residential buildings and the industry is in Sweden and the lowest in Romania.

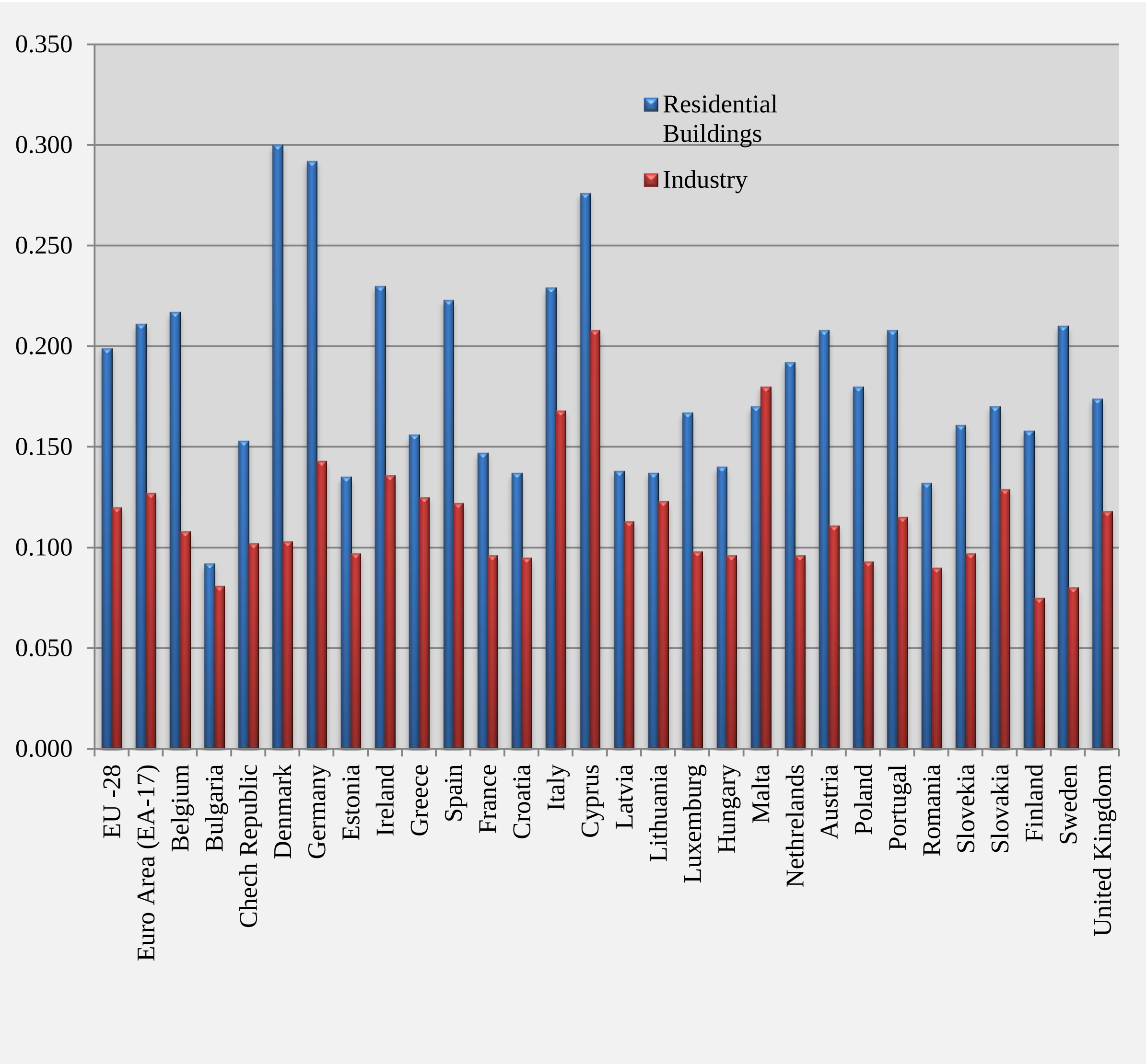


Figure 18: Electricity prices for the residential sector and the industry in 2013 (Eurostat)

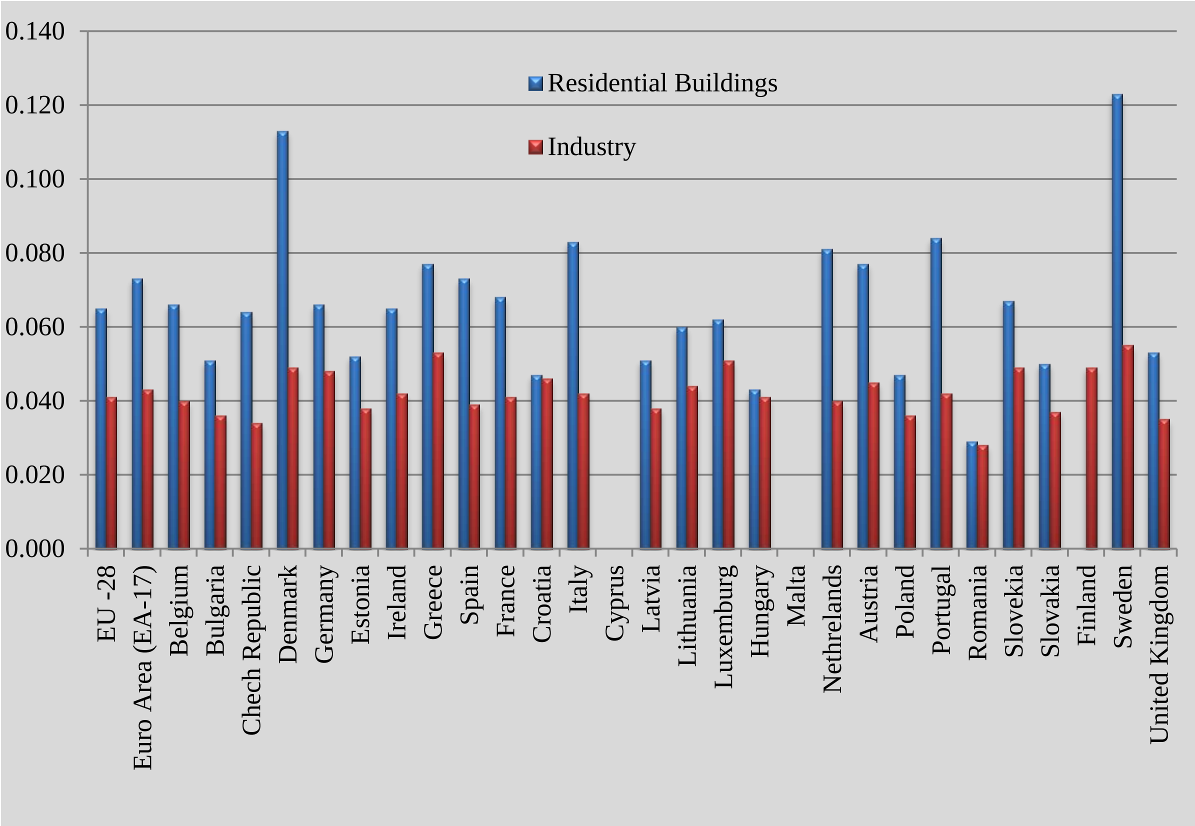


Figure 19: Natural gas prices for the residential sector and the industry in 2013 (Eurostat)

Therefore, the cost of the energy consumption could be calculated based on the following equation, using the average price of the EU-28 or the price of each member state. In that line, the environmental impacts and the energy consumption are expressed in euro and represent the environmental cost.

$$R_{SSD(Energy)} = P_{Energy} * Q_{Energy}$$

Equation 13: Energy consumption converted into costs

where: $R_{SSD(Energy)}$ is the global result for the sustainable structural design methodology expressing the financial value of the energy consumption;

P_{Energy} is the price of one kWh of energy (electricity and gas), expressed in euro/kWh;

Q_{Energy} is the amount of the energy resulted from the LCA analysis, expressed in kWh.

3.3.4 Other Environmental Impacts Converted to CO_2 equivalent. Conversion Factors

Methods have been developed by the Intergovernmental Panel on Climate Change (IPCC) that provide a system of equivalence factors, which allows the conversion of various substances associated with the global warming potential into CO2 emissions. These conversion factors express the direct CO2 emissions result from the production of various substances (78, 79).

The use of emission factors is important for reporting the national greenhouse gas inventories under the United Nations Framework Convention on Climate Change (UNFCCC). THE UNFCCC has 196 parties including United Nations member states and the European Union. The UNFCCC has adapted the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (80), which were developed and published by the Intergovernmental Panel on Climate Change (IPCC). Those estimation methods should be used by the parties in order to ensure transparency, consistency, comparability and accuracy of the national greenhouse gas inventories. The IPCC Guidelines are the primary source for default emission conversion factors.

The following table illustrates the direct 100-year time horizon global warming potentials (GWP) relative to CO_2. This data are adapted from the IPCC Fourth Assessment Report (2007) (79).

Industrial designation or common name	Chemical Formula	Conversion factors - 4th Assessment Report IPCC			
		SAR (100-yr)	20 years	100 years	500 years
Carbon dioxide	CO_2	1	1	1	1
Methane	CH_4	21	72	25	7.6
Nitrous oxide	N_2O	310	289	298	153

Table 1: Conversion factors related to CWP substances (IPCC)

In addition, tables that indicate equivalence factors for substances associated with the acidification and the eutrophication potential are also provided. Table 2 illustrates impact category indicators associated with consumption of resources, air pollution, water pollution and waste (81). Similarly to the European Union Emissions trading system that forms the prices of the carbon dioxide per tonne (76), the U.S. Environmental Protection Agency's (EPA) Acid Rain Program has developed the SO_2 Emission Allowance. Therefore, SO_2 allowances are recorded by the EPA in a central database called the Allowance Tracking System (ATS), which forms respectively a price for the SO_2 allowances (82). However, in Europe there has not been developed any similar trading system yet.

Impact Category Indicators		
Area of protection	Impact category	Scientific unit for the indicator
Consumption of resources	Total energy	MJ
Air pollution	Global warming potential	g eq. CO_2
	Acidification potential	g eq. SO_2
	Photochemical oxidation	g eq ethylene
Water pollution	Eutrophication potential	g eq. PO4
	Water pollution (critical volume)	m3
Waste	Municipal waste	kg
	Hazardous waste	kg

Table 2 : Impact Category Indicators (81)

Equivalence Factors of Various Acid Producers	
Acid producer (in air)	SO2 equivalence factor
1 kg HCl	0.88 kg eq SO_2
1 kg HF	1.60 kg eq SO_2
1 kg NO2	0.70 kg eq SO_2
1 kg SO2	1.00 kg eq SO_2
1 kg H2S	1.88 kg eq SO_2
1 kg NH4	0.89 kg eq SO_2
1 kg NH3	0.93 kg eq SO_2

Table 3: Equivalence factors for various acid producers (81)

To this regard, environmental impacts could be categorised and calculated with the equivalence factors. Through using the market prices those impacts could be converted into costs. Since, until today in Europe there are market prices for the carbon dioxide, only the environmental impacts associated with the global warming potential could be converted into costs.

3.3.5 Equation of the Global Assessment Parameter R_{SSD}

In the second step of the SSD methodology, the framework for calculating the total cost C_{TOT} was presented. The total cost C_{TOT} represents the total expected loss (L) which is the sum of the repair costs needed to restore building damages and the downtime losses and the initial construction cost (I). In the third step of the SSD methodology, possible methods to convert environmental impacts into costs were presented. Market prices could be used for expressing energy consumption into euro. The Global Warming Potential (CWP) can be calculated through the conversion factors that are equivalent to CO_2, while using the carbon prices formatted by the EU ETS it could be expressed into euro.

Therefore, the global assessment parameter of the SSD methodology is as follows:

$$R_{SSD} = R_{SSDt} + C_{TOT}$$

Equation 14: Global assessment parameter of the SSD Methodology

where:

$R_{SSDt} = R_{SSD(CO_2)} + R_{SSD(Energy)}$, [€]

$R_{SSD(CO_2)} = P_{CO_2} * Q_{CO_2}$, [€]

$R_{SSD(Energy)} = P_{Energy} * Q_{Energy}$, [€]

$C_{TOT} = L + I$, [€]

L is the Total Expected Loss that represents the repair costs and the downtime losses, calculated in the second step and expressed in euro and I is the initial construction cost.

Combination of Environmental and Structural Results

Step I of the SSD methodology focuses on the environmental performance of the building. Through using the Life Cycle Assessment methodology the environmental impacts resulting over the building's life cycle are calculated and expressed in CO2 and MJ regarding the carbon emissions and the energy consumption respectively. Step II of the SSD methodology considers probabilistic earthquake scenarios. Through the sPBA methodology the Total Expected Loss (L) resulting from those scenarios is calculated and is expressed in euro and summed to the initial construction cost (I) form the Total Cost (C_{TOT})

To combine the environmental and the structural results it is necessary to consider the same unit. Therefore, the environmental results are converted into euro in Step III. More specifically, carbon emissions are calculated with the carbon price provided by the European Union. This price results from the European Union Emissions Trading System, where member states according to the amount and the acceptable level of their carbon emissions format the carbon price. A clean and healthy industry indicates a high carbon price. In addition, the energy consumption prices result from the EU electricity and natural gas markets.

Therefore, the environmental impacts are converted into euro and are summed to the Annual Expected Loss that represents the structural results. Therefore, a global result is obtained that allows diverse stakeholder categories to compare and evaluate alternative construction solutions in terms of sustainability and technical performance.

Part III: Resource Efficiency; Its Importance in the European Union and the adaption of Respective Approaches in the Building Sector

4.1 Resource Efficiency and the European Union's Perspective

The final part of the report refers to resource efficiency, an issue that has long been considered as prominent and supported in the EU policy objectives. Nowadays, the demand and supply of resources is a non-balanced relationship, with the supply of raw materials being insufficient to meet the growing demand in resources.

Resource efficiency practices refer to the use of the Earth's limited natural resources (metals, metals, minerals, fuels, water, land, timber, fertile soil, clean air and biodiversity) in a sustainable way. The preservation of natural resources is essential as people depend on their use, while they are critical to keep economy functioning. Therefore, increasing resource efficiency is crucial to secure socioeconomic development and growth including an increase in employment and creation of opportunities.

Resource efficiency is linked to economic growth, improved productivity, reduction of costs and increased competitiveness. European Union policies support that resource efficiency is pivotal to induce technological innovation, to enhance employment in the green technology sector as well as to create new export markets and avail consumers through the availability of sustainable products. In this respect, a number of initiatives on resource efficiency have been introduced as well as many regulations have been adapted towards achieving resource efficiency (83).

4.2 Resource Efficiency and Supply of Raw Materials

Raw materials are of central importance to Europe's economy, growth and jobs and they are vital for improving the quality of people's life. Securing reliable, sustainable and non-distorted access of raw materials is a crucial issue both within the EU and globally. To support latter considerations, the Raw Materials Initiative (RMI) was introduced to support raw material related issues at an EU level.

Therefore, at the end of 2008 the European Commission published the Communication on the *''Raw Materials Initiative - Meeting our Critical Needs for Growth and Jobs in Europe*''. Considering the importance of resource efficiency, this Communication included a whole framework of measures in order to ensure security of raw material supply for Europe's economic growth. The RMI has been developed based on three pillars: *1. Ensuring a level playing field in access to resources in third countries; 2. Fostering sustainable supply of raw materials from European sources; 3. Boosting resource efficiency and promoting recycling* (84).

Furthermore, the '*'Report on Critical Raw Materials at EU Level*'' was published in 2010 introducing the concept of criticality and indicating 14 critical out of an analysis of 41 mineral raw materials (figure 19). A raw material is labelled as critical based on its risk for supply shortage as well as on its economic impact compared to other raw materials. Two categories of risks have been defined:

1. The ''supply risk'' considering the political-economic stability, the level of concentration of production, the potential for substitution and the recycling rate
2. The '' environmental country risk'' evaluating the risks resulting from the measures that a country with a low environmental performance might take in order to preserve environment and as a result to risk supply of raw materials to the European Union.

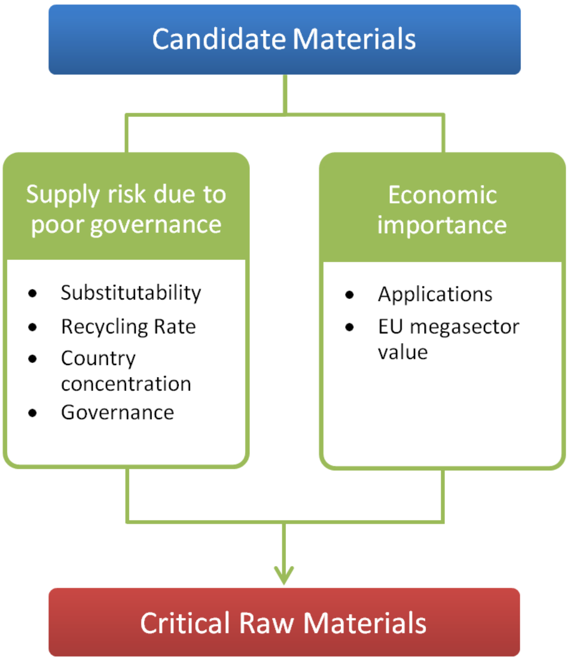


Figure 20: Methodology for addressing Critical Raw Materials

Criticality is determined based on a pragmatic approach that presents a transparent methodology and introduces a way to aggregate indicators, while it takes into account the substitutability between materials. Therefore, calculations are performed regarding the economic importance and supply risk of the 41 materials. The 14 critical materials are the Antimony, Beryllium, Cobalt, Fluorspar, Gallium, Germanium, Graphite, Indium, Magnesium, Niobium, Platinum Group Metals, Rare earths, Tantalum, Tungsten. The Production concentration of the critical raw mineral materials is illustrated in figure 20 (85).

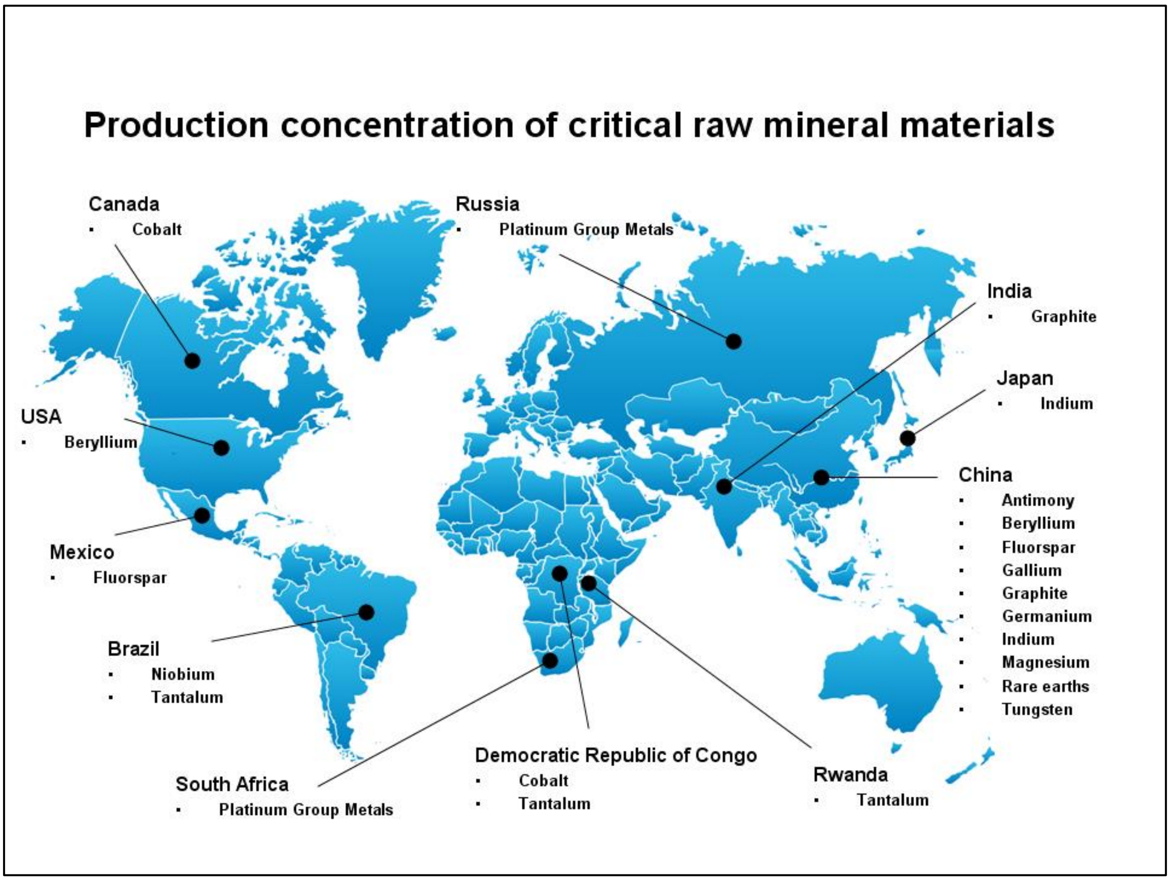


Figure 21: Production concentration of critical raw mineral materials

Following the latter, in 2013 the list with the critical mineral raw materials was updated based on an analysis on the same risk categories. This list indicates thirteen materials identified, with only tantalum not being included in the EU critical material list. The six new materials included in the list are borates, chromium, coking coal, magnesite, phosphate rock and silicon metal (Figure 21,22).

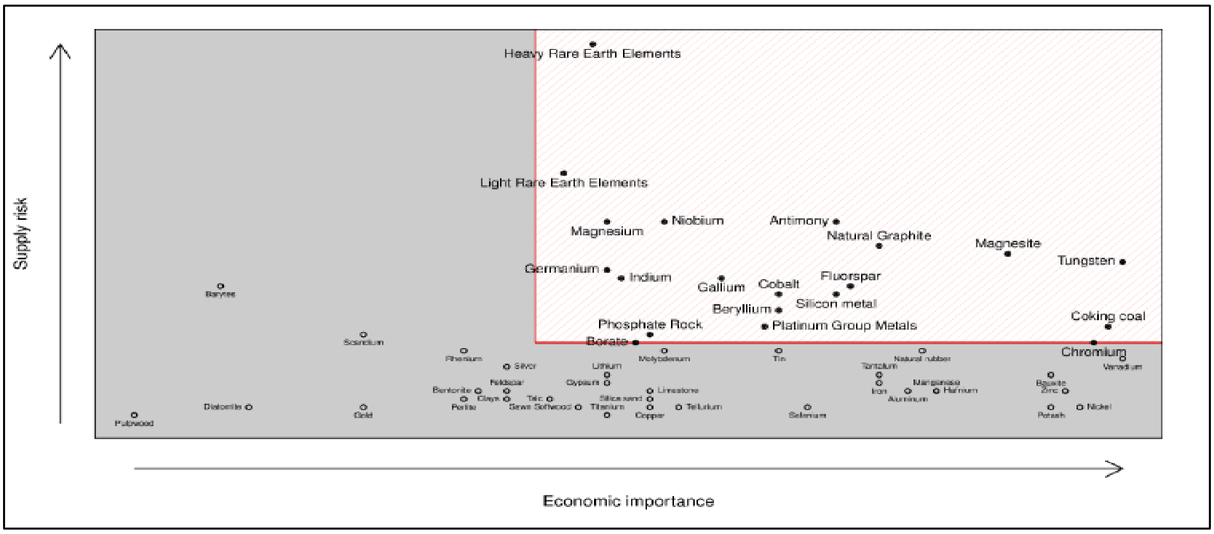


Figure 22: Critical materials based on supply risk and economic importance

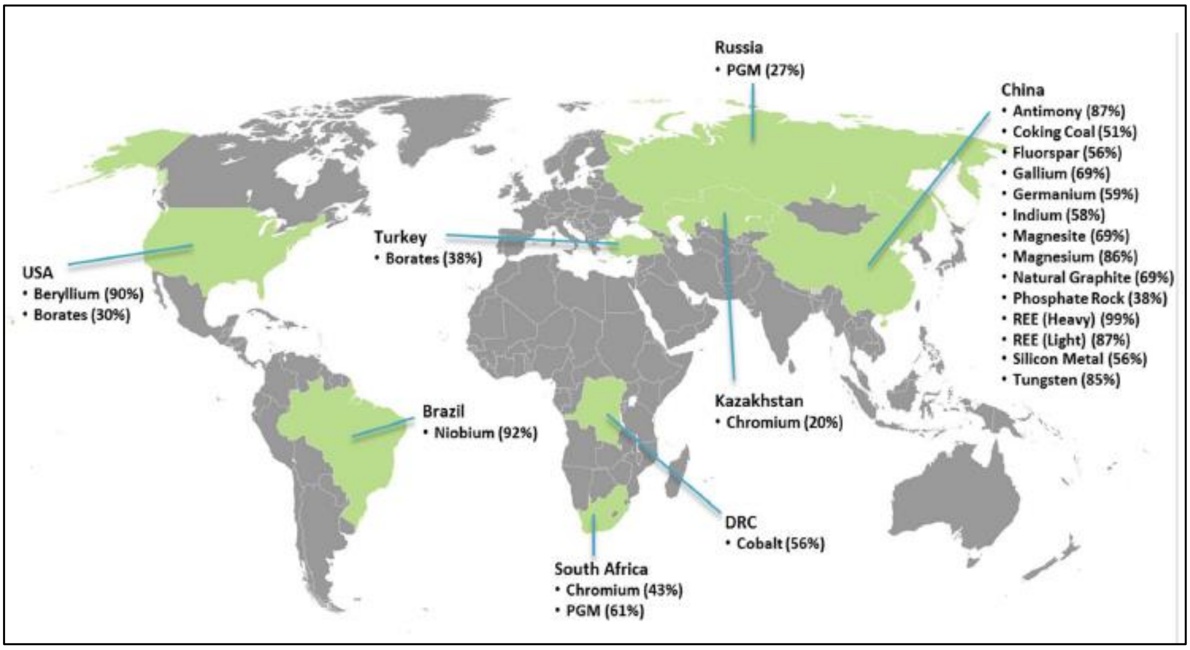


Figure 23: Critical materials by country

Raw materials are of high importance to the EU industry. Difficulties in the supply procedure of raw materials result in negative impacts on the industrial performance of Europe and therefore, on its overall economic performance. To reduce the dependence on non-EU virgin raw materials, the European Commission proposes mining and recycling as key action policies. Mining is a crucial approach to take advantage of Europe's unexploited minerals. Recycling is equally deemed another crucial approach for reducing European demand for non –EU raw materials (86).

4.3 European Policy Framework on Resource Efficiency

Considering the importance of raw material supply and thus resource efficiency, the European Union has introduced a whole framework of initiatives and policies towards achieving an efficient and sustainable way of using resources.

The EU ''*Strategy For The Sustainable Use of Natural Resources*'' indicated that the economy of member states is interlinked to the availability of natural resources and therefore, increasing resource efficiency is considered imperative (87). Furthermore, in line with sustainability the Flagship initiative of the Europe 2020 strategy – ''*A Resource Efficient Europe*'' underpins to move towards a resource-efficient, low-carbon economy in order to achieve sustainable growth. This initiative involves actions in many policy areas in a long-term perspective. Those areas are climate change, transport, energy, raw materials, fisheries, industry, biodiversity and regional development. The aim is at increasing investment stability and opportunities for innovation along with ensuring that respective policies factor in resource efficiency in a balanced way.

An example of EU actions already adapted towards a resource efficient Europe is the ''*Climate and Energy*'' package. This initiative has been fundamental in reducing greenhouse gas emissions through setting prices, defining targets indicating the way for further actions, fostering new technologies and broadening the opportunities for energy supply. Following the latter, the ''*EU Emission Trading System*'' represents a concrete example on how market can foster a more efficient use of resources. Furthermore, in 2008 the EU revised the legal framework for waste considering the whole product life cycle from generation to disposal. Emphasis was put on waste prevention, reuse, recycle and recovery. With reference to energy efficiency, the measures introduced under the ecodesign directive aimed at reducing power consumption, while the objective of the directive on energy performance of buildings is the reduction of the total final energy use in Europe (88).

In addition, the ''*Roadmap to a Resource Efficient Europe*'' employs ways to transform Europe's economy into a sustainable one by 2050. This initiative is part of the ''*Resource Efficiency Flagship of the Europe 2020 Strategy*'', which reflects the growth strategy of the next decade and aims at establishing a smart, sustainable and inclusive growth with increased levels of employment, productivity and social cohesion. The ''*Roadmap to a Resource Efficient Europe*'' provides proposals to increase resource productivity and dissociate economic growth from resource use and environmental impacts.

In general the ''*Resource Efficiency Roadmap*'' provides a framework that allows future actions to be designed and implemented in a coherent perspective. It defines a vision related to the structural and technological shift needed until 2050, with specific milestones to be succeeded by 2020. These milestones reflect what is essential to be implemented in order Europe to move towards a resource efficient and sustainable growth (89).

A follow-up of the ''*Resource efficiency Roadmap*'' as well as other EU environmental initiatives is the ''*Circular Economy*'' package published in July 2014. This package included a ''*Communication on Resource efficiency opportunities in the building sector*'', a legislative proposal in the direction of Waste policy, a Communication ''*Towards Circular Economy: A Zero Waste Programme for Europe*'', a communication on green jobs and a green action plan for SMEs. In general, this package aims at laying the foundations of an EU framework that fosters the model of circular economy. This model is built on re-use, recycling and restoring rather than extracting new resources (90).

4.4 Resource Efficiency in the Building Sector

Reducing both energy and resource consumption are central issues of the European Union's sustainable growth strategy to 2020, with a 20% reduction in EU primary energy use to be indicated as a major target. The 2020 strategy of the European Commission outlines resource efficiency as one of seven flagship initiatives needed towards creating a more sustainable Europe.

The building sector is considered as a major contributor to both energy and resource consumption throughout the EU (88). In addition, the ''*Roadmap for a Resource Efficient*

Europe'' adapted by the EU in 2011 indicates that this sector is responsible for approximately 40% of primary energy use and 50% of all extracted materials (89). Hence, this sector is under high pressure for implementing reduction efforts up to 2020 as well as for employing strategies that reflect long-term goals.

In 2014 the ''*Communication on Resource efficiency opportunities in the building sector''* was introduced, which aims at promoting a more efficient use of construction materials as well as to reduce the environmental impacts considering the whole life-cycle of buildings. This communication recommends that a transparent and comparable information system is needed in order these objectives to be achieved, in which the input will be founded on ''empirical and reliable'' data. Therefore, the development of transparent and comparable indicators that will allow the assessment of building performance as well as the development of a respective implementation framework is indicated as the next step. According to the communication these indicators will be built on the following areas (7):

- Total energy use, including embodied energy of products and construction processes
- Material use and their embodied environmental impacts
- Durability of construction products
- Design for deconstruction
- Management of construction and demolition waste
- Recycled content in construction materials and products
- Water in use phase
- Use intensity of (mostly public) buildings (e.g. flexible functionality for different users during different times of the day)
- Indoor comfort

The positive effects of adapting sustainable practices in the construction industry as well as the benefits that arise through deconstruction have been widely acknowledged, especially during the last decade. To this regard, a shift from the demolition and landfilling to deconstruction and reuse/recycling is gaining considerable interest. Design for deconstruction refers to those practices that structural and non – structural components could be reused at the end of the building's working life. A sustainable deconstruction strategy is based on a multi-dimensional assessment, considering cost, energy and emission parameters (91). In addition, this method employs design principles in order to facilitate and secure both reuse and recycle of building components through deconstruction (92).

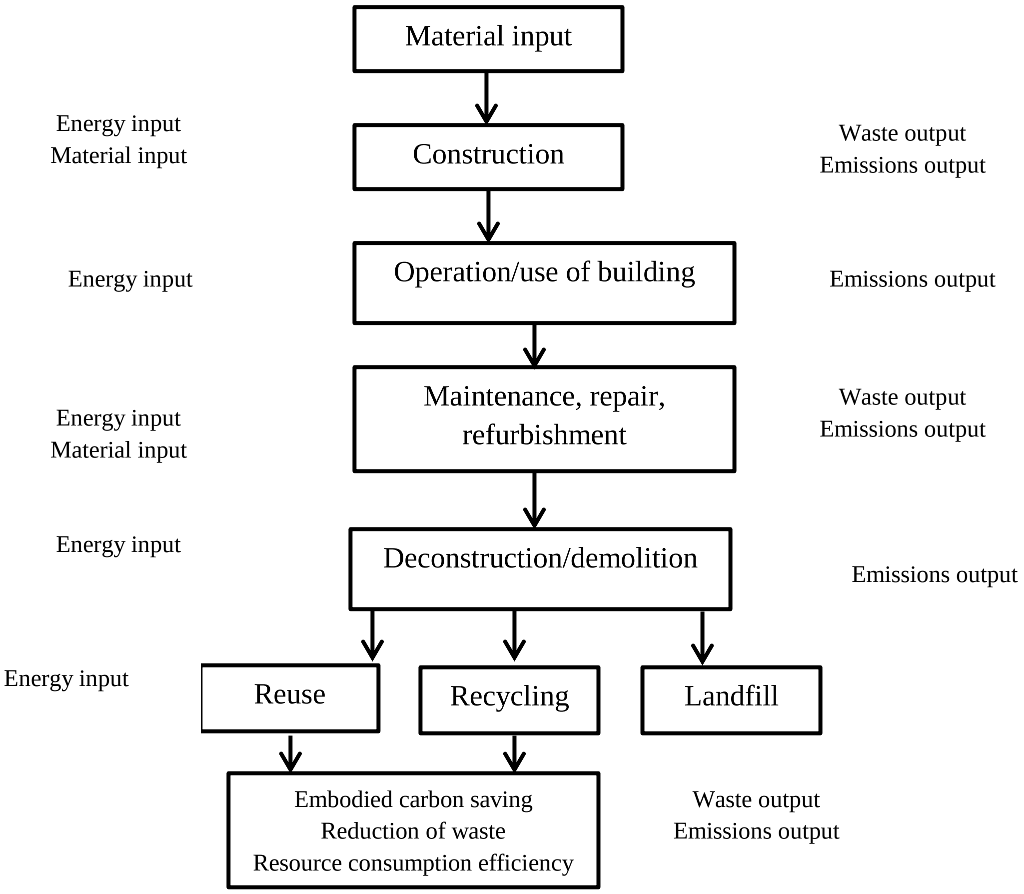


Figure 24: Building life cycle incorporating recycling and reuse practices (93)

Furthermore, buildings consume large amounts of resources in terms of energy and materials throughout their life cycle. Moreover, construction activities are associated with significant environmental impacts such as air, water pollution as well as waste generation, with large amounts to be produced during the demolition phase (figure 23). These issues should be taken into account in the framework of sustainable construction practices, including considerations for disassembling/deconstruction (92) as well as recycling. Recycling is one of the main strategies in construction and demolition waste management and is considered as a key option to move towards sustainability. It reduces the demand for extracting new resources as it provides recycled materials through the use of waste as well as it reduces the cost and energy use incurred by landfilling. However, a building is comprised by many and diverse components each one associated with different characteristics, which satisfy or not reusability and recyclability (91).

With reference to the principle of durability, this is associated with the conservation of the material's / product's properties (94). Durability may be defined as "the characteristic of those objects or materials that maintain their properties over time" (95). Various standards have been developed that define the properties and characteristics that a material should meet. In addition, ISO standards have been developed specifically for buildings and building components (ISO, 2009 and ISO, 1998). These standards set the requirement that the estimated service life of the product should meet or exceed its design life, namely the period for which the product is to be used (94).

In general, increased efficiency is interlinked to a reduction across the whole life-cycle of buildings. Resource efficient construction refers to this approach that affects in an efficient way the potential of other objectives, such as energy efficiency in buildings, reduction of carbon and other emissions, material and energy flows throughout the lifetime of a building. However, a legislation to reduce resource consumption does not exist in all major EU policies. Energy efficiency within the building sector is supported in a higher level and is believed to hold the largest potential (96).

Resource Efficiency

Resource efficiency is linked to economic growth, improved productivity, reduction of costs and increased competitiveness among respective sectors and it has long been addressed as a major issue by the European Union.

The construction and building sector needs to employ practices towards an efficient way of resource consumption. This sector is responsible for approximately 40% of primary energy use and 50% of all extracted materials and therefore, is under pressure for implementing reduction efforts up to 2020 as well as adapting long-term strategies towards these objectives.

EU has introduced a number of policy initiatives to achieve resource efficiency. The most recent one is the Circular Economy package published in July 2014. This package includes four proposals among which is the Communication on Resource efficiency opportunities in the building sector. This Communication aims at promoting a more efficient use of construction materials as well as to reduce the environmental impacts considering the whole life-cycle of buildings. The development of transparent and comparable indicators that will allow the assessment of building performance is considered as the next step towards achieving resource efficiency in the building sector. These indicators will build on areas such as total energy use, construction material use and their embodied environmental impacts, durability of construction products, design for deconstruction, construction management and demolition waste, recycling, water-use, intensity use of buildings and indoor comfort.

Conclusions

The issue of sustainability in the building sector is of considerable importance, as this industry from the one point of view causes large impacts on the environment but from the other point of view contributes greatly in socioeconomic perspective of development and growth. In the direction of sustainable construction, a number of efforts have been initiated to provide a building assessment framework. To this regard, the first part of the report provided a comprehensive description of the European Framework towards sustainable buildings as well as of the methods that have been developed by the International Organisation for Standardisation (ISO) and the European Committee for Standardisation (CEN). In addition, a description of the environmental methods such as BREEAM and LEED as well as of the footprint schemes was presented, while further analysis was devoted in the Footprint methods introduced by the European Commission; namely, the Product Environmental Footprint and the Organisational Environmental Footprint methods.

These efforts have been fundamental in providing environmental performance information as well as building environmental assessment frameworks in a life-cycle perspective. Footprint schemes provide an assessment on a product-level approach; however, a building, when considered as a product, is never finalised. In addition, a building is better described as a process rather than a product while considering the interactions in the building life cycle it is insufficient to consider buildings and/or its components in isolation. Therefore, to what extent do footprint schemes address sustainability in the building sector is questioned.

Current environmental assessment methods evaluate buildings over their life-cycle at a later design stage to provide an indication of their environmental performance. The sole aspect of environmental performance cannot provide comparable building solutions, while at this stage the information cannot be effectively used in the general design process. Moreover, given that the environmental impacts, the structural performance and the service life of the building are three correlating and complementary parameters, focusing solely on reducing the environmental impacts will not ensure environmental improvement. A more effective way of achieving building sustainability is to consider and incorporate environmental issues in the early design stage, where the principles of durability, probabilistic reliability and safety of structures are involved. Since these parameters are part of the same whole they need to be considered together.

The need for embracing a new approach to design structures has been highlighted in this report. Buildings are multi-dimensional systems and therefore, their assessment requires many parameters to be taken into account. To move towards sustainability, a new integrated-design approach is deemed essential that allows building assessment in a multi-performance perspective.

The Sustainable Structural Design (SSD) methodology was presented in the second part of the report, which is built on environmental and structural performance parameters based on a life-cycle approach. Emphasis was put on integrating environmental results in the structural performance, which is treated in a probabilistic manner through the introduction of a simplified Performance-Based Assessment method. Account for uncertainties in the structural design through probabilistic scenarios is deemed essential in order to move towards sustainability and building design optimisation, since actual responses and therefore respective costs as well as safety-related issues could be addressed in a more effective way. To combine structural and environmental results it is necessary to consider the same unit. Therefore, environmental impacts are converted into costs based on actual market prices under the EU Emissions Trading System, which forms the carbon price as well as based on respective data for energy prices. The final output of the SSD methodology is a global assessment parameter, which results as the sum of ecological costs, construction costs and the expected structural repair and downtime losses. This global assessment parameter allows diverse stakeholder categories to make decisions about design solutions in a multi-dimensional perspective.

The final part of the report discussed the resource efficiency. According to the EU, resource efficiency is vital to economic growth, improved productivity, reduction of costs and increased competitiveness. The EU stated that the building sector is responsible for approximately 40% of primary energy use, 50% of all extracted materials and 30% of carbon emissions and thus, is under pressure for implementing reduction efforts as well as for adapting long-term strategies towards these objectives. The recent communication on resource efficiency opportunities in the building sector indicated that the development of building performance indicators is the next step towards achieving efficient resource consumption in this sector. These indicators will be built on areas such as total energy use, construction material use and their embodied environmental impacts, durability of construction products, design for deconstruction, construction management and demolition waste, recycling, water-use, intensity use of buildings and indoor comfort.

One measure adopted alone will not ensure sustainability since buildings are multi-dimensional systems and involve aspects (safety, material properties, environmental impacts, actual response, costs) that are closely related and significant in resolving cost, resource and environmental constraints. A sustainable development is one that meets the needs of the present while maintaining the ability of future generations to sustain their own needs.

The approach which has been presented in this report is capable of accounting for all components of sustainability in the design process. The design process is traditionally driven by costs (construction costs, expected maintenance and transformation costs, expected losses in the event of extreme actions etc.). Therefore, a method based on the conversion of all parameters that are associated to the environment (energy consumption, GHG emissions, depletion of resources) into costs has been proposed. Different design options will be sorted with respect to the total cost, so that the most efficient solution could be identified.

This approach might also pave the way to many policy options. All the costs (energy, use of resources, GHG emissions) are driven by the market. However, an effective way to decrease the impact of the construction industry as well as of any other activity into the environment is to implement actions which increase the environmental costs. For instance, actions could be enforced to increase the difference between the cost of green, renewable energy with respect to conventional one and to increase the cost of scarce materials with respect to reusable ones.

References

1. Shena L, Tam V, Tam L, Ji Y. Project feasibility study: the key to successful implementation of sustainable and socially responsible construction management practice. Journal of Cleaner Production. 2010; 18:254-259

2. Ortiz O, Castells F, Sonnemann G. Sustainability in the construction industry: A review of recent developments based on LCA. Construction and Building Materials. 2009; 23:28-39

3. European Commission, Eurostat, Construction Statistics. Available from: ec.europa.eu/Eurostat

4. Ardente F, Beccali M, Cellura M, Mistretta M. Energy and environmental benefits in public buildings as a result of retrofit actions. Renewable and Sustainability energy reviews. 2011; 15:460-470

5. Teng J, Wu X. Eco-footprint-based life-cycle eco-efficiency assessment of building projects. Ecological Indicators. 2014; 39:160-168

6. Buyle M, Braet J, Audenaert A. Life cycle assessment in the construction sector: A review Renewable and Sustainability energy reviews. 2013; 26:379-388

7. European Commission. Resource Efficiency Opportunities in the Building Sector. 2014. Available from: http://ec.europa.eu/environment/eussd/pdf/SustainableBuildingsCommunication.pdf

8. European Commission. Sustainable Buildings. Available from: http://ec.europa.eu/environment/eussd/buildings.htm

9. Mateus R, Bragança L. Sustainability assessment and rating of buildings: Developing the methodology SBToolPTeH. Building and Environment.2011; 46:1962-1971

10. Ding G. Sustainable construction—The role of environmental assessment tools. Journal of Environmental Management. 2008; 86:451–464

11. Schwartz Y, Raslan R. Variations in results of building energy simulation tools, and their impact on BREEAM and LEED ratings: A case study Energy and Buildings. 2013; 62:350-359

12. Alyami S, Rezgui Y. Sustainable building assessment tool development approach,1 Sustainable cities and Society. 2012; 5:52-62

13. Wu P, Sui Pheng Low, Xia B, Zuo J. Achieving transparency in carbon labelling for construction materials – Lessons from current assessment standards and carbon labels. Environmental Science & Policy. 2014; 44:11-25

14. Haapio A, Viitaniemi P. Environmental effect of structural solutions and building materials to a building. Environmental Impact Assessment Review. 2008; 28:587–600

15. ISO/TC 59/SC 17 - Sustainability in buildings and civil engineering works. Available from: www.iso.org

16. CEN/TC 350 Sustainability of Construction works. Available from: http://portailgroupe.afnor.fr/public_espacenormalisation/CENTC350/index.html

17. Rossi B. Discussion on the use of stainless steel in constructions in view of sustainability. Thin-Walled Structures. 2014; 83:182–1897

18. European Union. http://ec.europa.eu

19. European Commission. Strategy for the sustainable competitiveness of the construction sector and its enterprises. 2012. Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2012:0433:FIN:EN:PDF

20. European Commission. Analysis of options to move beyond 20% greenhouse gas emission reductions and assessing the risk of carbon leakage. 2012. Available from: http://ec.europa.eu/clima/policies/package/docs/swd_2012_5_en.pdf

21. Cucek L, Klemes J, Kravanja Z. A Review of Footprint analysis tools for monitoring impacts on sustainability. Journal of Cleaner Production. 2012; 34:9-20

22. Galli A, Wiedmann T, Ercin E, Knoblauch D, Ewing B, Giljum S. Integrating Ecological, Carbon and Water footprint into a “Footprint Family” of indicators: Definition and role in tracking human pressure on the planet. Ecological Indicators. 2012; 16:100–112

23. Rees W. Ecological footprints and appropriated carrying capacity: what urban economics leaves out. Environment and Urbanisation. 1992; 4 (2): 121–130. Available from: http://eau.sagepub.com/content/4/2/121

24. Hoekstra A.Y. , Hung P.Q. Virtual water trade: A quantification of virtual water flows between nations in relation to international crop trade. 2002. Available from: http://www.waterfootprint.org/Reports/Report11.pdf

25. Radu A, Scrieciu M, Caracota D. Carbon Footprint Analysis: Towards a Projects Evaluation Model for Promoting Sustainable Development International Economic Conference of Sibiu 2013 Post Crisis Economy: Challenges and Opportunities, IECS 2013 Procedia Economics and Finance. 2013; 6:353 – 363

26. European Commission. Use of common methods to measure and communicate the life cycle environmental performance of products and organisations.2013. Available from: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013H0179&from=EN

27. Wu P, Low S.P., Xia B , Zuo J. Achieving transparency in carbon labelling for construction materials – Lessons from current assessment standards and carbon labels. 2014

28. Cohen M, Michael P. Vandenberg. The potential role of carbon labeling in a green economy Energy Economics. 2012; 34:S53–S63

29. Ball J. Can ISO 14000 and eco-labelling turn the construction industry green? Building and Environment. 2002; 37:421 – 428

30. Wu P, Xia B, Zhao X. The importance of use and end-of-life phases to the life cycle greenhouse gas (GHG) emissions of concrete– A review Renewable and Sustainable Energy Reviews. 2014; 37:360–369

31. The UNEP/SETAC Water Assessment Project Group. Available from: http://www.unep.org/

32. European Commission, IES JRC. Analysis of Existing Environmental Footprint Methodologies for Products and Organizations: Recommendations, Rationale, and Alignment. 2010. Available from: http://ec.europa.eu/environment/eussd/pdf/Deliverable.pdf

33. Ma, J., Hoekstra, A.Y., Wang, H., Chapagain, A.K., Wang, D. Virtual versus real water transfers within China. 2006; 361 (1469): 835-842.

34. Galli A, Wiedmann T, Ercin E, Knoblauch D, Ewing B, Giljum S. Integrating Ecological, Carbon and Water footprint into a “Footprint Family” of indicators: Definition and role in tracking human pressure on the planet. Ecological Indicators. 2012; 16:100–112

35. Onat N, Kucukvar M, Tatari O. Scope-based carbon footprint analysis of U.S. residential and commercial buildings: An input - output hybrid life cycle assessment approach. Building and Environment. 2014; 72:53-62

36. Wu P, Xia B, Pienaara J, Zhao X. The past, present and future of carbon labelling for construction materials - A review. Building and Environment. 2014; 77:160-168

37. European Commission. Integrated Product Policy: Building on Environmental Life-Cycle Thinking. 2003. Available from: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52003DC0302

38. European Commission. Sustainable Consumption and Production and Sustainable Industrial Policy Action Plan. 2008. Available from: http://ec.europa.eu/environment/eussd/pdf/com_2008_397.pdf

39. European Commission. Single Market Act I. Twelve levers to boost growth and strengthen confidence. "Working together to create new growth". 2011. Available from: http://ec.europa.eu/internal_market/smact/docs/20110413-communication_en.pdf

40. European Commission. 2013. Building the Single Market for Green Products Facilitating better information on the environmental performance of products and organisations. 2013. Available from: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52013DC0196&from=EN

41. European Commission. Environment, Product Environmental Footprint (PEF) news. Available from: http://ec.europa.eu/environment/eussd/smgp/product_footprint.htm

42. European Commission. Questions & Answers. Available from: http://ec.europa.eu/environment/eussd/smgp/pdf/q_a.pdf

43. Summary of Construction Product Working Group (CPWG) Meeting 30/7/2014

44. CEPMC (2013) Statement from CEPMC on the Product Environmental Footprint Guide, 26 April 2013.

45. Mora E. 2007. Life cycle, sustainability and the transcendent quality of building materials. Building and Environment. 2007;42:1329–1334

46. Dakwale V, Ralegaonkar R, Mandavgane S. Improving environmental performance of building through increased energy efficiency: A review. Sustainable Cities and Society. 2011;1:211– 218

47. Gil-Martin M , Gonzalez-Lopez M, Grindlay A, Segura-Naya A, Aschheim M, Hernandez-Montes E. Toward the production of future heritage structures: Considering durability in building performance and sustainability – A philosophical and historical overview. International Journal of Sustainable Built Environment. 2012; 1:269–273

48. Hooton R, Bickley J. Design for durability: The key to improving concrete sustainability. Construction and Building Materials. 2014; 67:422–430

49. Fujita K, Takewaki I. Sustainable building design under uncertain structural-parameter environment in seismic-prone countries. Sustainable Cities and Society. 2011; 1:142– 151

50. Lange D, Devaney S, Usmani A. An application of the PEER performance based earthquake engineering framework to structures in fire Engineering Structures. 2014; 66:100–115

51. Müller H, Haist M, 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

52. Cabeza L, Rincóna L, Vilariño V, Péreza G, Castella A. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renewable and Sustainable Energy Reviews. 2014; 29:394–416

53. Porter K. An Overview of PEER’s Performance-Based Earthquake Engineering Methodology Department of Civil Engineering, California Institute of Technology, Pasadena, CA

54. Hoogmartens R, Passel S, Acker K , Dubois M. Bridging the gap between LCA, LCC and CBA as sustainability assessment tools. Environmental Impact Assessment Review. 2014; 48:27–33

55. Pajchrowski G, Noskowiaka A, Lewandowska A, Strykowskia W. Materials composition or energy characteristic? What is more important in environmental life cycle of buildings? Building and Environment. 2014; 72:15-27

56. Azari R. Integrated energy and environmental life cycle assessment of office building envelopes Energy and Buildings. 2014; 82:156–162

57. Ramesha T, Prakasha R, Shuklab K. Life cycle energy analysis of buildings: An overview. Energy and Buildings. 2010; 42:1592–1600

58. Stephan A, Crawford R, Myttenaere K. Towards a comprehensive life cycle energy analysis framework for residential buildings. Energy and Buildings. 2012; 55:592–600

59. 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

60. Negro P, Mola E. Performance-Based Engineering Concepts: Past, Present and Future. 2006. First European Conference on Earthquake Engineering and Seismology.

61. Olmatia 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

62. Lagaros N, Garavelas A, Papadrakakis M. Innovative seismic design optimization with reliability constraints. Computer Methods Appl. Mech. Engineering. 2008; 198:28–41

63. Contini G, Mola E, Negro P. Practical Performance-Based Assessment of an Existing Plan-Wise Irregular Building. The 14th World Conference on Earthquake Engineering October 12-17, 2008, Beijing, China Report

64. Romano E, Negro P, Taucer F. Earthquake Engineering addressing sustainability and energy efficiency. Scientific and Policy Reports. 2014 Joint Research Centre, Institute for the Protection and Security of the Citizen.

65. Barbatoa M, Petrini F, Unnikrishnana V, Ciampoli M. Performance-Based Hurricane Engineering (PBHE) framework. Structural Safety. 2013; 45:24–35

66. Spence S, Gioffrè M. Large scale reliability-based design optimization of wind excited tall buildings. Probabilistic Engineering Mechanics. 2012; 28:206–215

67. Mitrani-Reiser J, Haselton C, Goulet C, Porter K, Beck J, Deierlein G. Evaluation of the seismic performance of a code-conforming reinforced-concrete frame building - Part II: loss estimation

68. Solberg K, Dhakal R, Mander J, Bradley B. Computational and rapid expected annual loss estimation methodologies for structures

69. Kunnath S. Application of the PEER PBEE Methodology to the I-880 Viaduct. 2007. Pacific Earthquake Engineering Research Center.

70. Vamvatsikos D, Dolšek M. Equivalent constant rates for performance-based seismic assessment of ageing structures. Structural Safety. 2011; 33:8–18

71. Vamvatsikos D., Cornell C.A. Incremental Dynamic Analysis. Earthquake Engineering and Structural Dynamics. 2002; 31(3): 491–514.

72. Seismic Load Combinations according to Italian code DM 14/01/2008

73. Lane T. Embodied energy: The next big carbon challenge. 2010. Available from: www.building.co.uk/technical/embodied-energy-the-next-big-carbon challenge/5000487.article

74. Whitehead B, Andrews D, Shah A, Maidmenta G. Assessing the environmental impact of data centres part 2: Building environmental assessment methods and life cycle assessment. Building and Environment. 2014; 1-11

75. European Union. Directive 2010/31/EU on the energy performance of buildings. 2010. Available from: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0031&from=EN

76. The EU Emissions Trading System (EU ETS). http://ec.europa.eu/clima/policies/ets/index_en.htm

77. http://www.sendeco2.com

78. Dattilo C.A., Negro P, Landolfo R. An integrated approach for sustainability (IAS): Life Cycle Assessment (LCA) as a supporting tool for Life Cycle Costing (LCC) and social issues. Available from: http://www.irbnet.de/daten/iconda/CIB17455.pdf

79. IPCC - Intergovernmental Panel on Climate Change. www.ipcc.ch/

80. United Nations Framework Convention on Climate Change. unfccc.int/

81. European Union. Annex 5: Environmental impacts analysed and characterisation factors. Available from: http://ec.europa.eu/environment/waste/pdf/study/annex5.pdf

82. US Environmental Protection Agency. www.epa.gov/

83. European Commission, Resource Efficiency. http://ec.europa.eu/environment/resource_efficiency/about/index_en.htm

84. Commission of the European communities 2008. The raw materials initiative — meeting our critical needs for growth and jobs in Europe. Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2008:0699:FIN:en:PDF

85. European Commission 2010. Report lists 14 critical mineral raw materials. Available from: http://europa.eu/rapid/press-release_MEMO-10-263_en.htm?locale=en

86. European Commission 2014. Report on critical raw materials for the EU. Report of the Ad hoc Working Group on defining critical raw materials. Available from:

http://ec.europa.eu/enterprise/policies/raw-materials/files/docs/crm-report-on-critical-raw-materials_en.pdf

87. Commission of the European communities (2005). Thematic Strategy on the sustainable use of natural resources.

88. European Commission (2011). A Resource-Efficient Europe – Flag-ship Initiative under the Europe 2020 Strategy.

89. European Commission (2011). Roadmap to a Resource efficient Europe.

90. European Commission (2014). Towards a circular economy: A zero waste programme for Europe

91. Akbarnezhad A, Ong K, Chandra L. Economic and environmental assessment of deconstruction strategies using building information modelling. Automation in Construction. 2014; 37:131–144

92. Jaillon L, Poon C.S. Life cycle design and prefabrication in buildings: A review and case studies in Hong Kong. Automation in Construction. 2014;39:195–202

93. Tingley D, Davison B. Developing an LCA methodology to account for the environmental benefits of design for deconstruction. Building and Environment. 2012; 57:387-395

94. Ardente F, Mathieux F. Environmental assessment of the durability of energy-using products: method and application. Journal of Cleaner Production. 2014; 74:62-73

95. Mora, E. Life cycle, sustainability and the transcendent quality of building materials. Building and Environment. 2014;42:1329-1334

96. Mandley S, Harmsen R, Worrell E. Identifying the potential for resource and embodied energy savings within the UK building sector. Energy and Buildings. 2015;86:841–851

.

Europe Direct is a service to help you find answers to your questions about the European Union
Freephone number (*): 00 800 6 7 8 9 10 11
(*) Certain mobile telephone operators do not allow access to 00 800 numbers or these calls may be billed.

A great deal of additional information on the European Union is available on the Internet.
It can be accessed through the Europa server http://europa.eu.

How to obtain EU publications

Our publications are available from EU Bookshop (http://bookshop.europa.eu),
where you can place an order with the sales agent of your choice.

The Publications Office has a worldwide network of sales agents.
You can obtain their contact details by sending a fax to (352) 29 29-42758.

European Commission
EUR 27116 EN – Joint Research Centre – Institute for the Protection and Security of the Citizen

Title: **Building Design for Safety and Sustainability**

Author(s): Kassiani Tsimplokoukou, Marco Lamperti, Paolo Negro

Luxembourg: Publications Office of the European Union

2014 – 82 pp. – 21.0 x 29.7 cm

EUR – Scientific and Technical Research series – ISSN 1831-9424 (online)

ISBN 978-92-79-45682-4 (PDF)

doi:10.2788/338223

LB-NA-27116-EN-N

JRC Mission

As the Commission's in-house science service, the Joint Research Centre's mission is to provide EU policies with independent, evidence-based scientific and technical support throughout the whole policy cycle.

Working in close cooperation with policy Directorates-General, the JRC addresses key societal challenges while stimulating innovation through developing new methods, tools and standards, and sharing its know-how with the Member States, the scientific community and international partners.

Serving society
Stimulating innovation
Supporting legislation

doi:10.2788/338223

ISBN 978-92-79-45682-4

Publications Office