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Seismic performance assessment addressing sustainability and energy efficiency

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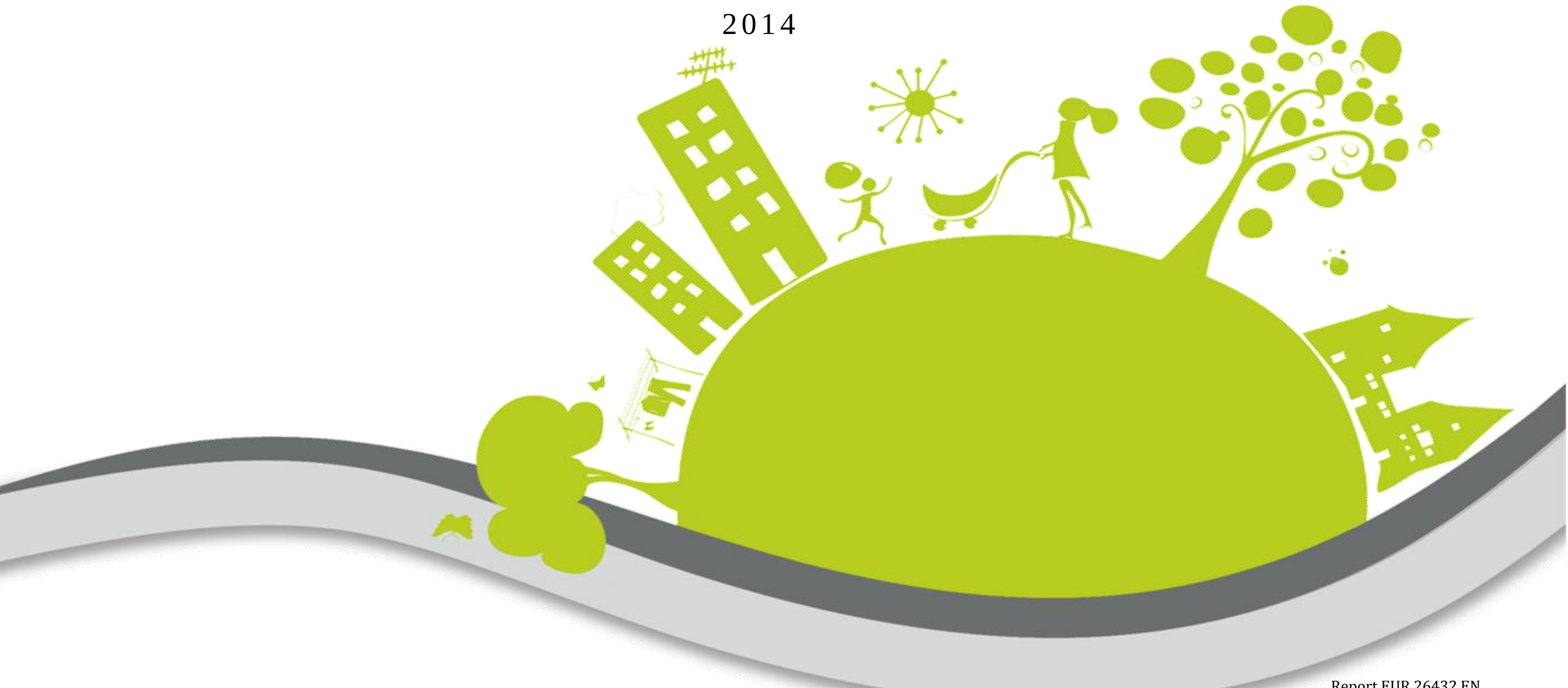

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ABSTRACT

Sustainability has become one of the most ambitious challenges for Europe growth, according to *2020 Europe Strategy*. This high-priority theme braces a lot of industrial sectors. In particular the construction sector bears a huge responsibility in relation to sustainable development because of several impacts produced on its three dimensions: environment, economy and society. A building has to fulfill its own performance not only in the abovementioned common triple-bottom line of sustainability, but also in usability, capacity, reliability, safety and comfort. In that context, designing a sustainable construction turns out to be a very complex issue, so a holistic view is the key of sustainability in the construction sector. Furthermore, buildings should be designed and assessed in the light of time with a future in mind which can be predicted only in probabilistic terms, so an integral life-cycle approach is required.

This report emphasizes the present need for the construction sector to develop a new way to conceive structures, with the aim to develop a competitive sustainable building market. In order to obtain this European objective a new design methodology is needed, focusing on a multi-performance, life-cycle oriented approach.

A potential *Sustainable Structural Design (SSD) methodology* with its three main steps is presented, addressing the possibility to include environmental aspects in structural design, in order to obtain a global assessment parameter in monetary terms. In details, the building environmental analysis in terms of CO_2 emissions and energy consumption, carried out by the Life Cycle Assessment (LCA) methodology should be combined with the structural analysis. For this reason environmental results have to be transformed in costs in order to be summed with structural results, expressed in economic terms thanks to the simplified Performance Based Assessment (sPBA) methodology.

Finally, the importance of considering the resource efficiency in construction sector is discussed, highlighting a possible way to measure it. The necessity to develop a research programme to consider the economic dimension of this aspect in order to include it in the SSD methodology is considered. Other possible options to ensure resource efficiency in the construction sector through the re-use of building materials and the recycle of construction and demolition waste or the reinforcement of economic instruments are underlined.

EXECUTIVE SUMMARY

Sustainable development, considered as the interaction of three dimensions (Environment, Economy, Society), is one of the fundamental objectives of the European Union. Several EU strategies and actions towards the adaptation of sustainable principles in the most impacting sectors of human activity have been undertaken by the European Commission in the last years.

PART I: MOTIVATION AND OBJECTIVE

According to the 2007 Lead Market Initiative, one of the markets which could favour the achievement of this essential transformation is the construction sector, incorporating the production, transport, use of building materials, use of building itself, maintenance, reuse of building or its materials, demolition and disposal of demolition waste.

The construction sector is one of the main contributor of CO_2 emissions, energy consumption, raw materials depletion and waste production, considering that buildings use 40% of total EU energy consumption, generate 36% of GHG emissions and produce a third of the total European waste. Moreover, people spend 90% of their time inside buildings so health, safety and comfort have to be ensured. With regard to the economic dimension, the construction sector generates 10% of GPD on European economy (Fig.a). On the basis of these evaluations, building sector turns out to be a market with a great potential to satisfy the eco-efficiency and sustainable goals during the whole life-cycle of a construction.

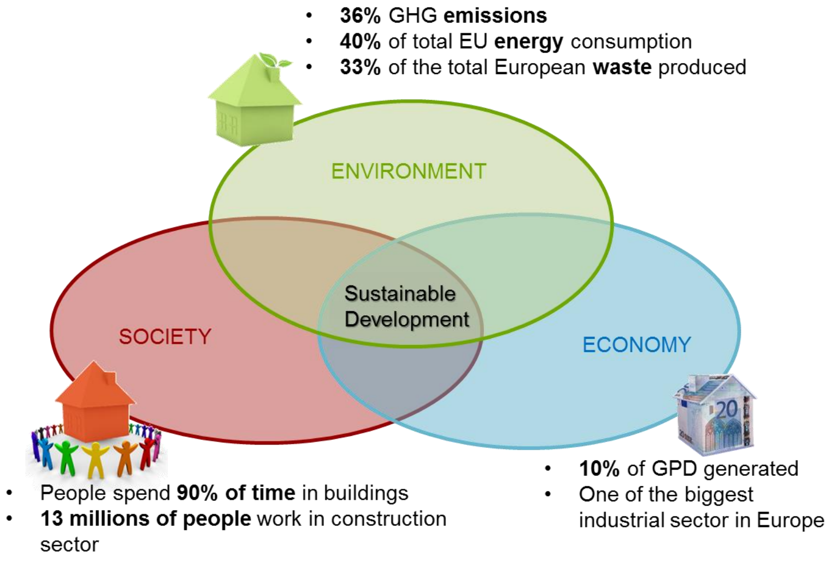


Fig.a: Impacts produced by construction sector on three dimensions of sustainable development

Awareness about negative consequences of impacts produced by buildings on environment, society and economy has led Europe to encourage stakeholders to develop a competitive sustainable construction sector. For this reason, the present way to conceive structures needs to change. Emphasis has to be placed on planet protection, people well-being and economic profit, but a building has also to ensure reliability and safety during all its life-cycle. Therefore, a sustainable construction should balance its performances between the three dimensions of sustainable development and the requirements of structural design.

Design for life-cycle becomes the starting point to conceive sustainable structures. It means design taking into account not only the structural performance of a building, but also the environmental and the economic ones during all the phases of the life-cycle (Fig.b).

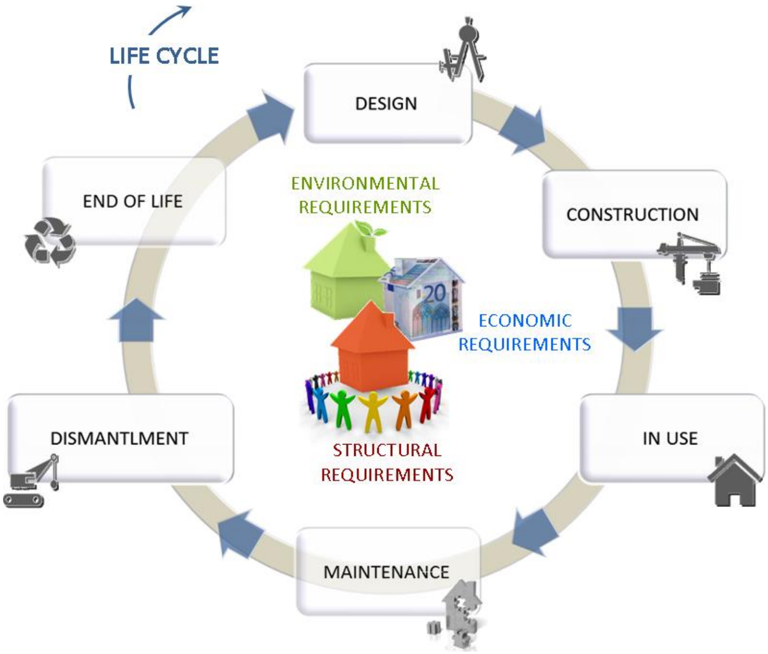


Fig.b: A sketch of building design for life-cycle towards an integrated sustainable approach

A new integrated methodology, focused on a **multi-performance, life-cycle oriented approach** is needed in order to reach an efficient sustainable construction market, as underlined by the 2012 competitiveness construction sector strategy.

PART II: THE FRAMEWORK OF THE SSD METHODOLOGY

This report proposes a **Sustainable Structural Design (SSD) methodology** which follows three main steps (Fig.c):

1. Environmental performance assessment
2. Structural performance assessment
3. Combination of ecological and structural results in economic terms.

The goal of this methodology is to obtain a global assessment parameter to compare alternative constructive solutions, addressing at the same time sustainability and energy efficiency from one side, and stability and reliability from the other.

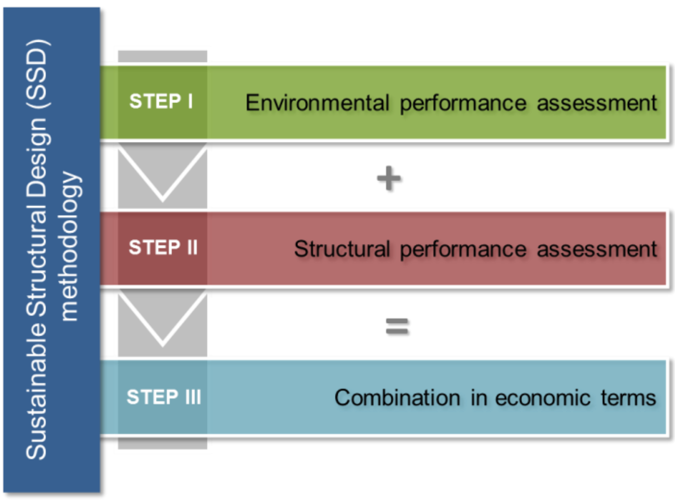


Fig.c: Main steps of the proposed Sustainable Structural Design (SSD) methodology

First step: Life Cycle Assessment (LCA)

The **first step** (Fig.d) of the SSD methodology is the **environmental performance assessment,** carried out through the **Life Cycle Assessment (LCA)** methodology, which allows environmental burdens or impacts to be assessed from extraction of raw materials to the end of life of a given product or process.

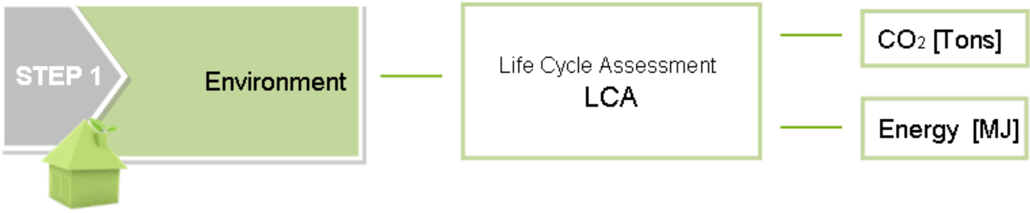


Fig.d: Sketch of Step 1

Europe recognizes the importance of using LCA methodology, so that Member States are involved in several initiatives in this direction. One of the most important European action is the development of the *European Platform on LCA* to harmonise the different methodologies used within the LCA communities and to give recommendations for the use of impact assessment methodologies.
Focusing on construction sector, the application of LCA has become a fundamental issue for sustainable structural design, allowing engineers and architects to assess the environmental impacts produced by a building throughout its whole life-cycle. Moreover, it can also result into a tool to help decision making, for instance influencing the choice of materials, the selection of technologies, the promotion of specific design criteria and recycling. In details, LCA methodology allows environmental performance of both construction materials/products and the entire building to be assessed. In particular, CO_2 emissions and energy consumption are considered. Several LCA supporting tools have been developed to carry out this analysis, even if further research is needed. The computer code *SimaPro* possibly represents one of the most flexible LCA pieces of software, since it includes several inventory databases. Thanks to some of *SimaPro* impact assessment methods, it is possible to assess the environmental performance of buildings in a quantitative way, obtaining ecological results, above all in terms of equivalent tons of CO_2 and MJ of energy.

Indeed, these impacts turn out to be the most common and dangerous problems related to the environmental dimension of buildings, considering that already in 2005 the construction sector accounted for 26.6% of final energy consumption.
In that light LCA becomes also a tool to support the achievement of energy efficiency building stock in accordance to the 2020 Europe Strategy and to the 2012 Energy Directive that foresees zero CO_2 and positive building by 2050. Several eco-efficient technologies have been developed to reach this goal. For instance, use of insulation materials for envelope that turns out to be the most critical element in relation to energy saving, and use of glazing windows with double and triple glazed units could perform a lot in energy terms.
The energy consumed during the use phase of a building has always been considered the most, but in the last years attention has also to be posed on the embodied energy. For high energy efficient buildings, the energy consumed for the operation of the building (use-phase) tend to become equal to the one taken up to build or dismiss. For this reason a LCA approach becomes really essential, considering that energy consumption during the construction and disposal phases of a building becomes more and more important when the operating energy consumption decreases. Finally, an European effort should be made in stimulating a further gradual increase of the share of renewable energy. Indeed, the optimal solution for the future building stock should be the interaction of three strategies: energy saving (structure and envelope), energy efficiency and energy production by renewable sources.

Once the importance of conducting LCA analysis in construction sector has been established, the open question is how to combine environmental performance with the structural one, considering that these performances have different measure units.
In details, the structural performance of a building can be quantified in terms of costs. The environmental performance, instead, is expressed in equivalent tons of CO_2 for emissions in the air and in MJ for energy consumptions. In such a way it is clear that these results can not be summed, so the challenge is to identify a way to obtain a global assessment parameter and to identify the best solution among different opportunities.
The second and the third step of the SSD methodology allow a solution to be reached.

Second step: Performance-Based Assessment (PBA)

The **second step** (Fig.e) of the SSD methodology is the **structural performance assessment**, referring for instance to the methodology for the Performance Based Earthquake Engineering (PBEE), developed by the Pacific Earthquake Engineering Research (PEER) center.

Fig.e: Sketch of Step 2

PEER has developed a detailed methodology for the seismic Performance-Based Assessment (PBA) of buildings, bridges and other engineered facilities that allows building performance to be predicted in a probabilistic format.
The PBA methodology has the aim to describe the performance of a building in terms of losses due to damages to buildings components.
This methodology follows a rather complicated approach, but the objective to incorporate monetary losses and seismic risk into the structural assessment turns out to be really interesting and efficient.
Such a comprehensive approach to PBA may not be necessary for most ordinary structures, therefore a ***simplified PBA*** **(sPBA)** process can be considered.
Focusing on the SSD methodology, the sPBA consists into the evaluation of costs and the expected monetary losses for each limit state considered, at which different peak ground accelerations and inter-storey drifts correspond. The aim of this analysis is to obtain the total expected loss *(L)* in each configuration through the *total probability theorem.*
This simplified approach allows structural behaviour to be assessed in economic terms considering monetary loss in relation to damages that a structure could be subject throughout its entire life-cycle. It could be useful to consider different damage scenarios during the lifespan of a building, already in the design phase. In such a way an a-priori analysis about the management of a building could be carried out, considering the expected annual loss (EAL) in terms of percentage of reconstruction cost, in order to understand for instance whether it is preferable a refurbishment or a reconstruction.

Third step: A global assessment parameter

The **third step** (Fig. f) of the SSD methodology has the scope to define a **global assessment parameter** that allows stakeholders to consider at the same time structural, environmental and economic performances of buildings.

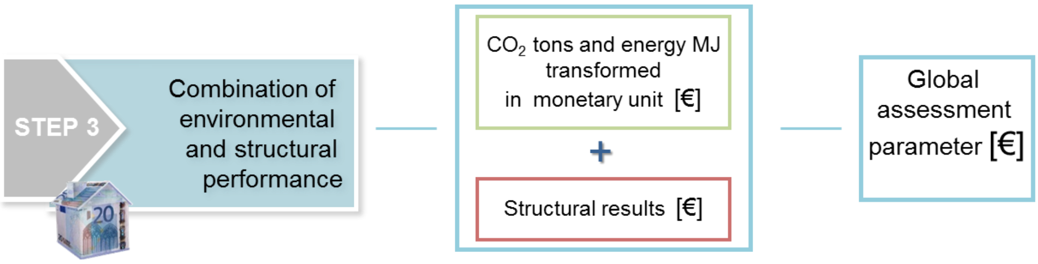


Fig.f: Sketch of Step 3

In details, a way to convert environmental analysis into economic terms has to been defined. In particular, it is necessary to **transform tons of equivalent CO_2 and MJ of energy in monetary unit**, so that structural and environmental performances can be considered as the sum of structural and ecological costs, obtaining a global sustainable result.

In order to reach this goal, firstly unitary price of CO_2 and energy have to be considered, as described below:

- Carbon emissions (CO_2): the cost of tons of CO_2 is strictly connected to Kyoto Protocol adoption in 2005. For the purpose of reaching targets of CO_2 emission reduction, "flexibility mechanisms" that allow the parties involved to reach their commitments at the lowest cost were considered. These projects generate carbon credits. Early in 2005 the European Union Emission Trading System (EU-ETS) has been adopted to anticipate the Kyoto target. This system represents the first large "cap and trade" scheme in the world to combat the climate change, becoming the major pillar of EU climate policy. Its aim was to help EU Member States to respect their obligations of reducing CO_2 emissions in a profitable way, allowing industries to buy or sell emission's quotas, called European Emission Allowances (EUAs). One EUA represents the right to emit one ton of CO_2.
  In short, EU-ETS has been essential to define a price for carbon.
  The Exchange of SENDECO$_2$ reports the data related to prices development of EUAs. For instance, 2013 has been opened with a price of 5.19 € (January), declining in May to median average of 3.51 euro, but in October the price has risen to median average of about 5 €/ton.

- Energy: energy market in Europe, underlines that Member States are so great consumers of energy that Europe accounts for a considerable dependence from foreign countries. In order to define energy prices for the building sector, taking into account consumption and import, it could be useful to consider separately electricity and gas, the most used forms of energy consumed in the use phase of a building (Tab.1).

Electricity price	Natural gas price
The most recent Eurostat data about retail electricity prices by households with a medium size annual consumption, including all taxes, are relative to the first half of 2013. In details, the highest price is paid in Denmark (30,0 c€/kWh), turning out to be three times higher than Bulgarian one (9,92 c€/kWh). The latter is the lowest electricity price paid in Europe.	Eurostat data show that, for medium size household consumers, natural gas prices during the first semester of 2013 were the highest in Sweden, Denmark and Portugal. The lowest natural gas prices in the EU for households were found in Romania, Hungary and in Croatia. Natural gas price for households in Sweden (12,3 c€/kWh) was more than four times the price that was charged in Romania (2,9 c€/kWh).

Tab.1: Electricity and natural gas unitary price in Europe

Once the price of carbon emissions and energy (electricity and gas) has been defined, environmental results, assessed by the LCA methodology can be converted into *"ecological cost"*, expressed in monetary units. In particular, the price of one ton of CO_2 and one kWh of energy have to be multiplied by the total quantity of CO_2 emissions and energy, calculated with LCA analysis.
In such a way structural results could be summed to environmental ones because both are expressed in monetary unit, obtaining a global sustainable assessment parameter.

An important aspect to consider in this study is that a low price of CO_2 emissions is still maintained. Moreover, the big difference between the prices of energy and CO_2 depends on high taxes considered for the energy. In particular, in order to understand the importance of environmental impacts in the construction sector, the price of CO_2 emissions should change to better reflect the environmental and social costs. In short, externalities should be taken into account.
The effect of an activity that may influence in a positive or negative way an otherwise uninvolved party who has no decision role in this activity is defined as an *externality*. CO_2 emissions and energy consumption produce several damages on the environment and society which are defined negative externalities. In order to assess and compare externalities with each other and with costs, it is advantageous to transform them into a common unit, in particular in monetary unit. In such a way the negative externalities result in external costs which are not accounted for by the decision maker.
In order to control these effects, a process of *internalisation* is needed, so appropriate instruments have been developed by economists and governments to adequately internalise externalities such as fiscal measures (taxes), tradable permits (EU-ETS), command and control (directives and regulations). Because of negative effects produced by EU-ETS such as over-allocation of emission permits and price volatility, the right way to consider external costs of CO_2 emissions could be to introduce environmental taxes. Full internalisation of external costs is difficult to achieve because the environmental damage value is generally not known, so the consecutive definition of environmental taxes becomes not so easy. In order to find a solution in this direction in 2005 a European project tried to develop a methodology to account damages and relative external costs.
Thanks to this project external costs per unit of emissions of CO_2 have been estimated. It is not possible to define a single value so the damage factors for CO_2 used range from 19 EUR/t CO_2 (low estimate, based on ExternE-Pol) to 80 EUR/t CO_2 (high estimate, based on Watkiss et al., 2005).
The limit of this estimate is clear: a precise price is not given, so the range considered has to be seen as indicative. Although large uncertainties remain in determining and monetizing the external costs, the importance of the problem is illustrated by the value range of cost estimates.
In that light, these costs are not negligible, indeed starting from these values, in 2005 the average external costs of electricity production across Europe ranged from 0.2 to 17.8 eurocent/kWh.

PART III: RESOURCE EFFICIENCY IN THE CONSTRUCTION SECTOR

Resource efficiency is an important topic in the light of the sustainable construction sector that can not be anymore omitted, considering that building sector accounts for 50% of raw materials consumption. Encouraging this topic brings several benefits not only on the environment, avoiding degradation and depletion of planet, but also on the economy of Member States because it depends on natural resources availability.

The attention on resource-efficiency has grown a lot, leading Europe to adopt several strategies and initiatives in this direction in the last decade, focusing on the achievement of a more sustainable use of resources. An important step has been obtained with the replacement of Construction Product Regulation in 2011, through the introduction of the 7th basic requirement about the sustainable use of resources.
A list of raw materials subject to risk of supply chain interruption has been presented, showing that some elements included in this list are largely used in sustainable constructions. In line with that, the

promotion of eco-innovation and recycle/re-use of materials is essential to ensure the future raw materials availability.
According to 2011 European flagship initiative on “A resource efficient Europe” *indicators are needed to cover issues such as the availability of natural resources, where they are located, how efficiently they are used, waste generation and recycling rates, impacts on the environment and biodiversity.* The challenge to include also this aspect in the sustainable structural design methodology has to been analysed, considering a way to quantitatively measure resource efficiency.
In line with that, in a recent study conducted by the University of Dundee, a raw material indicator as a combination of availability to future generations and quantity used is defined as a current scarcity score (CSS). This indicator is based on the report of quantities and residual lives of all resources (abiotic, biotic, fuels, water and secondary resources). Thanks to the development of a characterization model, raw material use is converted into current scarcity score and a hyperbolic function among the various potential models examined is regarded as giving the best relationship between the residual life and the CSS indicator.
Even if steps to accurately measure the resource efficiency in the sustainable construction sector are increasing, further aspects have to be developed. Potential options that could be considered to promote an ‘optimal’ use of resources in construction sector are:

1. **Economic dimension of resources:** an effort to assess the economic dimension of this issue should be done, in order to include this aspect in the proposed SSD methodology. In such a way, once the resource price has been defined, the true cost of resource use could be combined with environmental and structural results thanks to the third step of the proposed SSD methodology. In that line, taxes on raw materials should possibly be taken into account, encouraging in such a way the resource efficiency achievement.

2. **Satisfying waste and recycling targets:** re-use and recycling of building materials should become a normal practice. According to Waste Directive, 70% of construction and demolition (C&D) waste should be reused and recycled by 2020. With regards to the generation and recycling of C&D waste, although data availability is generally poor, around 850 million tonnes of C&D waste is generated in the EU per year. This represents 31% of the total waste generation in the EU. The generation of C&D waste in Member States in tonnes per capita varies considerably, from 0.04 tonnes in Latvia to 5.9 tonnes in Luxembourg. In 2004 (year for which the most data is available), the recycling rate was 60% or over in 10 Member States. In details, Denmark, Germany, Ireland and the Netherlands but also Estonia, recycle even over 80% of C&D waste generation. Even if the potential recycle of some construction materials is really high, further efforts are needed in this direction. For instance, flat glass and gypsum have high capacity to be recycled, but this potential is not adequately exploited.
   The waste directive target could be ensured in two ways:
   - *Design for Deconstruction.* Discarding materials rather than reusing them will continue to require extraction of huge quantities of new materials and the associated impacts on our ecosystems. A new mental model that clearly envisions these “wastes” as valuable resources harvested from existing buildings and used to build new ones, is needed. Design for deconstruction seems a possible good solution. This emerging concept allows building materials and components to be easily disassembled. By easing deconstruction and separation of components within buildings, it facilitates the development of closed loop material cycles, ensuring resources efficiency.

   - *Economic instruments.* It would seem that a correlation between landfill taxes and increasing of C&D waste recycling exists. In spite of that, scarcity of data does not allow to consider a significant link, but this economic instrument seems to be essential (in combination with other policies) to meet the existing minimum EU targets and ensure the goal of zero residual waste.

CONTENTS

INTRODUCTION

Nowadays Europe is more and more oriented toward the promotion of sustainability in all its activities. The increasing interest towards environment, management of natural resources and quality of citizens' life that several times conflicted against economic growth has led international research to focus on a new way to develop many industrial markets. For this reason the Sustainable Development is a fundamental objective of the European Union. It has been pursued since decades by two complementary strategies: the Lisbon Strategy, launched in 2000 with the aim to reach an economic and social renewal and the European Sustainable Development Strategy (EU SDS) which added the environmental dimension to the Lisbon Treaty. The latter, reviewed in 2009, takes the lead in the fight against climate change and the promotion of a low-carbon economy, priority issues for strategic EU objectives. Although some progresses have been already reached in this direction, unsustainable trends persist in many areas therefore significant efforts need to be intensified. In that line, the Europe 2020 Strategy has been presented in 2010 with objectives of smart, sustainable and inclusive growth.

The construction sector deserves attention with regard to the sustainable development concept, because it turns out to be one of the sectors with the major impacts on its three dimensions: environment, society and economy. Quality of construction works has a direct impact on the life of Europeans. In addition, the energy performance of buildings and resource efficiency in manufacturing, transport and use of products for the construction of buildings have an important role on energy, climate change and environment. On that basis, building and construction activities are recognized as substantial to respond to climate risk and other environmental and social changes (an integrated industrial policy). Finally, because of its economic importance, the performance of construction sector can significantly influence the development of overall European economy.
Thus, this sector plays a fundamental role in the delivery of the Europe 2020 strategy goals. Indeed two of the seven flagship initiatives launched in relation to that strategy: "Resource efficient Europe" and "Industrial Policy for the Globalisation Era" concern the construction sector thanks to their perspectives to a low carbon economy, renewable energy sources and resource efficiency. In such a way the competitiveness of this sector should become an important issue not only for growth and employment in general but also to ensure the sustainability of the sector.
In order to support the sector for this purpose, these strategies are complemented with several initiatives and action plans that have rapidly increased in recent years because of eco-efficiency and sustainability objectives. In general, emphasis is put on the need to support growth and employment in the construction sector, but they are turned out to be essential to precede the preparation of new legislation or modify the existing one.

In that line, an important legislative step has been obtained through the replacement of the Construction Products Directive (CPD) with the Construction Products Regulation (CPR) in 2011.
The most significant change consists on the addition of the 7th basic work requirement (7BRW), concerning the *Sustainable use of natural resources*. In such a way, an essential focus on the importance of considering natural resources during the design, construction and dismantlement stages of life cycle of buildings has been carried out. In details, this requirement tries to ensure reuse and recycle of building materials, durability of construction works and use of environmentally compatible raw and secondary materials.
Furthermore the *European Committee for Standardization - CEN* - is involved in the development of standards related to construction sector sustainability through the work of *CEN/TC 350 - Sustainability of construction works.* These standards should be applied so that an integrated performance assessment of buildings during the entire life-cycle could be obtained. In such a way a harmonized methodology could be created, favouring not only the environmental and economic assessment, but also the analysis of aspects related to the comfort and healthy of users.

Indeed, standardization is regarded as one of the essential mechanisms to implement the strategic objectives of several European policy documents, considering that harmonization allows Member States to apply same methods throughout the European Union concerning testing, quality assurance, assessment of products.
In details, standards EN 15643 (1-4), formulated by CEN/TC 350 between 2011 and 2012 highlight that environmental, economic, social and functional aspects turn out to be necessary to define requirements for constructions sustainability assessment, as shown below:

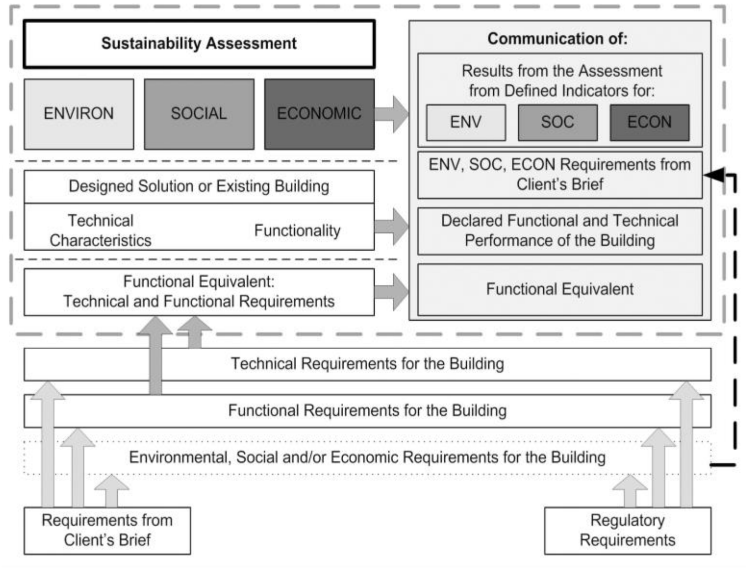


Fig.1: requirements of standards EN 15643 (1-4)

In this articulated framework it is worth noting that the sustainability applied to constructions covers a huge number of branches such as ecology, green practises, life-cycle concept, costs optimization, safety, durability and structural design. Several studies in this context have been already carried out to achieve the optimization of performances with respect to environmental, social and economic requirements. Nevertheless further development and research programmes are needed to implement integrated methodologies useful to consider as a whole sustainability requirements, according to multi-performance-based design approaches.

The scope of this document is indeed to highlight the actual need in construction sector to include environmental and economic aspects in structural design in order to reach the goal of a sustainable construction that can ensure safety, stability and, at the same time, take into account green friendly solutions, costs optimization and users' comfort during its whole life cycle.
The challenge is to define a framework for a possible Sustainable Structural Design (SSD) methodology which allows all performances to be assessed by a global parameter, considering that structural, environmental and economic results have completely different units of measure.

The document consists in three main parts and each part is completed with a focus to summarize the most important aspects of this report (Fig.2).
Part I is focused on the description of necessity to consider a new way to conceive constructions in the light of sustainability requirements and EU policies. An integrated approach is needed to define a new multi-performance, life-cycle oriented methodology.

Part II describes the framework of the proposed *Sustainable Structural Design (SSD)* methodology, focusing on its three main steps. Firstly the importance of applying the *Life Cycle Assessment (LCA)* methodology to assess the environmental performance of a building from cradle to grave is exposed, underlining how this method could give a fundamental contribute to CO_2 emissions reduction and to energy efficiency achievement. Secondly, a *simplified Performance-Based Assessment (sPBA)* methodology is presented to carry out the structural performance assessment. In particular, structural behaviour could be assessed in economic terms considering damage costs and relative monetary losses. Finally, a way to combine environmental and structural results is defined in order to obtain a global assessment parameter for sustainable constructions.

Part III has the aim to underline the actual importance to preserve natural resources use, focusing on the possibility to consider a *Current Scarcity Score (CSS)* to measure resource efficiency.
Two potential options to promote resource efficiency in construction sector are exposed. In details:

1. On one hand further research should be developed with the aim to define the economic dimension of resources, so this parameter could be included in the SSD methodology.
2. On the other hand, an important focus is also posed on the possibility to reach recycling targets set by Waste Directive in order to favour the resource efficiency achievement. In line with that, two possible ways to develop this issue are considered:
    - Design for Deconstruction (DfD)
    - Economic instruments such as landfill taxes or refunded compliance bonds.

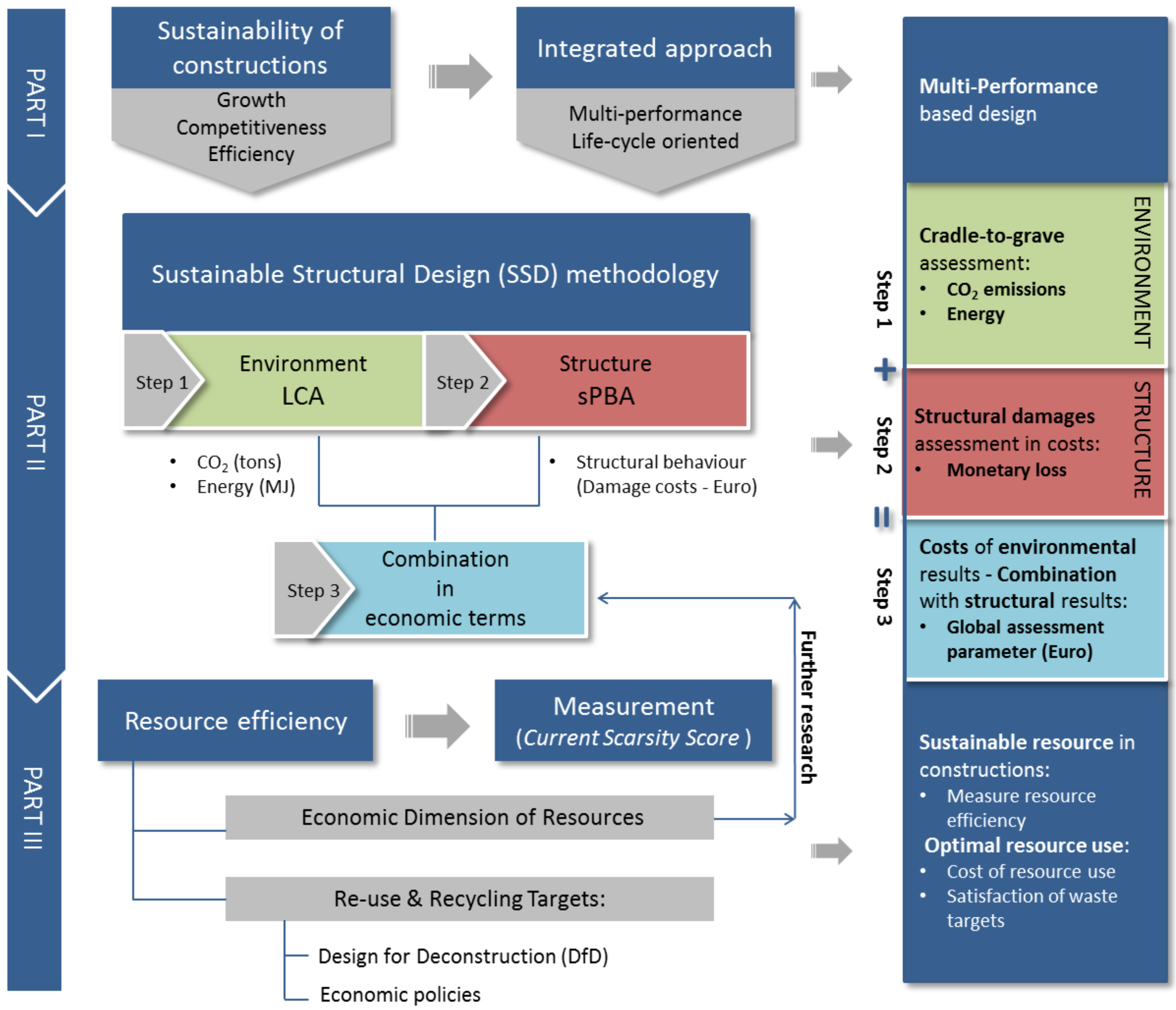


Fig.2: Document framework flowchart

PART I: MOTIVATION AND OBJECTIVE

1_Sustainability in general

The concept of *Sustainable Development* was defined in 1987, by the World Commission on Environment and Development, as the *“development that meets the needs of present without compromising the ability of future generations to meet their own needs”*.

Sustainability has gained attention since ‘60s -‘70s, when it became evident that a development exclusively oriented towards the economic growth, would have produced the natural and social systems’ collapse in short time.
One of the first action to control this problem dates back to 1961, when the World Wildlife Found (WWF), the biggest world organization for the protection of natural environment, was founded. Important WWF studies [1] underline that since the late 1980s a considerable “ecological overshoot” has been shown. Indeed the ecological footprint, an indicator tracking the pressure on the biosphere caused by our consumption in global hectares, has exceeded the planet’s regenerative capacity as of 2003 by about 25%. In 2008, the most recent year for which data are available, a consistent trend of over consumption has been registered with a percentage of exceedance by more than 50% [2] (Fig.3).

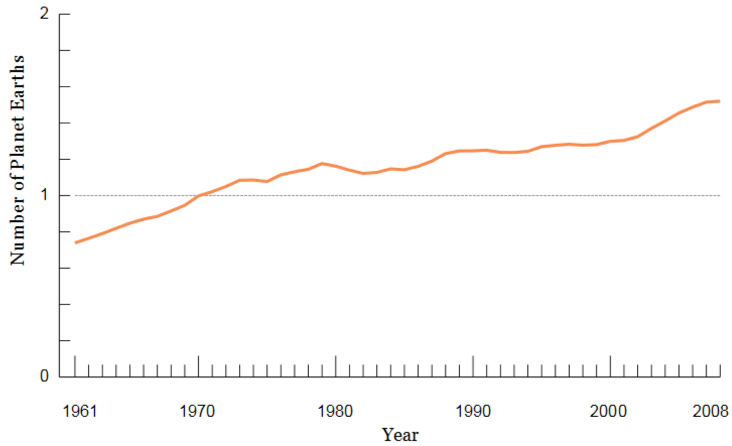


Fig.3: Humanity’s ecological footprint 1961-2008
(WWF Living Planet Report 2012)

This situation has caused an irreversible decrease in bio-capacity and an accumulation of waste. In addition this trend could continue in the next decades because of increasing population and the consequent demand of energy, materials and resources.

From this point of view there is no doubt that one of the most important European challenge to reach is a more rapid transition towards a sustainable society. Indeed it could ensure the quality of our ecosystems and, at the same time, could increase and guarantee the social and economic well-being of all world’s inhabitants. In spite of that, the awareness of the need to consider the sustainable development has been obtained only in the last decade with the evolution of its meaning. Indeed the sustainability, initially referred only to the planet protection, has also extended its interests towards the social satisfaction and the economic growth.

In line with that, nowadays the sustainable development is considered as the interaction of three main fields:

1. **Environmental dimension** indicates the capacity to satisfy and conserve the quality and the reproducibility of natural resources;

2. **Economic dimension** has to generate profit and work for the sustenance of populations;

3. **Social dimension** represents the capacity to guarantee human well-being conditions, equally distributed.

1.1_Sustainability and the construction sector

The European construction sector has a huge responsibility in terms of sustainable development, considering that it provides 20 million jobs and generates almost the 10% of GPD on European economy [3]. At the same time it causes the major impacts on the natural environment being the largest energy consumer in EU (about 40%) and the main contributor to GHG emissions (36% of the EU total CO_2 emissions) [4]. Moreover the waste arising from activities such as construction and demolition of buildings or civil infrastructures consists of a third (970 million tonnes) [5] of the total waste, produced in EU.

This vision has highlighted that *"there is an urgent need to a radical transformation in construction sector"* [6], therefore the actual European challenge is to reduce negative impacts of construction sector. The promotion of the sustainable construction market, as underlined by the Lead Market Initiative (LMI) in 2007, could be the right way to allow Member States to reach this essential objective.

One of the first definition of sustainable construction considers this sector as *"the creation and the management of construed environment, based on the resources efficiency and on the principles of ecological design"* [7]. This description leads to focus on the importance of the environmental dimension in the sustainable construction sector. It follows two directions, indeed buildings turn out to be directly linked to the natural environment as well as to users. In details, on the one hand environmental impacts, above all in terms of CO_2 emissions are generated during all the stages of the building process, from activities (sub-processes) related to construction (production, assembly), to their use (use-phase and maintenance) and to their dismantlement (end of life) - *from cradle to grave*. On the other hand the use-phase produces considerable impacts in terms of energy consumption necessary to ensure indoor comfort for users, allowing them to live in a suitable space for their activities.
In such a way not only the planet preservation but also the social well-being is involved into the environmental dimension of sustainability.

All that considered, the interest on environmental issues related to construction sector has led Europe to adopt initiatives and action plans especially focused on the achievement of energy efficiency and resource efficiency. In particular in the last years Member States are engaged in satisfying their ambitious 2020 targets: a 20% reduction of CO_2 emissions from 1990 levels, a 20% share of energy from renewable energy sources in the gross energy demand and a 20% reduction in the use of primary energy by improving energy efficiency [4]. In addition the construction sector is on its critical path to decarbonise the European economy by 2050, reducing its CO_2 emissions by at least 80% and its energy consumption by as much as 50% [8].

In order to favour the achievement of these targets, in the last years European attention to build in a sustainable way, considering life-cycle approaches has grown a lot.
The increasing interest on sustainability has led international research to develop several life cycle assessment methodologies such as the *Life Cycle Assessment (LCA)*, the *Life Cycle Costing (LCC)*. The LCA and LCC methodologies, currently received by the International Standard Organization (ISO), are

respectively focused on the assessment of the environmental and economic performance of a construction during its whole life cycle (Fig. 4).

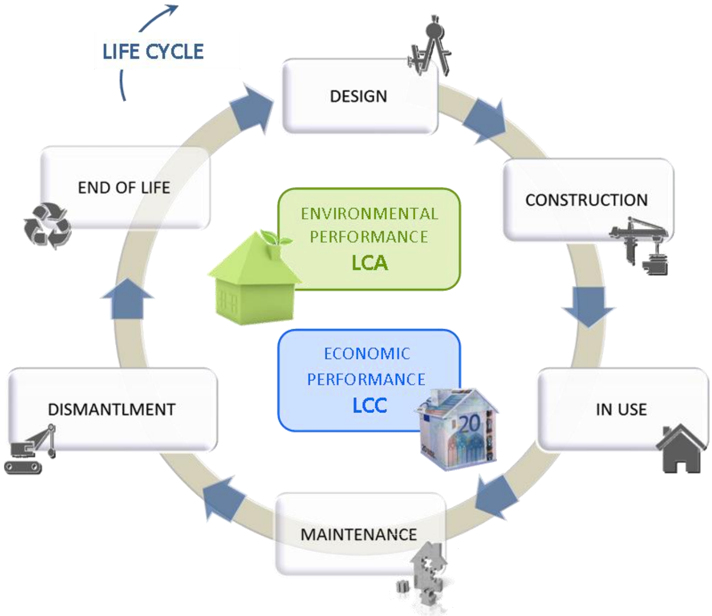


Fig.4: A sketch of life-cycle methodologies applied to constructions

In details:

- *Life Cycle Assessment (LCA)* is an approach which allows environmental burdens or impacts to be assessed from extraction of raw materials to the end of life of a given product or process by identifying energy and materials used and wastes released to the environment throughout the life-cycle.
- *Life Cycle Costing (LCC)* is a calculation methodology through which it is possible to estimate, in monetary terms, costs of a product during its entire life cycle. In such a way, the real value of investment is shown, considering not only initial costs but also the maintenance, inspection, repair and dismantlement ones.

In particular, testing LCA methodology in construction sector turns out to be essential in the light of huge impacts it causes on the natural environment, consuming a significant proportion of limited resources of the planet such as energy, raw materials, water and land.
The knowledge and the assessment of environmental impacts during the entire life-cycle of a building, conducted through the LCA methodology, aim to reach important goals for sustainability in the construction sector. A better use of energy resources, the control of CO_2 emissions in the air, a more conscious use of natural resources and the reduction of waste load for natural environment should be obtained if an approach strictly related to LCA analysis is considered.

The realization of these objectives could also be accelerated, promoting various areas of research and development [9], such as:

- **use of new materials, products and technologies** with several advantages related to prefabrication, dry assembly or dismantling process, could favour the optimization of raw materials usage and the minimization of construction and demolition waste. In addition Europe has already focused its interest on the eco-innovation through many action plans [10, 11] related to the development of environmental technologies.

- **re-use and recycling** of materials and components, above all increasing the use of recycled waste as building materials could provide important solutions in terms of resource-efficiency. In particular, according to the Waste Framework Directive, the goal of re-using, recycling and/or recovering 70% of construction and demolition waste by 2020 represents a business opportunity for the construction value chain [3].

- **energy-efficiency** that represents the most environmentally benign way to address impacts positively, brings along several benefits also for urban sustainability. The importance of this topic has been also confirmed by the necessity to review the Energy Performance of Buildings Directive (EPBD) in 2010. In particular a policy to boost the use of nearly Zero Energy Buildings (nZEB) by 2020 for both new and existing buildings is presented [12].

The development of these areas should lead to obtain important results for the sustainable built environment, ensuring not only natural environment protection and reduction of pollution, but also economic saving and profits through the use of less resources and the production of less waste. In such a way eco-efficiency, considered as "*the efficiency with which the ecological resources are used to meet human needs*" (OECD, 1998) [13], could be also achieved in the construction sector. Thanks to eco-efficiency the environmental excellence could be linked to the economic one, favouring the competiveness of construction sector. Indeed one of the five key objectives of the *EU strategy for the sustainable competitiveness of the construction sector* is to improve resource efficiency, environmental performance and business opportunities of buildings.

In order to satisfy the actual changes necessary to develop the sustainable construction sector, a new way to design structures is needed. Also the construction sector should follow the recent studies about the Life Cycle Sustainability Assessment (LCSA) which allow environmental, economic and social performance to be valued in a holistic way.
From an engineering viewpoint this methodology has to be integrated with the basic requirements of ordinary structural design, so another dimension, the Project, has to be introduced in the interaction of the triple bottom-line (Planet, People, Profit). A sustainable construction shall be considered as a "product" which satisfies not only the requirements of ordinary structural design, but also several requirements related to the three dimensions of sustainability. The challenge is to assess and to balance in a holistic way these requirements to achieve the environmental, economic and structural quality of a building throughout its whole life cycle.

1.2_The main challenge of the construction sector: towards a Sustainable Structural Design (SSD) methodology

According to the previous considerations, a methodology based on the *life cycle thinking* concept, should be a right approach to balance in a holistic way the requirements of a building.

Design for the life cycle becomes the possible answer to conceive sustainable structures. It means to design taking into account not only the structural performance of a building, but also the environmental and the economic ones during all the phases of the life-cycle.
The structural, environmental and economic performances have to be considered in a holistic way, satisfying the sustainable approach and accelerating the transformation of the European construction sector into a competitive and efficient market.

The need to face rigorously this new topic includes the dynamic of many actors and besides the design stage it embraces a large number of aspects as management of buildings, choice of materials, interaction with urban and economic development and management [6].
A sustainable building should be designed for durability, maintenance and dismantling, thus it could satisfy structural, economic and environmental requirements in all the stage of its life cycle: design phase, use phase and end of life.

In particular each building, during its life cycle, will face with deterioration which could lead to a decrease of performance so that it could be not able to satisfy the basic serviceability and safety requirements before the design life has expired. In order to prevent a premature failure of structures, it is essential to evaluate the period of time during which a structure or any component is able to achieve the performance requirements defined at the design stage with an adequate degree of reliability [14]. For this reason performance design scenarios should be foreseen.

A consequent inspection and maintenance plan should be already considered in the design phase and applied in the use stage. Thanks to preventive maintenance operations the structural performance is ensured and an optimization of costs is guaranteed, considering that not only the initial costs but also the maintenance and repair costs will be evaluated before building construction.

Buildings should be deconstructed at the end of their life, encouraging design for deconstruction. This discipline could be a right way to improve green practices, obtaining important environmental benefits such as:

- reduction of primary resource use and waste to landfill,
- less site impacts caused by demolition,
- reuse and recycle of materials and structures.

The disassembly technique is a new discipline, so it should be useful to point out that few designers yet have the right awareness and capacity to plan for it and to explain how buildings are demolished, or how materials can be reused and respectively recycled in their end-of-life [15]. Further developments in this direction are needed. Architects and engineers need already in design stage to specify how they can stimulate higher reuse and recycling rates of materials at end of life. Moreover they should plan new buildings considering design for deconstruction principles.
In details, important points should be promoted such as:

- Use prefabricated sub-assemblies and industrialized systems
- Minimize types of components for an easy sorting
- Modular structures design
- Appropriate design of connections

Connection elements should facilitate dismantling and mutual independency between the elements should be considered, so the last point of the above mentioned principles becomes a primary way to ensure easy deconstruction and increase the recycling/reuse rate. For this reason innovative connections should be launched for the sustainable market.

All that considered, the design phase turns out to be essential to make decisions that will affect on the entire life-cycle and it also becomes a tool to protect environment and control costs, conducting to a cost - benefit analysis.

The goal of this study is to define a framework focusing on the actual importance for the building sector to use a *Sustainable Structural Design (SSD)* methodology aimed to assess structural, environmental and economic performances of different constructive solutions.
This approach should consider structural performance of a building and at the same time its environmental effects assessed by LCA methodology, considering the entire life-cycle and focusing on the possibility to obtain a global parameter of assessment that can provide an appropriate element of comparison.

In particular, the suggested approach follows three main steps:

- **Step I:** environmental performance assessment through the *Life Cycle Assessment (LCA)* methodology;

- **Step II:** structural performance assessment through the *Simplified Performance Based Assessment (sPBA);*
- **Step III:** combination of environmental and structural results in economic terms.

Focus on Sustainability in construction sector

Sustainability is one of the main research theme of last years at European and international level. In particular the goal is to reach a sustainable development in the most of industry sectors. Focusing on construction sector, it turns out to be one of the most impacting one on three dimensions of *Sustainable Development* (Planet - Profit - People). For this reason the actual European challenge, pursed with several initiatives and action plans, is to develop the market of sustainable constructions. This objective leads to consider a lot of issues. Indeed a sustainable construction has to satisfy at the same time several requirements related to environment, society, economy and structural design. In addition all these requirements should be guarantee during all the life-cycle of structure.

In order to reach the competitiveness, efficiency and growth of construction sector, a new way to conceive structures is needed. It should be a multi-performance, life-cycle oriented approach, on the basis of the *life-cycle thinking* concept. In that light a Sustainable Structural Design methodology, following three main steps could be the solution to design constructions, considering all buildings requirements in a holistic way.

PART II: THE FRAMEWORK OF THE *SSD METHODOLOGY*

The core of this report is represented by the Sustainable Structural Design (SSD) methodology.
A reference flowchart (Fig.5) about the three steps composing the methodology framework is presented below.

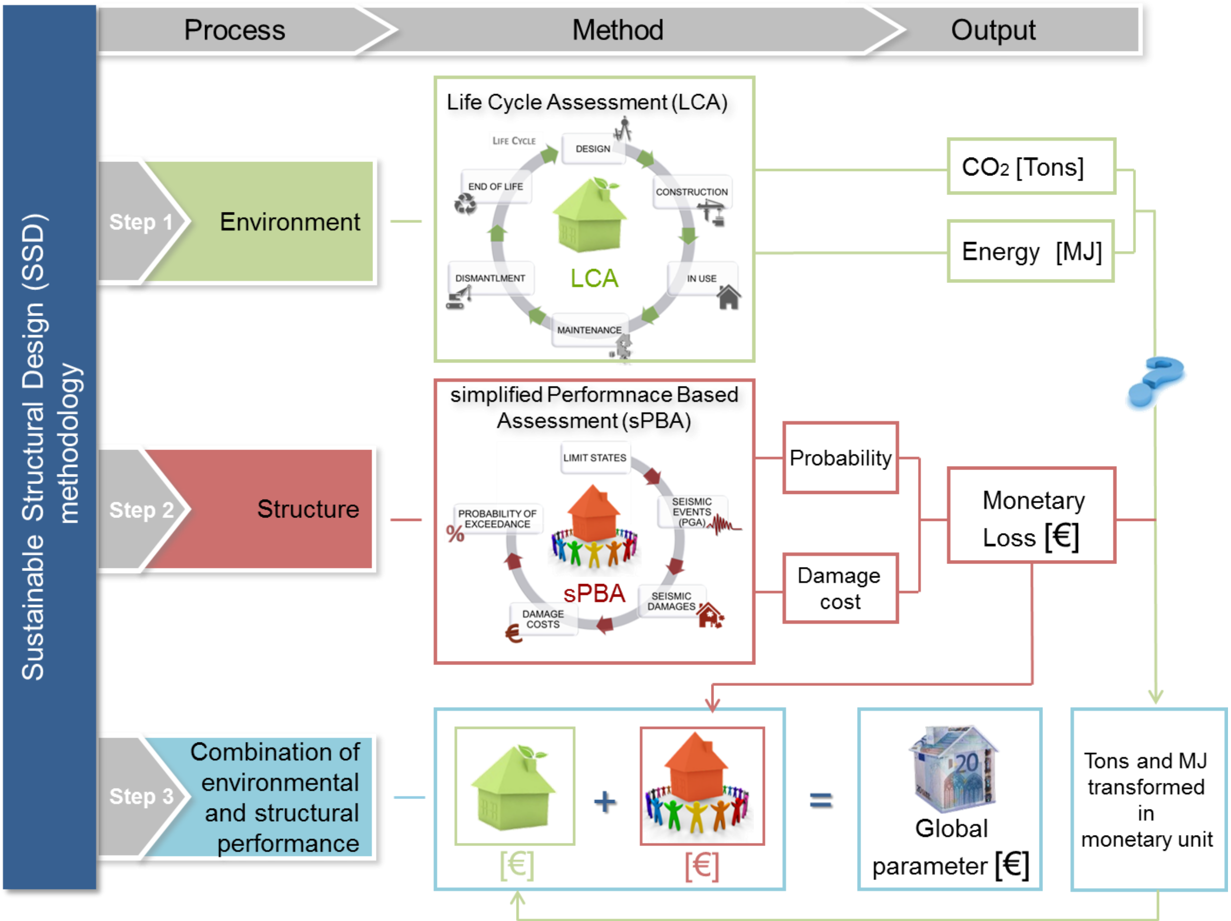


Fig.5: SSD methodology steps flowchart

These steps are illustrated in details in the following sections.

1_Step I: *Life Cycle Assessment* (LCA) methodology to assess the environmental performance of structures

The Life Cycle Assessment (LCA) methodology has been developed a relatively long time ago (60's - 70's). The interest for it gained more attention with Brundtland report (1987) arriving in 90's to realize a standardization process through the work of SETAC (*Society of Environmental Toxicology and Chemistry*) and ISO (*International Standard Organisation*), with the release of the standard ISO 14040 [16]. This document provides a definition of LCA as the *"compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life-cycle"*.

Nowadays the LCA methodology is an accepted approach because it provides an appropriate support to output the best solution in terms of environmental sustainability related to the whole life-cycle of a structure. Indeed it is possible to define different opportunities for the best solution, identifying the environmental effects of a determinate construction. Furthermore this methodology also gives the possibility to pose the attention on where and how to allocate benefits of recycling and reuse of materials, considering that the end-of-life phase is one of the main causes of waste problems. For this reason LCA could also become a tool to make decisions already in the design phase of a building, allowing architects and engineers to control not only the environmental performance, but also the social and economic one.

Fig. 4_LCA-based methodology (available on line: http://www.athenasmi.org)

The framework of the LCA-based approach is described in **ISO 14040:2006** [16] and **ISO 14044:2006** [17] and it follows four major standardized steps:

1. **The Goal and Scope definition:** the goal defines the purpose and the use of the LCA; the scope should ensure that the details of the study are sufficient to address the stated goal. It includes the product system and its functions, the system boundary, materials flow, impact categories selected and it defines the required data quality, the technology and the assessment parameters.

2. **The Life Cycle Inventory analysis (LCI):** at this stage all the data is collect on inputs (resources) and outputs (emissions, wastes).

3. **The Life Cycle Impact Assessment (LCIA):** this phase has the aim to evaluate the potential environmental impacts using inventory data which are translated in indictors to understand burdens on environment, on human health, on the availability of natural resources and on other possible categories.

4. **Interpretation:** this step is the last one of the procedure where results of LCI and LCIA are interpreted in accordance with the defined goal of the study. In particular these results should reach conclusions, explain limitations and provide recommendations.

The European Commission has developed methodological guidance for LCA practice in response to its 2003 Integrated Product Policy (IPP) Communication, launching the European Platform on Life Cycle Assessment in mid-2005 and e.g. publishing the International reference Life Cycle Data (ILCD) Handbook series (JRC, 2013). It is a joint project between DG Environment and the Commission's Directorate-General Joint Research Centre (JRC-IES). The aim is to favour harmonization of different methodologies used within the LCA communities and to give recommendations for the use of impact assessment methodologies. The platform also develops a Life Cycle Inventory database comprising life cycle emission and resource consumption data from business associations and other sources for key materials, energy carriers and waste management.

In addition the IPP also supports development of environmental product regulation EPDs as they "provide quantified environmental data based on life-cycle assessment methodology for a product or product group".

The European Platform of Life Cycle Assessment addresses good practice in LCA use and interpretation. The objective is to promote life cycle thinking in business and in policy making in the European Union by focusing on underlying data and methodological needs. The Platform is planned to provide quality assured, life cycle based information on core products and services as well as consensus methodologies.

LCAs have been used increasingly by industry to help reduce the overall environmental burdens across the whole life cycle of goods and services. LCA is also used to improve the competitiveness of the company's products and in communication with governmental bodies. LCA is used in decision making as a tool to improve product design, for example the choice of materials, the selection of technologies, specific design criteria and when considering recycling.

The European Platform on LCA emphasized also the 2008 Sustainable Consumption and Production/Sustainable Industrial Policy Action Plan (SCP/SIP). The core of this plan is to improve the energy and environmental performance of products and foster their uptake by consumers.
Several legislative documents have been revised or extended to support this plan:

- <u>Extension of *Eco-design Directive*</u>
  The directive has been extended in 2009 so that it covers all energy related products (ERPs), when the previous version focused on energy-using products (EUPs). In details, ERPs are products which do not necessarily use energy, but have an impact on energy consumption such as windows, insulation materials. EUPs, instead, are products which use, generate, transfer or measure energy such as boilers, house appliances.

- <u>Revision of EU *Eco-label Regulation*</u>
  This regulation presents rules for a voluntary EU Ecolabel award scheme for goods and services on the Community market. It helps to identify products and services that have a reduced environmental impact throughout their life cycle, from the extraction of raw material through to production, use and disposal.

- <u>Revision of the *Eco-management and Audit (EMAS) regulation*</u>
  The third revision to the EMAS Regulation (EMAS III), entered into force on 11 January 2010, has improved the scheme's applicability and credibility and strengthened its visibility and outreach. Organisations with a proactive approach to environmental challenges look for ways to continually improve their environmental performance. EMAS is the premium environmental management tool to achieve this. EMAS is a voluntary tool available for any kind of organisation aiming to:
    - Improve its environmental and financial performance;
    - Communicate its environmental achievements to stakeholders and society in general.

- <u>Revision of the *Energy Labelling Directive*</u>
  Initially established for household appliances, the scope of the Directive has been extended in 2010 to energy-related products, which are likely to have a direct or indirect impact on the consumption of energy and potentially of other resources during use. Energy labels help consumers choosing products which save energy and thus money. They also provide incentives for the industry to develop and invest in energy efficient product design. Products are ranked, according to their energy consumption, on an A to G scale with colours from dark green to red.

Information from LCA can also support public policy making in eco-design criteria setting, such as contributing to performance targets within the Environmental Technology Action Plan (ETAP) and for energy-using products (EUPs) and energy related products within the Eco-design Directive, in green public procurement (GPP) and in environmental product declarations (EPDs).
According to the abovementioned analysis, LCA is an important aspect in EU policies and its weight is increasing. In particular, with regard to the potential application areas, the construction sector is regarded as one where the life cycle approach is particularly useful.
Although the importance to conduct a *Life Cycle Assessment* for a construction has been stated in order to reduce its global potential environmental impacts, it is not simple to apply this method for this sector. In particular LCA requires advanced skills and comprehensive databases, so it is necessary a continue research refining the existing tools, even if nowadays many different LCA-based software are available.

One of the most flexible supporting tool for environmental assessment in construction sector is possibly *SimaPro* [18]. This software for the life-cycle analysis can measure the environmental impact of products and services during all life cycle stages. Moreover it allows users to see the hotspots in all aspects of the supply chain, from extraction of raw materials to manufacturing, distribution, use, and disposal.
SimaPro includes several inventory databases. In particular it is fully integrated with the *Ecoinvent* database, the world leader in LCA databases, so that a global environmental assessment can be easily carried out, above all with regard to CO_2 emissions and energy consumptions. This evaluation is possible thanks to various impact assessment methods, such as:

- **IPCC 2007 GWP**, developed by the *International Panel on Climate Change (IPCC)* , lists climate change factors of IPCC with a timeframe of 20, 100 and 500 years. This method is characterized by a system of equivalence factors to weight the influence of the various greenhouse gases, using the amount of CO_2 as reference. In such a way it is possible to assess the direct Global Warming Potential (GWP) of air emissions though the calculation of CO_2 equivalent emissions, expressed in tons.

- **Cumulative Energy Demand (CED)** quantifies energy taken from the natural environment and stored in the production of a product, expressed in MJ (Boustead & Hancock, 1979). This method allows energy consumption of a productive process to be evaluated through the calculation of direct energy (it means energy used in productive process) and indirect one (energy stored in a product and ready to be consumed). This assessment is carried out considering five impact categories:
  - non-renewable energy, fossil;
  - non-renewable energy, nuclear;
  - renewable energy, biomasses;
  - renewable energy, water;
  - renewable energy, solar, wind, geothermal.

1.1_ Importance of LCA for an energy-efficient building stock

Buildings *demand energy in their whole life cycle both directly and indirectly. Directly for their construction, operation and eventually demolition; indirectly through the production of materials they are made of* (Sartori and Hestnes, 2007) [19]. In particular, the operating energy is the energy consumed during the use phase of buildings as for heating, cooling, lighting, expressed both in terms of end use and primary energy; the embodied energy, instead, is the sum of all energy needed to manufacture a good, generally expressed in terms of primary energy.

The construction sector has the highest potential for energy efficiency, considering that the residential sector already in 2005 accounted for 26.6% of final energy consumption (EEA, 2008) [20]. In the use phase, the energy consumption of households is an important source of environmental impacts. The majority of environmental pressures are caused by energy use during the operation stage of houses' life cycle, while around one fifth are caused during their construction (EEA and ETC/SCP, 2010; JRC/IPTS, 2008).
In details, space heating accounts for 67 % of household energy consumption in the EU-27, followed by water heating and appliances/lighting (Odyssee database, 2010). There are large differences in final energy consumption per person for space and water heating, cooking and electricity in households across Europe. These differences are influenced by many factors including different consumption patterns, climate, energy efficiency of dwellings, type of heating systems and energy prices.
Final energy consumption per person in the *European Environment Agency (EEA)* member countries (EU-27, EFTA and Turkey) increased by 3% between 1990 and 2007. This increase was reversed between 2005 and 2007 when it decreased by 9% in the EU-27 member states. In particular household electricity consumption per person increased more rapidly than other energy consumptions: on average by more than 30% between 1990 and 2007. The main reasons behind the increase in electricity consumption are the steady increases in the numbers of appliances - including TV sets and dishwashers owned by households, consumer electronics and information and communication equipment - and a rising demand for air conditioning and cooling technologies, especially in the Mediterranean countries (EEA, 2010)[21].
In addition the overall energy consumption is such an important factor of greenhouse gas emissions, taking into account that energy-related GHG emissions account for 80% of the total emissions, with the largest emitting sector being electricity and heat production [20].

For this reason in the last years a lot of attention has been focused on energy saving and CO_2 emissions reduction of construction sector, especially in use phase of buildings. The European Commission continues to recognize the necessity of applying LCA methodology, promoting the use and further developments in this direction. Indeed LCA method applied to buildings turns out to be really essential to assess energy performances, but it allow also to evaluate acoustics, accessibility, comfort indoor air quality in line with Vision 2030. In such a way the mutation of the European construction sector into an innovative, mature and energy efficient industry is facilitated.

In the last decades the operating energy in buildings was accepted to be the major part while the embodied energy represented only a small friction of consumption (10-15%). For this reason an important effort has been made towards the reduction of the operating energy, increasing the promotion of low energy buildings. In 2006 the *Energy-Efficiency Action Plan (EEAP)* has already highlighted that the most consistent energy saving could be obtained by residential (households) and commercial buildings (tertiary sector) with a potential reduction between 27% and 30% [22].

Whilst in recent years, although the efficiency of energy production has increased, the potential for further improvement is still significant, for example, through a greater use of combined heat and power and other energy-efficient technologies that are already available or close to commercialisation.
In spite of that, many goals should be still achieved, indeed in 2011 the Commission's estimations, which take into account the national energy efficiency targets for 2020 in the context of the Europe 2020 strategy, suggested that the EU will achieved only half of the 20% target in 2020. For this reason the *Energy Efficiency Directive* has been adopted in 2012 and the actual EU objectives of climate and energy policies are based on a scenario with "zero CO_2 and energy positive buildings" by 2050.

Large measures have been taken to reach this goal. According to BPIE, in 2011 the average energy intensity of residential buildings in the EU was around 200 kWh per m^2 (all end uses, final energy), so in order to dramatically reduce the average energy consumption from the buildings sector in OECD countries to 50 kWh/m^2, a large-scale upgrade of the existing building stock would be needed and 60% of buildings would require retrofits by 2050 [23].

In details, for new building, materials and energy equipment integration based on high heat resistant, integrated ventilation systems, allow constructions to reach very low energy demand. For refurbishment, instead, the diversity of architectures requires an innovation process where design, technology choice and construction are more difficult than for new buildings.

In particular the envelope becomes the most critical part in relation to energy efficient buildings, considering that it impacts 57% of the building thermal loads [4]. For this reason energy efficient building should use envelopes that are durable, adaptable and cost-efficient. In spite of that, materials and components are critical to envelope not only for insulating properties but also for anchoring the resulting envelope on existing or new structural elements. Further research is needed to better understand material and components behaviour in the whole life-cycle, therefore LCA could be an important tool to improve this sector.

In addition technological innovation such as modern glazing solution focused on the use of double and triple glazed units with inert gas between glazing panels and invisible low-emissivity coatings have significantly improved the insulation properties of windows and facades. Moreover glass helps lower artificial lighting needs, consequently reducing lighting energy consumption [24].

In spite of that, investments in the future markets for energy efficient technologies and materials have to increase to satisfy the additional demand created by new nearly zero energy buildings (nZEBs), after the recast of the Directive on the energy performance of buildings (EPBD). It stipulates that by 2020 all new buildings constructed within the European Union after 2020 should reach nearly zero energy levels. However nZEBs should not be regarded as an energy-efficiency endpoint, but only as an interim step towards even better buildings, e.g. so called “plus energy” or “energy positive” buildings.
In order to satisfy the calculated demand, the current market for insulation materials should grow by about two to three times. The market for heat pumps, pellet boilers and solar thermal systems should grow at least in the same range [25].

In addition, the free solar gains have a crucial influence on the heating and cooling energy demand of a building. The nZEB design phase turns out to be crucial to satisfy also future demand of a building, considering that solar gains may easily vary by around 25% at the same location, being strongly influenced by the orientation and by potential shading of the building facades. For this reason, before starting the construction of a new building, careful consideration of the positioning and orientation needs to be done in order to maximise or minimize respectively the solar gain [25].

It is clear that advanced and high performance materials are needed to reduce the building energy demand in the use phase, but at the same time further actions are necessary to lower the content of embodied energy. Indeed recent studies have demonstrated that for high energy efficient buildings, the energy consumed to live (use-phase) tend to become equal to one taken up to build or dismiss. In light of that, the structure plays a key role considering that 85-95% of all embodied CO_2 of construction materials used in the building structural parts build up prior to leaving the factory gates, instead the remaining 5-15% relates to the construction, maintenance and demolition of the building [4], so it is necessary to consider life cycle approaches when new materials, components

and processes are developed through an LCA analysis. A life-cycle assessment (LCA) approach becomes really essential, considering that energy consumption during the construction and disposal phases of a building becomes more and more important when the operating energy consumption decreases [25].
All this considered, with regard to structure and envelope of building, further developments should be focused on the sustainability of the materials fabrication process, the durability of materials and components, the recyclability and reusability, the real performances of the integrated envelope.

Beyond existing technologies, further breakthrough solutions should be expected from heating/cooling systems combined with renewable energy sources, storage. This field indeed should be improved in accordance to the Renewable Energy Directive (2012).
The renewable energy market and industries have developed significantly over the last decade and, for most of the technologies, it will be possible to reach competitive prices in the near future and consequently to cover a much larger share of the energy demand.
On the one hand, renewable energy integration aiming towards supplying 100% of the energy demand will provide the lowest amount of greenhouse gas emissions, resulting in a theoretical 100% carbon free energy supply. From photovoltaic panels to ground source heat pumps, technology can help consumers to save emissions while reducing their energy bills. In spite of that several constraints are still important such as:

- in the context of a fast growing world population and related energy demand, the potential to supply an almost 100% renewable system by 2050 will only be possible by undertaking simultaneous and very ambitious energy savings measures
- import of renewable energy might also become necessary (e.g. solar electricity from northern Africa), leading to political and financial dependencies.

On the other hand, moving towards very low energy buildings by implementing energy efficiency measures may consistently reduce the energy demands of the building sector and may indirectly avoid building new energy capacities or using more energy resources, renewable or not. In this case some constraints could be underlined too:

- efficiency has its limits and it is not possible to drive energy demand down to zero
- need for the energy supply will still remain because active supply also needs to balance demand peaks over a year (e.g. more demand during winter), so carbon emissions will still be generated through the use of fossil fuels.

In conclusion today we do not know exactly how much renewable energy will be available for supplying buildings by 2050. On that basis, the precautionary principle requires taking measures for the worst case scenario if only a limited renewable capacity were available for building.
The logical answer could be to minimize the demand for renewables by implementing energy efficiency measures, but an important European effort should be made stimulating a further gradual increase of the share of renewable energy. Indeed the optimal solution for the future building stock should be the interaction of three strategies: energy saving (structure and envelope), energy efficiency and energy production by renewables.

1.2_The interaction between LCA and structural design

On the basis of previous considerations, LCA methodology has become really important to develop and improve the competitiveness of sustainable construction sector. In particular, thanks to the LCA analysis the planet preservation is ensured, reducing environmental pressures and improving efficiency of buildings, but LCA could also become a tool to guarantee the well-being of users and the reduction of costs.

Although the necessity of applying LCA methodology in construction sector is recognized at European level, results obtained through this analysis should be included in the structural design, so that a holistic balance of all the requirements necessary to define a sustainable construction could be really achieved.

The structural performance of a building can be quantified in terms of costs. The environmental performance, instead, is expressed in tons of CO_2 for emissions in the air and in MJ for energy consumptions. In such a way it is impossible to compare the different performances. A new approach that allows environmental effects to be considered in structural choices throughout the entire life cycle of a building has to be defined. In short a sustainable structural design methodology is needed.
The challenge is to decide how to combine environmental aspects, assessed by LCA analysis, with structural design in order to obtain a global assessment parameter and to identify the best solution among different opportunities.

Focus on Environmental performance assessment

The first step of the proposed *Sustainable Structural Design (SSD)* methodology is the environmental performance assessment through the use of LCA methodology. Indeed it is considered the best framework to evaluate the environmental cradle to grave impacts produced by goods and services. With regard to the construction sector, the use of LCA supporting tools such as 'SimaPro' allows the most common environmental impacts produced by buildings, such as CO_2 emissions and energy consumption to be quantified. In such a way LCA becomes a tool to help stakeholders in decision making process, controlling also economic and social performances. In addition LCA could be a good support to improve energy efficiency of new and existing buildings, considering the EU objectives for 2020 in relation to energy saving and CO_2 emissions reduction.

The open question is how to combine environmental performance with the structural one, considering that the abovementioned performances have different measure units.
Step II and III of the SSD methodology have the aim to solve this problem.

2_Step II: Standard *Performance-Based Assessment* (PBA) methodology

In order to define a global approach for sustainable structural design, it is worth referring to a methodology for Performance Based Assessment (PBA), such as the methodology for the Performance Based Earthquake Engineering (PBEE), developed by the Pacific Earthquake Engineering Research (PEER) center. The "*PBEE implies design, evaluation, construction and maintenance of engineered facilities whose performance under common and extreme loads respond to the different needs and objectives of owners-users and society."* (Krawinkler and Miranda, 2004)

PEER has developed a detailed methodology for the seismic Performance-Based Assessment of buildings, bridges and other engineered facilities that allows building performance to be predicted in a probabilistic format. It consists into a quantitative evaluation of the performance of a given building aimed at facilitating an informed decision making for risk management. (Zareian and Krawinkler, 2009)

PBA methodology involves four main consecutive analysis stages [26]:

1. **Hazard Analysis**: the first step of this procedure carries out the calculation of the frequency with which the intensity of a ground motion, described by the *Intensity Measure (IM)*, is exceeded. Traditionally, the spectral acceleration has been used as *IM* for its simplicity and easiness of computational work and the analysis is performed probabilistically through the Probabilistic Seismic Hazard Analysis (PSHA). The output of a PSHA is a seismic hazard curve that shows the relation between an *IM* and its annual frequency of exceedance ($\lambda(IM)$).

2. **Structural Analysis:** known the information provided by PSHA, in this stage the *Engineering Demand Parameters (EPDs)* are obtained. The *EPDs* are structural response parameters at different hazard levels such as inter-storey drift ratio, maximum roof drift or deformations. The output of the Structural Analysis is a probabilistic assessment of building response at different hazard levels, expressed as P ($epd \geq EPD \mid im = IM$). It means the probability that the variable *epd* exceeds a certain value of *EPD*, considered that the variable *im* is equal to a value of *IM*.

3. **Damage Analysis**: in this stage *EPDs* are related to *Damage Measures (DM)* that quantify the level of damage to building components (structural, non-structural, contents) induced by an earthquake. In such a way *DMs* allow different repairs or replacement actions of building components to be defined. The goal of this stage is firstly to identify damage states in building components and secondly to obtain relationships between EPDs and DMs in the form of P ($dm = DM \mid epd = EPD$). It represents the probability of being in damage state *DM*, given that the variable *epd* is equal to the value of *EPD*.

4. **Loss Analysis:** in this step *Decision Variables (DVs)* that describe the performance of building are taken into account. In particular losses due to damages to buildings components are estimated, considering three categories of losses: *monetary loss*, *downtime loss* or *life loss*. In this way it is possible to define DVs in terms of quantities such as total repair costs, total downtime and total number of casualties.

Using these four steps the process of executing the PBA methodology can be completed and its outcome is a probabilistic representation of DVs. Two different probabilistic representations of DV, could be used: a *scenario-based realization* or a *Mean Annual Frequency (MAF)-based realization*. In the first one the probability of DV exceeding a certain value, given the value of IM, is estimated in accordance with the total probability theorem, as follow:

$$G(DV \mid IM) = \int_{\substack{all \\ EPDs}} \int_{\substack{all \\ DMs}} G(DV \mid DM)\, dG(DM \mid EPD)\, dG(EPD \mid IM) \qquad (1)$$

In the MAF-based realization of DV, instead, the annual frequency of exceedance λ(DV) is obtained by integrating G(DV | IM), calculated with (1), as shown in the equation (2):

$$\lambda(DV) = \int_{\substack{all \\ IMs}} G(DV \mid IM) d\lambda(IM) \tag{2}$$

2.1_*Simplified Performance-Based Assessment* (sPBA) methodology

The concept of Performance-Based Earthquake Engineering has received increasing attention over the past few decades in an ongoing effort to better control the expected seismic behaviour of structures. As a direct result of collaborative efforts across the field of earthquake engineering, the capability of existing methods to incorporate monetary losses and seismic risk into the assessment has been realized with current applications pertaining to the assessment of large populations of buildings providing assistance to decision makers on a city-wide or regional scale. There is an increasing need, however, to provide engineers with practical tools for loss assessment of individual buildings in order to enhance the value of the engineer-owner interface upon which specific design and retrofit decisions can be made.

The PEER Performance-Based Earthquake Engineering framework marks an important step towards the realisation of such building-specific loss assessment tools. In spite of that, some consider that comprehensive probabilistic methodologies, such as that incorporated within the PEER framework, could be too complex for most practising engineers [27].
The rigorous approach for PBA methodology is a process which needs a very large amount of data and computational work, turning out to be not a so easy and practical methodology. It was demonstrated [26, 28] that such a comprehensive approach to PBA may not be necessary for most ordinary structures. For this reason a *simplified PBA (sPBA)* process can be considered. In particular given the building, its location and characteristics, the mean information in the hazard domain, structural domain and loss domain can be generated. The *simplified PBA* allows the expected value of DV to be estimated, in particular the monetary loss at a discrete hazard level of the building in the form of E(Loss |IM).

Starting from these considerations a sPBA methodology, which may be useful for the sustainable structural design can be created. It consists into the evaluation of costs and the expected losses for each limit state considered, at which different peak ground accelerations and inter-storey drifts correspond. The aim of this analysis is to obtain the total expected loss *(L)* in each configuration through the *total probability theorem*, so the calculation of the *probability of exceedance* *(R_N)* is needed.
For instance, according to the Italian standard NTC 2008 [29] in which a state-of-the-art definition of seismic hazard is provided, this parameter can be calculated as:

$$R_N = 1 - \left(1 - \frac{1}{T_R}\right)^N \tag{3}$$

in which N is the expected lifespan of the structure expressed in years
T_R is the return period

In particular it is possible to evaluate the damage costs for each limit state to create a relation between economic assessment and structural behaviour of a building. Indeed once the damage costs (*C_i*) and the probability of exceedance (*R_N*) for each configuration have been estimated, the total expected loss (*L*) is calculated as shown:

$$L = \sum C_i \left(R_{Ni} - R_{Ni+1} \right) \quad (4)$$

This simplified method can be used to identify a possible sustainable structural design approach able to assess the structural performance of a building in economic terms. In order to consider also the environmental performance in costs, a global assessment parameter is needed.

In order to ensure safety and reliability of structures during all the life cycle of a building, the simplified loss assessment methodology is based on the definition of key limit states that best signify the relationship between expected loss and seismic intensity (demand) [27]. In such a way considering future scenarios it is possible to estimate the economic impact on the building management and not only the initial costs.
To evaluate expected costs, one has to consider the *Expected Annual Loss (EAL)* to repair seismic damaged buildings. In details, building vulnerability curve and site hazard curve have to be defined. The first parameter can be carried out associating the intensity of a ground motion (PGA) to the expected repair cost. In such a way it is possible to know if a refurbishment can be advantageous or not in economic terms, considering the expected loss in terms of percentage of reconstruction cost.
The second parameter, instead, can be expressed as the peak ground acceleration (PGA) associated to the probability of annual exceedance.
Through the combination of these two curves the expected annual losses could be defined in relation to different probability of annual exceedance.

It could be really important to consider this aspect because in some cases the refurbishment of a high damaged building could be more expensive than a reconstruction, so this aspect should be considered already in the design phase in order to really satisfy life cycle analysis.

Focus on Structural performance assessment

The structural performance of constructions could be assessed developing a simplified approach which has its basis on PEER methodology. In particular it allows structural behaviour to be assessed in economic terms considering monetary loss in relation to damages to which a structure could be subjected throughout its entire life-cycle.
In short the second step of the SSD methodology consists of defining the structural performance of a building in monetary terms.

Considering different scenarios, already in the design phase, turns out to be really useful in relation to the management of the building. Indeed it could be happened that a refurbishment of a damaged building could be more expensive than a reconstruction, so in that case assessing the monetary loss turns out to be essential in the light of life cycle analysis.

3_Step III: LCA and cost-benefit analysis: towards a global assessment parameter

LCA methodology allows environmental performance of a structure to be assessed, especially focusing on major impacts produced in construction sector in terms of CO_2 emissions and energy consumptions.
In order to evaluate the sustainability of a construction, a global assessment that allows stakeholders to consider at the same time structural, environmental and energy performance of structures should be carried out. The aim is to define a way to convert environmental analysis into economic terms. In particular, it is necessary to transform tons of CO_2 and MJ of energy in monetary unit, so that structural and environmental performances can be considered as the sum of structural and ecological costs, obtaining a global sustainable result.

In order to explain how reaching this goal, it could be better to consider separately costs related to CO_2 emissions and to energy consumption.

With regard to **carbon emissions**, the cost of tons of CO_2 is strictly connected to the first tentative to check the increase of global climate, promoted in 2005 with the Kyoto Protocol. This international agreement established states' obligation to reduce GHG emissions below 1990 level by the period of 2008-2012. For the purpose of reaching this goal three so-called "flexibility mechanisms": International *Emission Trading(IET), Joint Implementation (JI)* and *Clean Mechanism Development (CDM),* that allow the parties involved to reach their commitments at the lowest cost were considered. Indeed these instruments are used by governments in industrialized countries to achieve parts of their emission reduction commitments through projects abroad rather than through action or policy changes at home. These projects generate carbon credits in form of Emission Reduction Unit (ERU) for JI projects and in form of Certified Emission Reduction (CER) for CDM ones.
Under the Kyoto Protocol, Europe was committed to reduce GHG emissions by 8% below its 1990 level. For this reason early in 2005 European Union Emission Trading System (EU-ETS), standardized by the Directive 2003/87/EC, has been adopted to anticipate Kyoto target. This system represents the first large "cap and trade" scheme in the world to combat the climate change, becoming the major pillar of EU climate policy. Its aim was to help EU Member States to respect their obligations of reducing CO_2 emissions in a profitable way, allowing industries to buy or sell emission's quotas, called European Emission Allowances (EUAs). One EUA represents the right to emit one ton of CO_2.
The national governments, under the European Commission supervision, define a cap of emissions for each industry, giving them an equivalent number of allowances. In such a way a single industry can sell more credits to the other companies, more it respects its cap.

The EU-ETS was coincident in its second phase with the Kyoto Protocol, integrating with the International Emissions Trading (IET) foreseen by the protocol. For this reason EUAs (European quotas) have been converted in AAUs (Kyoto quotas). Moreover EU ETS allows a regulated operator to use carbon credits in form of ERU or CER, as defined by the *EU Linking Directive* (Fig.5).

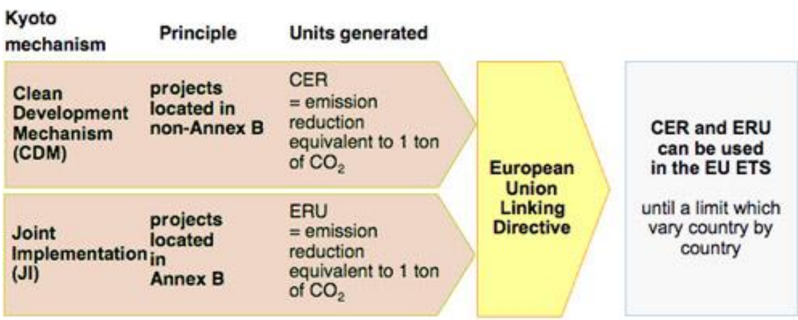


Fig. 5_Kyoto credits linked to the credits exchange market in Europe (EU-ETS) (Source: EU Linking Directive)

EU-ETS has been essential to define a price for carbon (CO_2), necessary to carry out this type of trade. In particular the price of quotas depends on market, considering the interaction between demand and offer.

The Exchange of SENDECO$_2$ [30] reports the data related to prices development of EUAs: it is possible to notice that in 2008 the record price at 26,86 euro per ton has been registered in June. During the following three years, from 2009 to 2011, the maximum registered prices varied between about 14 and 16 euro per ton. In 2012, instead, the cost of one ton of CO_2 fell down to 6.85 € at the beginning of the year, maintaining itself more and less unvaried during all the year, except in February when the price arrived at 8,39 euro per ton. The year 2013 has been opened with a price of 5.19 € (January), declining in May to median average of 3.51 euro, but in October the price has risen to median average of about 5 €/ton.
In particular (Fig.6) the graphic about carbon emission historical prices related to the end of September 2013 and the first half of October 2013 is shown below.

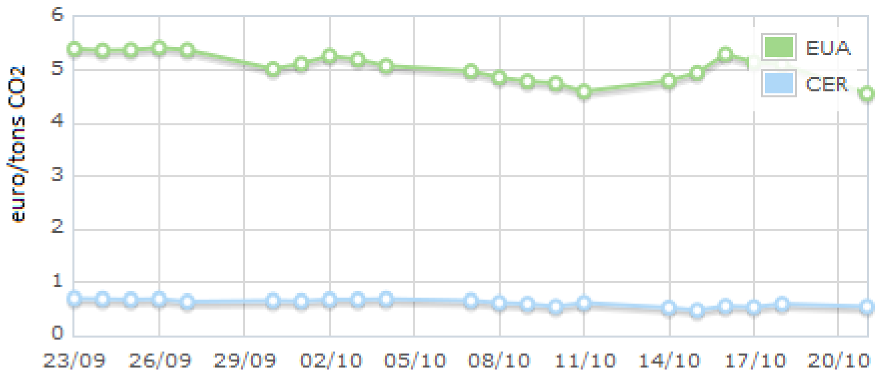


Figure 6_Historical prices of CO_2 emissions for October 2013
(Source: SENDECO$_2$)

In that line it has been shown [31] that the quantity of equivalent CO_2 emissions (Q_{CO2}), calculated with LCA analysis can be converted in Euro unit, considering the unita
ry cost of ton of CO2 (P_{CO2}), as follows:

$$R_{SSD(CO_2)} = P_{CO_2} \times Q_{CO_2} \tag{5}$$

in which R_{SSD} is the global result for the sustainable structural design (in Euro)
P_{CO2} is the price of one ton of CO_2 emission, expressed in euro/ton
Q_{CO2} is the quantity of equivalent CO_2 emissions, calculated with LCA analysis

In such a way one can combine environmental analysis in terms of carbon emissions with the structural performance analysis, expressed in cost thanks to the simplified-PBA methodology.

With regard to **energy consumptions**, it is necessary to refer to energy market developed in Europe. Member States consume one fifth of energy produced in the world even if their reserves are limited, so one of their main characteristic is the energy dependence from foreign countries. Member states are obligated to import over half of the needed energy, being subjected to prices related to international markets [32].

The solution could be to consume better and in a more efficient way, obtaining many advantages: decrease of CO_2 emissions and reduction of energy importations. The energy efficiency in construction sector should be enhanced not only to reduce environmental pressures, but also to limit costs, maximizing benefits for member states. For this reason Europe is committed in many energy efficiency initiatives, highlighting that the most important objectives of Member States related to energy efficiency are the reduction of 20% targets agreed for 2020 and the use of energy systems able to lead towards decarbonisation by 2050.

Focusing on the consumption of energy sources in different sectors, natural gas was mostly used for power generation and in households, accounting for 31.7% and 27.2%, respectively in 2010 (Fig. 7a). Turning to electricity consumption (Fig. 7b), industry continued to be the largest consumer, followed by household consumption that increased by 21 TWh in 2010 respect 2009 trends [33].

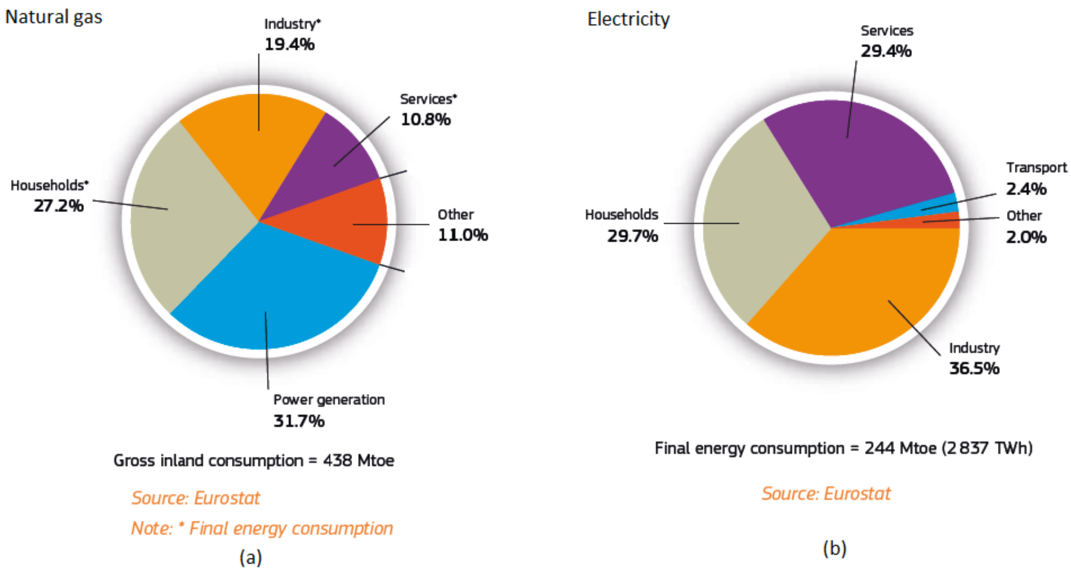


Figure 7_ (a) use of natural gas by sector in 2010 (as % of total Mtoe) – (b) use of electricity by sector in 2010 (as % of total Mtoe) [33]

In particular (Fig. 8) gas turns out to be the most common fuel used in buildings in all regions which stands at 41%, 39% and 26% in North & West, South and Central & East regions, respectively. Oil use, instead, is highest in North & West Europe where Germany and France are the biggest consumers. The highest use of coal in the residential sector is in Central & Eastern Europe where also district heating has the highest share of all regions. Renewable energy sources (solar heat, biomass, geothermal and wastes) have a share of 21%, 12% and 9% in total final consumption in Central & Eastern, South and North & West regions, respectively [34].

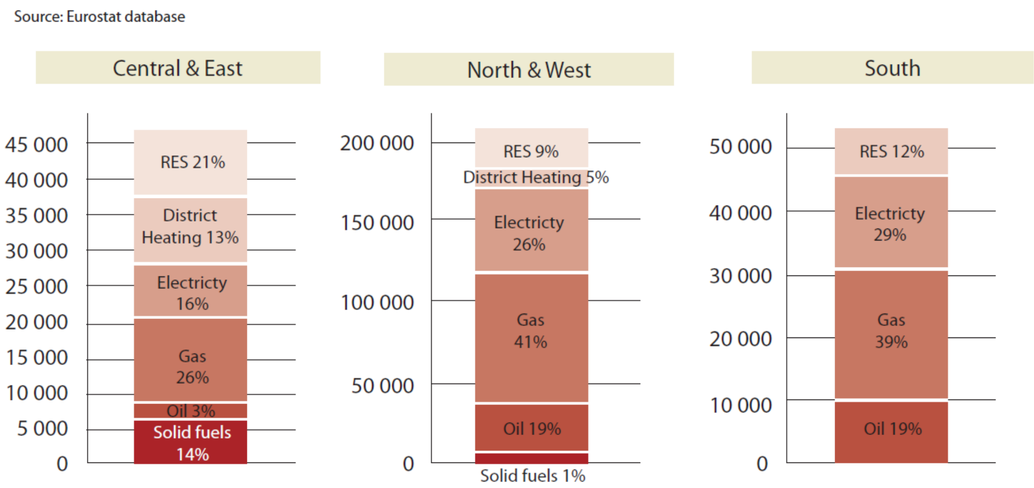


Figure 8_ Final energy mix in residential buildings (thousand toe) by region (BPIE, 2011)

In order to define energy prices for building sector, taking into account consumption and import, it could be useful to consider separately electricity and gas, the most used form of energy consumed in the use phase of a building. Indeed space heating accounts for 70% of household energy consumption in the EU-27, followed by water heating and appliances/lighting (Odyssee database, 2010).

- <u>Electricity</u>

An overview [35] (Fig.9) of electricity imports and exports in 27-EU Member States in the first ten months of 2011 and 2012 shows that some countries like France or Sweden are net power exporters, but others such as Italy, the Netherlands, Austria and Finland are net power importers.

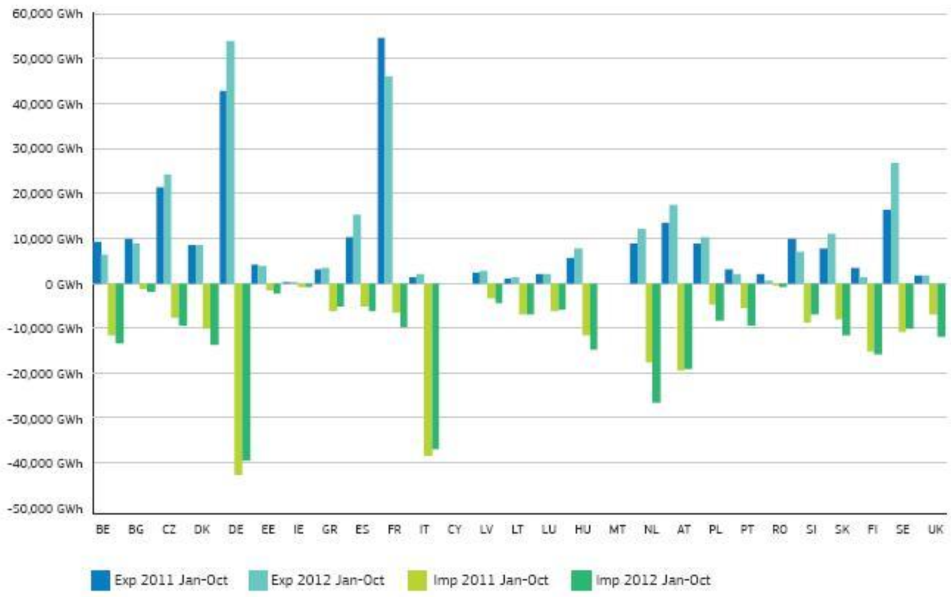


Figure 9_Electricity imports and exports in 27-EU Member States.
(Source: Quarterly report on EU electricity markets, 2012)

This factor falls on price of electricity in large measure. In the following graphic (Fig.10) is shown the evolution of the monthly average regional power prices in seven different region of Europe between 2010 and the first semester of 2013 [36].

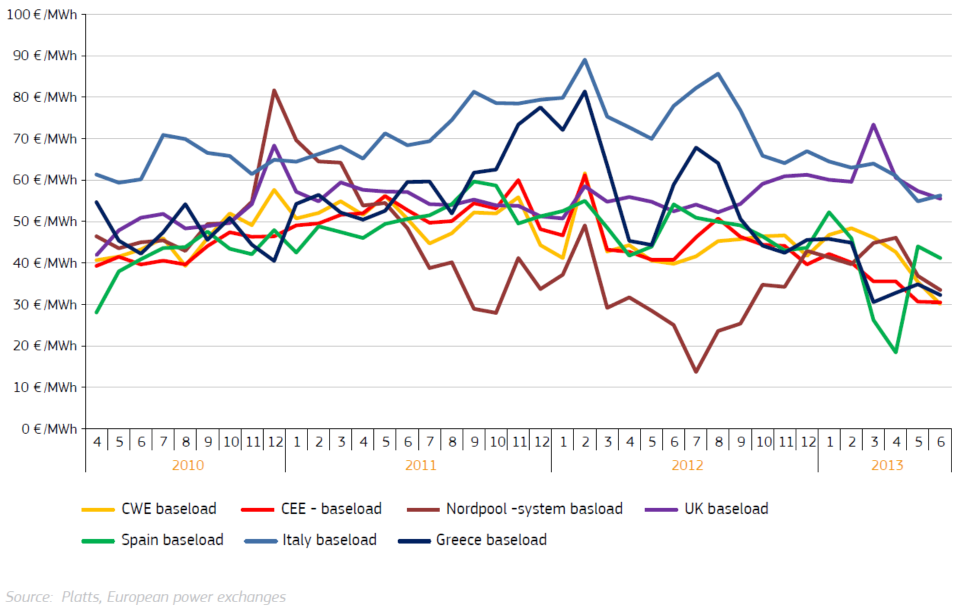
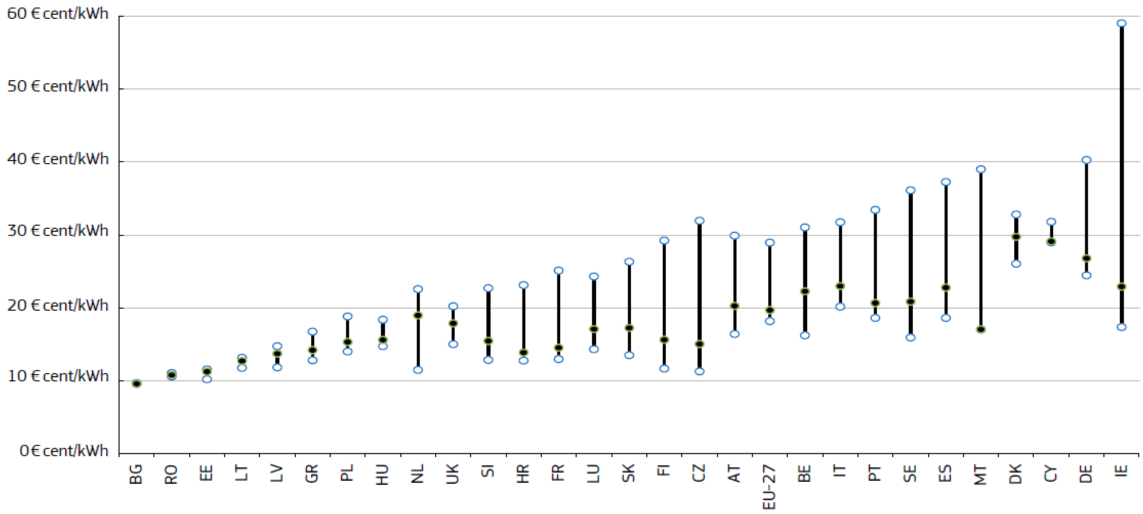


Figure 10_Electricity prices in different region of Europe in the period 2010-2013.
(Source: Quarterly report on EU electricity markets, 2013)

Data on the retail electricity price ranges for household and industrial consumers in the second half of 2012, for different consumption bands (Fig.11) show that in most Member States the higher the consumption, the lower the retail electricity price paid in the case of both household and industrial consumers. This is possibly due to the existence of fixed elements of retail electricity price invoices, which are independent from the amount of electricity consumed and which therefore contribute proportionally more to the final retail price in lower consumption categories.

The blank bubbles at the top and bottom of the ranges show the highest and the lowest prices in different consumption bands, while the black filled bubble shows Dc and Ic band prices, which are prices paid by consumers with average consumption.

In household consumption band Da (annual consumption less than 1,000 kWh) households in Bulgaria paid the lowest price (9.6 €cents/kWh, including taxes), while households in Ireland paid the highest price (59 €cents/kWh, including taxes) for the consumption band De [36].



Source: Eurostat
Prices include all taxes. Price categories refer to annual consumption bands defined by Eurostat.
Band DA : Consumption < 1 000 kWh
Band DB : 1 000 kWh < Consumption < 2 500 kWh
Band DC : 2 500 kWh < Consumption < 5 000 kWh
Band DD : 5 000 kWh < Consumption < 15 000 kWh
Band DE : Consumption > 15 000 kWh
The black bubble shows Band Dc price.

Figure 11_Range of electricity prices (all taxes included) paid by household consumers in different annual consumption bands in EU Member States, second semester 2012 [36].

The most recent Eurostat data [37] about retail electricity prices by households with an annual consumption between 2500 and 5000 kWh (band Dc), including all taxes, are relative to the first half of 2013. In particular the lowest price is paid in Bulgaria (9.92 c€/kWh), instead the highest price is paid in Denmark (30.0 c€/kWh). The price of electricity for households in Denmark was more than three times compared to the price in Bulgaria, really similar to the 2012 trend.

The following graphic (Fig.12) indicates retail electricity prices, expressed in euro/kWh, by households and industry consumers in Europe.

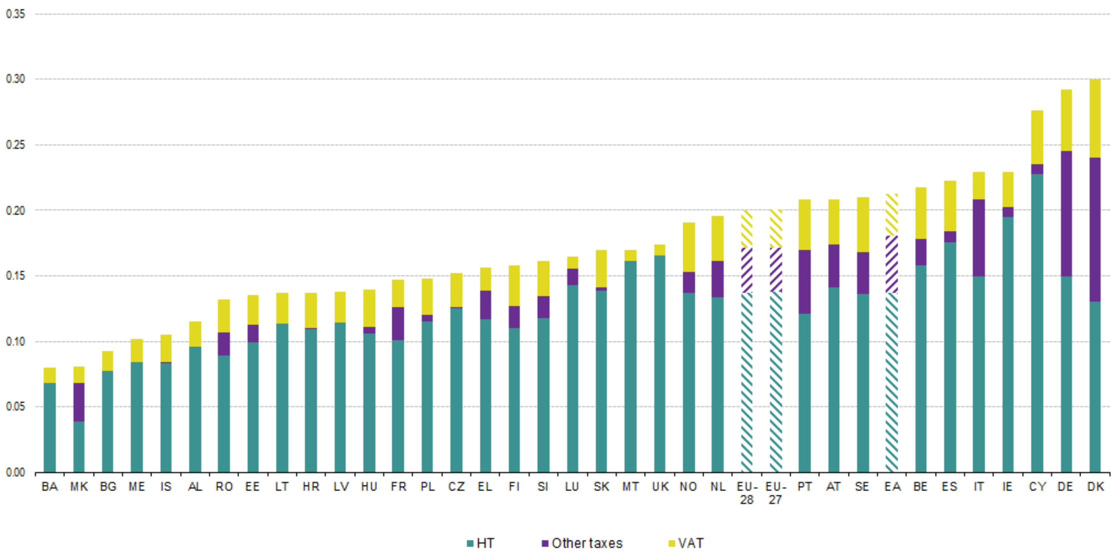


Figure 12_Retail electricity prices in Europe for first half 2013-band Dc (2500 -5000 kWh)
(Source: Eurostat database)

- <u>Gas</u>

EU's natural gas consumption remained relatively stable over the first quarter (Q1) of 2013. Preliminary data shows that consumption in the first quarter of 2013 increased slightly compared to the same period in 2012.
In the first quarter of 2013 gas imports into the EU increased by more than 10% relative to the same period in 2012, while EU production of natural gas remained stable (Fig. 13).

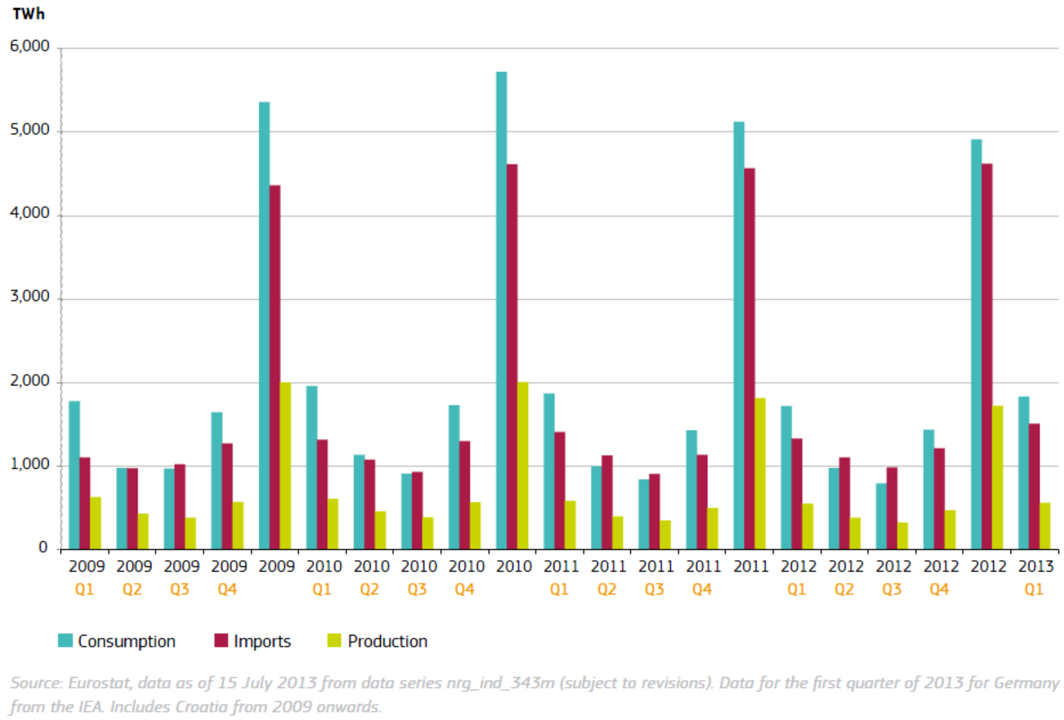


Figure 13_EU 27 gas consumption, imports and production [38]

Weather was an important determinant of natural gas consumption over the first quarter of 2013 with unseasonably cold weather in large parts of Europe, in particular in March 2013. Whereas in January and February 2013 the number of heating degree days was close to the long-term average, March 2013 experienced a particularly high number of heating degree days, far exceeding the long term average [38].

Comparing oil, gas and coal prices in the EU, it is possible to note a clear decoupling between coal prices on the one hand and oil and gas prices on the other since 2011. The decoupling appears to have been slowing down over the second quarter of 2013, when the prices of all three commodities went down respective to the first quarter of the year (-8% for Brent crude, -11% for the NBP spot after the price spike of March 2013, -7% for coal) (Fig. 14).
The different price dynamics between the various energy commodities that have prevailed over most of 2012 has been important in defining demand. EU coal demand and imports have been sustained as prices for the commodity have been falling. In contrast, demand for natural gas has been falling as prices have been rising [38].

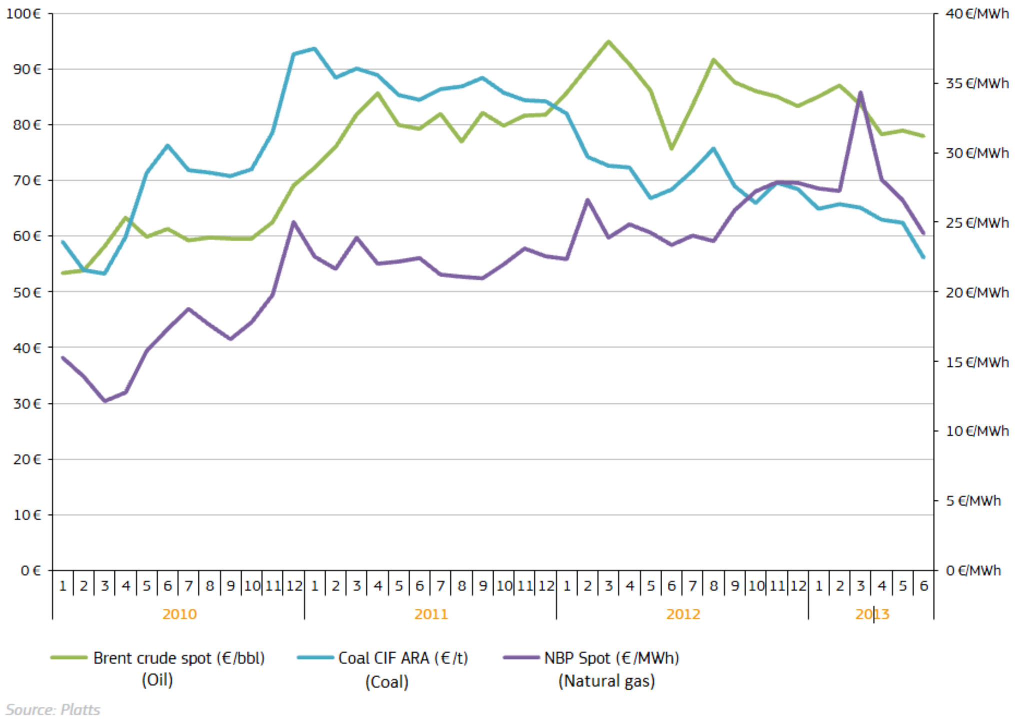
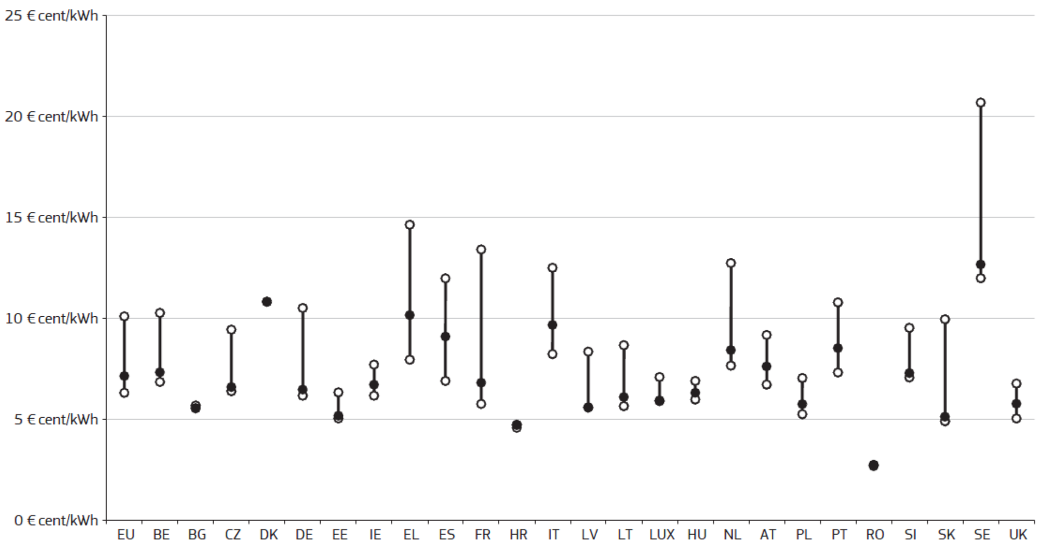


Figure 14_Spot prices of oil, coal and gas in the EU

In particular, a comparison of retail gas prices across the EU continues to reveal significant differences, with the prices paid in the most expensive Member States representing several times the price paid in the cheapest (even if taxes and duties are excluded).
In almost all Member States, there are significant differences in the range of retail prices paid by household and industrial consumers in different consumption bands. The range of retail prices (including all taxes) reported for the three household consumption bands in each Member State are shown in figure 15, also denoting the retail price in the mid-consumption band D2 (black dot) in the second half of 2012 [38].
Between the first half of 2012 and the first half of 2013, natural gas prices for households consumers increased in most of the EU Member States. In Slovenia, the gas price decreased however in this period with more than 16 %. Cyprus, Malta, Greece and Finland did not report these prices.



The black dot denotes the retail price in consumption band D2.
Source: Eurostat.
Band D1 : Consumption < 20 GJ
Band D2 : 20 GJ < Consumption < 200 GJ
Band D3 : Consumption > 200 GJ

Figure 15_Range gas price ranges (all taxes included) paid by household consumers in different annual consumption bands in EU Member States, second semester 2012 [38]

The most recent Eurostat data [37], show that, for medium size household consumers (band D2 _ 5.56 – 55.6 MWh), natural gas prices during the first semester of 2013 were the highest in Sweden, Denmark and Portugal (fig. 16). The lowest natural gas prices in the EU for households are found in Romania, Hungary and in Croatia. The price of natural gas for households in Sweden (EUR 0.123 per kWh) was more than four times the price that is charged in Romania (EUR 0.029 per kWh).

Figure 16_Retail gas prices in Europe for first half 2013-band D2 (5.56 – 55.6 MWh)
(Source: Eurostat database)

It has been shown [39] that the expected losses (structural performance) can be combined with the expected energy cost, obtained multiplying energy consumption (Q_{Energy}) with the energy unitary cost (P_{Energy}), as follow:

$$R_{SSD(Energy)} = P_{Energy} \times Q_{Energy} \tag{6}$$

in which R_{SSD} is the global result for the sustainable structural design (in Euro)
P_{Energy} is the price of one kWh of energy, expressed in euro/kWh
Q_{Energy} is the quantity of energy in kWh, calculated with LCA analysis

In line with the previous considerations, once the price of carbon emissions and energy (electricity and gas) has been defined, environmental results, assessed by the LCA methodology can be converted into *"ecological cost" ($R_{SSD(CO2)}$, $R_{SSD(ENERGY)}$)*, expressed in euro.
In particular, the "*total ecological cost" (R_{SSDt})* that is given by summing $R_{SSD(CO2)}$ and $R_{SSD(ENERGY)}$ could be considered, obtaining in such a way the total environmental performance of a building in monetary terms.
In such a way the comparison allows to take into account also damages costs and benefits derived from climate change and environmental impacts.

The actual challenge is to define a global assessment parameter R_{SSD}, considering at the same time environmental and structural performance through the use of one parameter of comparison among different constructive solutions. Indeed structural results (Expected Annual Loss - EAL) could be summed to environmental ones *(R_{SSDt})* because both are expressed in monetary unit, as follow:

$$R_{SSD} = R_{SSDt} + EAL$$

3.1_The importance of considering *external costs* in CO_2 and energy price

Although the environmental preservation is one of the most discussed topics of the last years, a low price of CO_2 emissions is still maintained. Moreover the big difference between the price of energy and carbon depends on taxes considered for the energy. In order to understand the importance of environmental impacts in the construction sector, the price of CO_2 emissions should change to better reflect the environmental and social costs.

It is well-known that CO_2 emissions and energy consumption produced by construction sector cause damages and impose risks on human beings and on ecosystems. They emit pollutants that are transported in the atmosphere and then when inhaled can create a health risk or after deposition can disturb ecosystems. The damages occurring thus are external effects, not taken into account by the person or institution causing the effects [40].
In short these damages are defined as *negative environmental externalities*.

The effect of an activity that may influence in a positive or negative way an otherwise uninvolved party who has no decision role in this activity is defined as an *externality*. In such a way an externality turns out to be related to social welfare and to economy.
In order to assess and compare externalities with each other and with costs, it is advantageous to transform them into a common unit, in particular in monetary unit. In such a way the negative externalities result in external costs which are not accounted for by the decision maker.
An external cost arises, when the social or economic activities of one group of persons have an impact on another group and when that impact is not fully accounted, or compensated for, by the first group [40].

If a way to correct the inefficiency derived by negative externalities is not considered, the market failure occurs. Therefore in order to control these effects, a process of *internalisation* is needed.
For this reason appropriate instruments have been developed by economists and governments to adequately internalize externalities such as:

- **fiscal measures**, known as *Pigouvian taxes*
- **tradable permits** related to the so called *bubble* instruments (for instance the EU-ETS)
- **command and control** through direct regulations and laws such as environmental standards, policy targets, directives [41].

In order to be able to carry out an internalisation process, external costs have to be quantified so that relevant externalities can be include in marginal private costs, obtaining the marginal social cost.
In short the social cost is the sum of private cost and external cost.
Considering and internalising external costs becomes the right way to satisfy the optimal market condition when negative externalities occur, because in such a way the true price of a production, corresponding to the social one, is considered.

According to the *Energy and Environment Report* of EEA (2008), in view of climate change, it is crucial to provide the true cost of energy and carbon. This is *needed in order to give correct price signals for much-needed investment in the infrastructure for energy supply as well as demand side management measures*.

Even if the EU-ETS represents a way to internalise the environmental costs as previously described, further development are needed in this direction. Indeed in the emission trading system the market price of carbon is considered, but not the external costs.
Several limits have been noticed during the two phases of this market [42]:

- **over-allocation of emission permits**: in the second phase of the market a way to solve this problem has been considered with a quota of emitted permits 12% lower than the first period
- **price volatility**: although a range of 10-20 euro had been foreseen in the second phase, prices were really lower, in particular during the last two years (2011-2012).

Although a lot of changes have been considered for the third period (2013-2020), such as auctioning allocations, volatility control, availability of spending during the active phase of market, the price of CO_2 is still volatile and really low compared with the expected previsions.

For this reason Europe has suggested instruments that include fiscal measure, such as environment-related taxes. The 2007 commission green paper on the use of market-based instruments for environment and related policy purposes reinforced this view.
The main advantage of taxes is that the price signal should encourage producers and consumers to change their behaviour.

The external effects can be internalized through environmental taxation in two ways:

1. tax level should be set at level of marginal damage costs (extern costs).
2. tax level is set to attain certain environmental objectives and policy targets (environmental purpose tax).

The first point is the ideal way to carry out tax level, but it turns out to be difficult to define, so the second one is commonly considered. Both approaches run the risk of being economically sub-optimal, when the tax level is set to be too high or too low. In spite of that a zero tax would mean that external costs are not accounted for at all, so the true price is not taken into account [20, 43].

In any case the preferred approach is the first one because the way of taxing results in the most efficient use of resources. However, full internalisation of external costs is difficult to achieve because the environmental damage value is generally not known (EEA, 2005) [43].
In short environmental taxes have to be defined, after assessing external costs, but this process is quite difficult.
For this reason in 2005 the European project Extern-E (Extern Energy) developed a methodology to provide the external cost of energy following three steps: firstly to measure the damages to society which are not paid for by its main actors; secondly, to translate these damages into a monetary value; and thirdly, to explore how these *external costs* could be charged to the producers and consumers.

Thanks to this project external costs per unit of emissions of CO_2 have been estimated. This assessment is not so easy therefore the external costs of CO_2 emissions must thus be interpreted with care. Watkiss [44] (2005) stresses that there *is no single value and that the range of uncertainty around any value depends on ethical as well as economic assumptions*. The damage factors for CO_2 used range from 19 EUR/t CO_2 (low estimate, based on ExternE-Pol) and 80 EUR/t CO_2 (high estimate, based on Watkiss et al., 2005). These two values are common to all countries and turn out to be a shadow price of carbon, which is similar to the social cost and allow carbon externalities to be taken into account.
The limit of this estimate is clear: a precise price is not given, so the range considered has to be seen as indicative. Although large uncertainties remain in determining and monetizing the external costs, the importance of the problem is illustrated by the value range of cost estimates.

In that light, these costs are not negligible, indeed starting from these values, in 2005 externalities of electricity production were estimate to be in order of 0.6 - 2% of the GPD [6, 43]. In details, the average external costs of electricity production across Europe ranged from 0.2 to 17.8 eurocent/kwh.

All this considered, taking into account the external costs of carbon could be a way to update the true price of carbon, as it happens with energy price thanks to the energy taxes.

Focus on Combination of environmental and structural results

Step I and step II of the proposed methodology respectively allow buildings environmental and structural performances to be defined in a quantitative way. In details, environmental results are expressed in tons of CO_2 and in MJ of energy, instead structural results are expressed in Euro. It is clear that these measure units cannot be summed. For this reason a global assessment parameter is needed. Step III is focused on this objective. In details, environmental results should be transformed in monetary unit considering the price of one ton of CO_2, according to EU-ETS mechanisms and the price of one kWh of energy, according EU electricity and gas markets, so that they can be combined with the structural ones. In such a way a global result is obtained and it could be really useful to compare alternative constructive solutions, allowing stakeholders to choose the most advantageous one, in respect of sustainability requirements.

In spite of that the real price of CO_2 is not still considered because external costs are left out, so the solution could be to introduce taxes or other market instruments necessary to consider the true price, as it happens with energy prices that already include taxes and VAT.

PART III: RESOURCE-EFFICIENCY IN CONSTRUCTION SECTOR

1_The present European importance of considering the resource-efficiency

Nowadays the supply of resources is so limited that the growing global demand adds pressure on the environment. Respecting the natural limits of the Planet is essential not only to avoid environmental degradation and depletion of natural resources, but also for the European economy. Indeed according to the EU *strategy for the sustainable use of natural resources* [45], the economy of Member States depends on natural resources availability. For this reason one of the European priorities is to increase the resource efficiency. This issue could be the key both to secure growth and job and to protect the natural environment, but if European society has to become more resource efficient, prices need to change to reflect the real costs of resource use.

The attention on resource-efficiency has grown a lot, leading Europe to adopt several strategies and initiatives in this direction in the last decade. In particular since 2005 one of the most important goals for the European environment policy has been launched. It was focused on the achievement of a more sustainable use of resources. Indeed the challenge is to facilitate and stimulate the European growth, ensuring that the environment state does not get worst. In particular *a reduction of the negative environmental impacts generated by the use of natural resources in a growing economy* [45] should be reached. For this reason the necessity by 2008 to define indicators to measure progress in efficiency and productivity in the use of natural resources and also an eco-efficiency indicator has been highlighted.
This concept is also recalled and strengthened in the 2011 European flagship initiative on “A resource efficient Europe”. Indeed according to this European initiative “*indicators are needed to cover issues such as the availability of natural resources, where they are located, how efficiently they are used, waste generation and recycling rates, impacts on the environment and biodiversity”* [46].

Using resources more efficiently will help Member States to achieve many of the EU's objectives. It will be an essential key in making progress to deal with climate change and to achieve the target of reducing EU greenhouse gas emissions by 80 to 95% by 2050.
In addition, by reducing reliance on increasingly scarce fuels and materials, boosting resource efficiency can also improve the security of Europe's supply of raw materials and make the EU's economy more resilient to future increases in global energy and commodity prices [46].

In line with that, the use of natural resources in an efficient way becomes an essential issue that should be included in a sustainable structural design methodology, considering that the building sector plays a key role with the 50% of extracted materials [47].

1.1_The state of the resource-efficiency in construction sector

In the last years the attention on resource efficiency in the construction sector has led Europe to increase its interest both on the adoption of thematic strategies and initiatives and on the implementation of law mechanisms to favour the awareness of this issue.

According to the *Roadmap for a resource efficient Europe* [47], launched in 2011, better construction and use of buildings would contribute to the development of a resource-efficient building stock. For this reason existing policies for promoting energy efficiency and renewable energy use in building need to be further complemented with policies for resource efficiency, which look at wider range of environmental impacts across the life-cycle of buildings and infrastructure.

An important step towards an efficient use of resources could improve the competitiveness of the construction sector promoting the use of waste as resource. In line with that, the promotion of recycle or reuse of materials and the increase of innovation and technology with the development of green industries are needed [47].

Eco-innovation is closely linked to the way we use natural resources and to how we produce and consume. Thanks to the promotion of this field, it is possible to reduce pressures on natural resources, improve the life quality of European citizens and stimulate economic growth. In line with that, the expected environmental, social and commercial benefits of wide-spread adoption of eco-innovation could be considerable, taking into account that eco-industries are already a significant economic sector with about 2.5% of the EU's gross demand product (GDP) [11]. In line with that, eco-innovation can be considered as a key driver towards a greener and more sustainable economy, with a particular focus on its potential to generate growth and create new jobs. For this reason the necessity of developing new technologies and the importance of focusing on eco-innovation at European level were pursued for a long time. In particular, the Environmental Technologies Action Programme (ETAP), adopted in 2004 and followed by Eco-Innovation Action Plan (EAP) in 2011, had the aim to capitalize on full potential of environmental technologies, especially using solar and wind energy. The construction sector has played a key role in this strategy because "*many environmental technologies offer scope for reducing the consumption of raw materials, to promote the reuse and recycling of construction and demolition waste and to enhance energy efficiency*" [10], above all in the light of the Raw Materials Initiative [48].

In accordance to this initiative, a report on critical raw materials which are subject to a particularly high risk of interruption of their supply chain was published in 2010 (Fig. 17). This report lists 14 elements among which rare earth elements are indicated. They are a group of 17 metals, largely used in the modern and high technology industry. The "green industry" depends on these materials. The production of photovoltaic (PV) systems and concentrated solar power (CSP) systems, low consumption lamps, wind turbines and other innovative elements used for sustainable constructions are strictly connected with these metals such as neodymium, dysprosium, terbium and with other critical raw materials such as indium, gallium and tellurium.

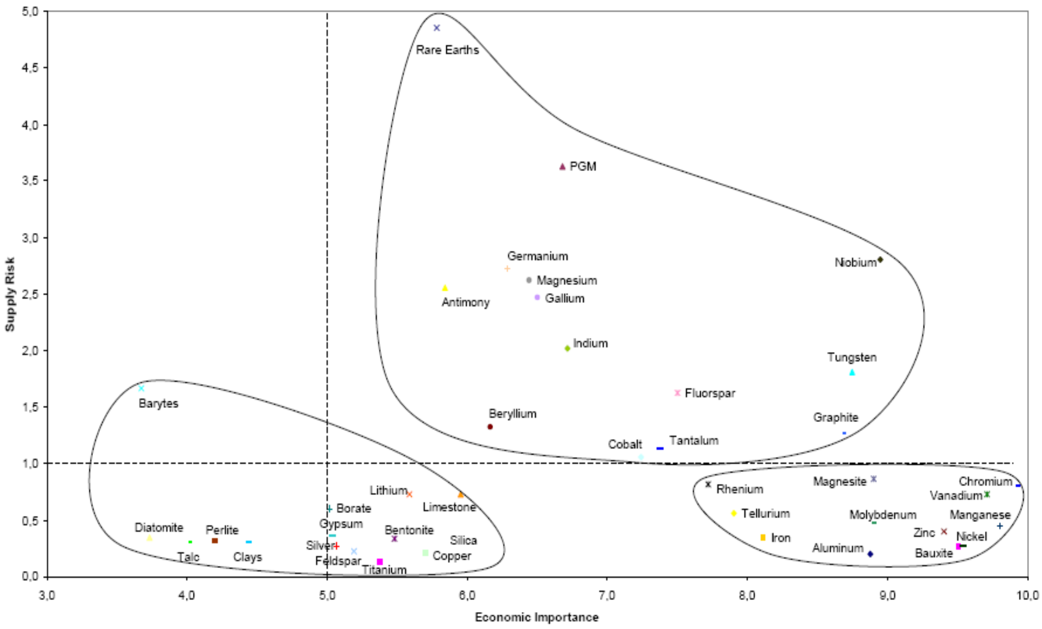


Figure 17_Raw materials subject to supply risk.
(Raw Materials Initiative - RMI)

The implementation of the Construction Products Regulation (CPR) in 2011 should create the conditions for improving eco-efficient resource use and incentives for moving towards more sustainable production and consumption patterns.

1.2_A possible way to measure the resource-efficiency in construction sector

In the light of the aforementioned background, a recent study [49], conducted by the University of Dundee about the *"Measurement on resource efficiency"* highlights the importance to define a raw material indicator as a combination of availability to future generations and quantity used (Harrison, 2013). In particular the residual life of a resource, defined as its remaining life in years if we continue to use it at the current rate of use, turns out to be an essential parameter to reach a resource efficient society. In particular, in the light of the RMI, supply risk and economic importance can be converted to an equivalent residual life.

This research is focused on the definition of the Current Scarcity Score (CSS) indicator, based on the report of quantities and residual lives of all resources (abiotic, biotic, fuels, water and secondary resources). Thanks to the development of a characterization model, raw material use is converted into current scarcity score to compare alternatives solutions. A hyperbolic function among the various potential models examined is regarded as given the best relationship between the residual life and the CSS indicator (Fig.8), highlighting that:

- proportionally higher values for shorter residual lives
- little difference with long residual lives

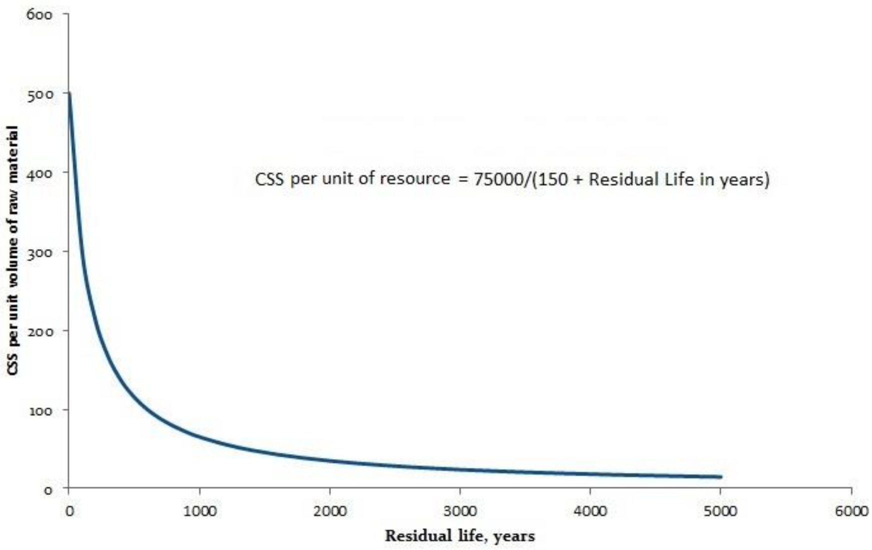


Figure 18_CSS per unit volume of raw material (Harrison T., 2013)

In short CSS is a quantity and scarcity measure of the resources used. For example UK data show that an average concrete in the UK has a CSS of 26.75. If in the future this number reduces, the UK concrete industry will show to be more resource efficient.
One way to reduce this indicator is to encourage maximum use of secondary materials such as: reclaimed brick, recycled aluminium or recycled concrete, for which is given a CSS of 5.

Two main open questions have to be considered with regard to this research:

- if the Raw Material Initiative should be included;

- if it is necessary to provide a *"Combined Resource Score" (CRS)* in addition to the CSS.

Although further research is required, an important step to measure the resource efficiency has been considered.

1.3_Next potential steps to consider resource-efficiency in construction sector

Measuring resource efficiency is the first step to consider quantitatively the problem of resource efficiency in construction sector. Other potential options could be considered to promote an 'optimal' use of resources in construction sector, focusing on:

1. Economic dimension of resource efficiency

In order to also include resource efficiency in the proposed SSD methodology, it could be necessary to consider the economic dimension of resources used in the life cycle of a building. In such a way this aspect could be included in the definition of the global assessment parameter obtained thanks to the third step of methodology exposed in the previous section. For this reason future research needs in this direction should be provided.

2. How to respect waste and recycling targets

An important topic strictly connected to resource efficiency is the production of waste and the possibility to reuse and recycling it. Indeed in order to move towards a European recycling society with a high level of resource efficiency, the Waste Framework Directive (2008/98/EC) [50] sets the following targets:

- the separate collection of paper, metal, plastic and glass by 2015;
- at least 50% of paper, plastics, metal and glass from households and similar origins prepared for reuse or recycled by 2020;
- at least 70% of non-hazardous construction and demolition (C&D) waste reused, recycled or undergoing material recovery by 2020.

With regard to the third point, it could be really useful to make an effort to respect targets on waste and recycling proposed by the waste directive, in a double way:

- promote design for deconstruction
- consider economic instruments

These options are exposed in details in the next section.

1.3.1_Further research needs to consider economic dimension of resource-efficiency in construction sector

Resources are often used inefficiently because the information about the true costs to society of consuming them is not available with the result that businesses and individuals cannot adapt their behaviour accordingly. Policy measures to improve resource efficiency and overall economic competitiveness must place greater emphasis on 'getting prices right' and making them transparent to consumers, for instance in transport, energy and water usage, so that prices reflect the full costs of resource use to society (e.g. in terms of environment and health) and do not create perverse incentives [46].

It is important to acknowledge the potential for application of taxes on primary materials as a means to:

a) reduce the consumption of materials generally,
b) encourage re-use and preparation for re-use,
c) increase the proportion of material use which is accounted for by recycled materials.

In theory, this could be an attractive option for improving the sustainability of materials management, but in practice this may be a difficult policy option to execute. Indeed there are still a number of obstacles which confront the use of such an instrument [51]:

- with regard to the ongoing trade in materials and products which occurs both within EU countries, and between the EU and the rest of the world, it would be necessary to implement some form of border tax adjustment (BTA) which enabled imports to be taxed at an equivalent rate to domestic production, and exports to be exempted from the tax. For individual Member States, the option of using BTA effectively does not exist since it would appear to contravene principles regarding the operation of the internal market. BTA is a possibility for EU wide taxes, but even at the EU level, the information requirements in order to apply BTA in a fair way would be significant. This is because for all imports, an estimated 'default' material content would be needed, but there must also be flexibility for the importer to demonstrate a level of use differing from that default.
- EU level taxation would require unanimity amongst MS, which could be difficult to achieve

For these reasons the scope of application of such taxes has been limited in the EU, with taxation generally being focused on materials such as aggregates and gravel. These materials are not so widely traded and such taxes have been applied successfully in, amongst others, Denmark, Sweden and the UK [51].

On that basis, further research and developments that could take into account also the economic dimension of this issue are needed. Indeed market instruments have to effectuate an important role in correcting market failures, introducing environmental taxes, fiscal incentives, rights or other instruments in this direction. In addition new policies should help to align the price of resources that are not appropriately valued on the market, as well as for the price of CO_2 emissions [46].
In such a way this aspect could be included in the proposed *SSD* methodology, obtaining a quantitative way to consider it during the design of a new building or for the assessment of an existing one. Indeed considering the price of resources, the cost of resources can be considered and combined with the environmental and structural one through the third step of the SSD methodology.

1.3.2_A potential way to respect waste and recycling targets in construction sector

Waste policies can help to develop secondary raw materials markets and strengthen their supply in the EU, thus improving the resource-efficiency of the EU economy, according to the 2011 Thematic Strategy on the prevention and recycling of waste [52]. New market mechanisms favouring secondary raw materials should be explored, including economic incentives, notably to better take into account the significant potential in terms of GHG emission reduction conferred by recycling. Defining new and more ambitious prevention and recycling targets as well as moving towards material-specific targets can directly contribute to meet the Europe 2020 objective of "promoting a resource efficient economy" and to the related Flagship Initiative. In that sense, materials having negative environment and health impacts over their entire life cycle, including on energy use and climate change should be better targeted.

Improving the competiveness of EU recycling industries is essential for the generation of jobs in the EU. In that context, ensuring that competition takes place within a framework maintaining high levels of environmental protection is a key priority for the Commission. In addition, the Commission will look into how to better prevent illegal exports of waste and ensuring that waste exported to third countries is treated in high standard facilities, particularly for ship dismantling [52].

In that light even if the Waste Framework Directive (2008/98/EC) sets precise targets, they are not respected yet.
In particular, with regards to the generation and recycling of **construction and demolition (C&D) waste**, it should be noted that data availability is generally poor. In spite of that it is possible to refer to data from the European Topic Centre on Resource and Waste Management [53] to analyse this topic. Around 850 million tonnes of C&D waste is generated in the EU per year. This represents 31% of the total waste generation in the EU. The generation of C&D waste in Member States in tonnes per capita varies considerably, from 0.04 tonnes in Latvia to 5.9 tonnes in Luxembourg (Fig. 19). Apart from Germany, all countries where data for more than one year is available show an increase in generation per capita in the period 1995 to 2006. The differences between countries in generation of C&D waste per capita are much higher than the differences in generation of municipal waste [51, 53]. It can be assumed that some differences in the amount of waste from C&D activities derive from differences in building tradition and differences in geography/geology, but the economic activity within the sector will also influence waste generation. The economic activity in the construction sector can explain, for example, Germany's decline in generation per capita. In recent years the construction activities have been lower in Germany after a huge activity caused by the unification of Germany in 1990 [52].

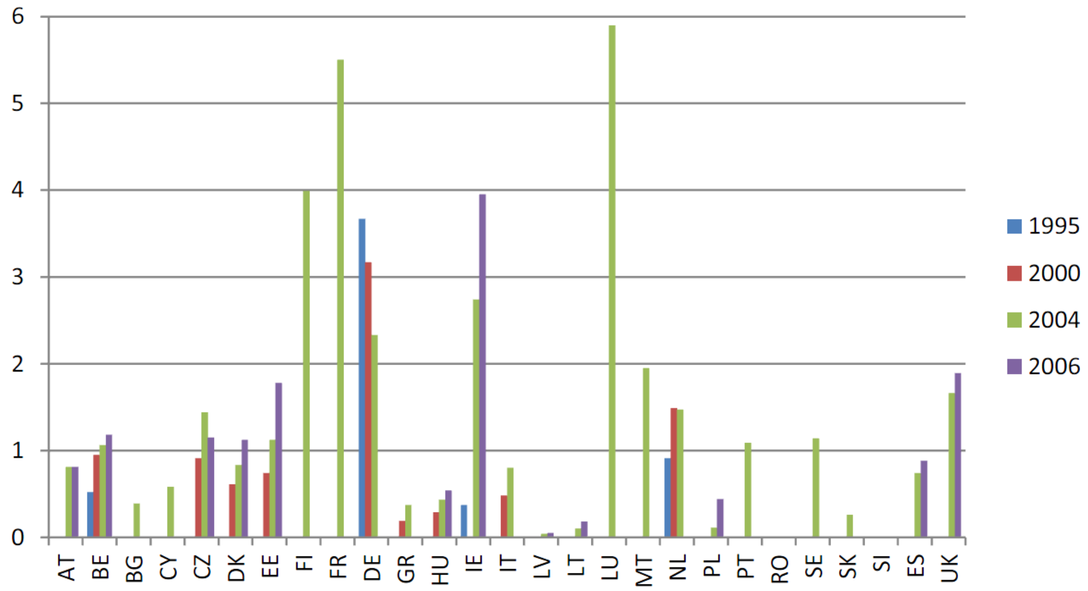


Figure 19_Generation of C&D waste (tonnes per capita) in EU-27

The Waste Framework Directive (2008/98/EC) sets a target for 70% by weight preparation for re-use, recycling and other material recovery (including backfilling operations using waste to substitute other materials) of non-hazardous C&D waste by 2020.
Figure 20 shows the recycling rate for C&D waste in those Member States for which data are available, in particular it has been only possible to obtain information about recycling of C&D waste for 18 out of the potential of 28 countries (EU-27 and Norway) covered by the 2009 ETC/SCP study.
The recycling rate in tonnes per capita differs among countries, but the differences are not as large as those seen for municipal waste. In addition, there is not a great difference in recycling rates between the old and the new Member States. In 2004 (year for which the most data is available), the recycling rate was 60% or over in 10 Member States. In details, Denmark, Germany, Ireland and the Netherlands but also Estonia, recycle even over 80% of C&D waste generation [51, 53].

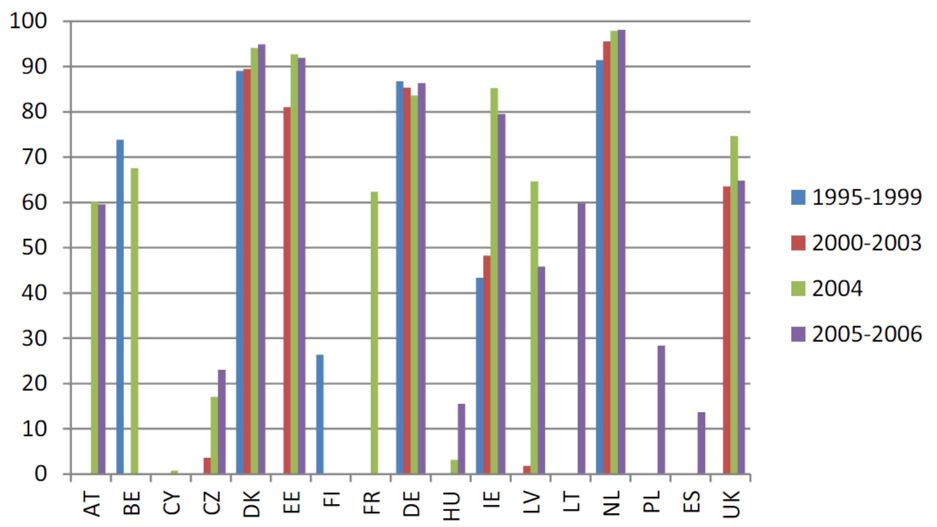
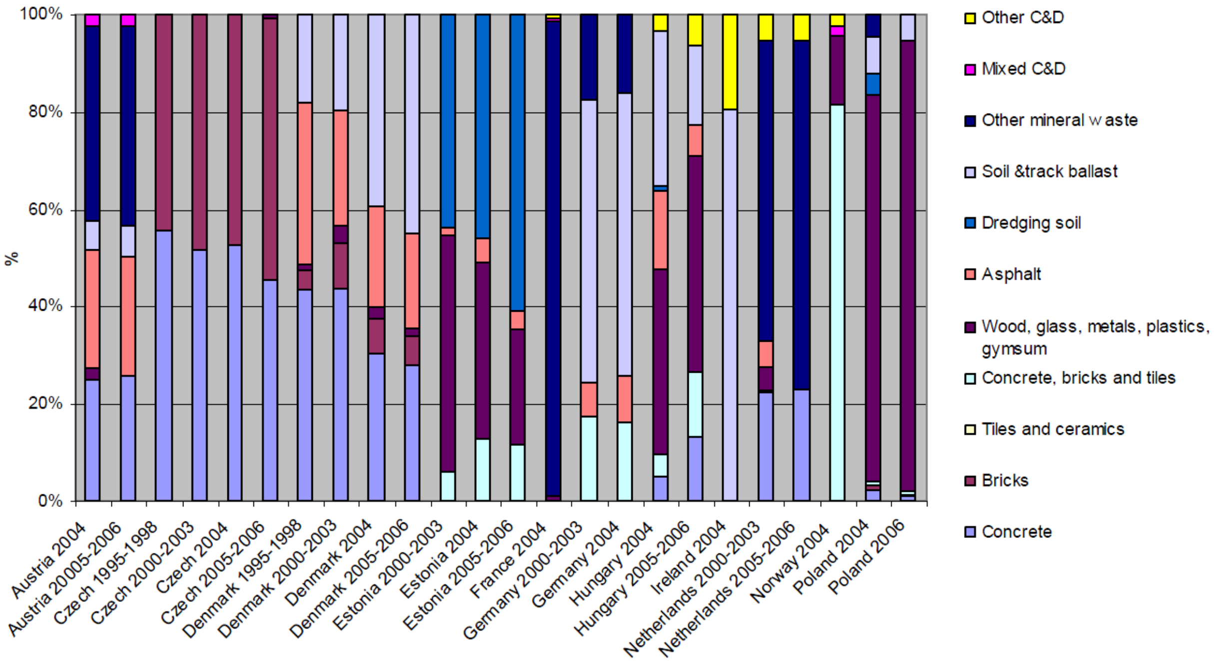


Figure 20_Recycling of C&D waste (% of amount generated)

The very high recycling levels in the abovementioned countries can possibly be explained by the composition of the recycled waste (Fig. 21).
It is clearly shown that dredging soil, soil & track ballast constitute a large part of the recycling, so Denmark, Estonia, Germany and Ireland all recycle over 70% of generated C&D waste, but a minimum 40% of the total recycling is by way of recycling dredging soil, soil and track ballast.
In any case almost all of the countries where recycling has been identified, register recycling of concrete, bricks, tiles and asphalt, except Ireland and France [53].



Source: ETC/RWM, 2008 based on national reports and statistics

Figure 21_ Percentage composition and development of recycled construction and demolition waste in the EU and Norway

In that context recycling has to become a normal practice to accelerate progress, extend efforts to other areas and reap the benefits that a successful strategy can bring for competitiveness, job creation and prosperity.
Indeed, even if the potential recycle of some construction materials is really high, further efforts are needed in this direction.

An indicative example is the flat glass. In spite of its recyclability, the “post consumer” flat glass is almost never recycled into new glass products but 95% is landfilled or recovered together with other C&D waste (aggregates).
This turns out to be a considerable lack, taking into account that 3.4 to 6.4 Mt of building glass waste is generated each year (7 to 13 kg/inhabitant) in EU27 and 96% of the waste is “post-consumer”.
Moreover the flat glass recycle has also evident positive impacts on environment, as underlined in a recent 2013 study conducted by BIO intelligence service [54]. In details, 1 ton of cullet saves 1.2 tons of raw materials and nearly 300 kg of CO_2 and 3% in energy savings can be achieved for every 10% of cullet replacing raw materials.
Another construction material with a huge recycling potential is gypsum [55]. This is a rock-like mineral used in construction in different applications such as plasterboard, building plaster and gypsum blocks. One of the most important characteristic of this material is its fully and eternally recyclability, so that gypsum products can be recycled because their chemical composition remains unchanged. Furthermore re-incorporation of recycled gypsum is not a technical difficulty for low recycling rate except with some specific plaster boards. In spite of that still a low quantity of gypsum is recycled.

This background considered, in order to improve building materials recycle and re-use, respecting targets provided by the Waste Directive and favouring the EU resource-efficiency goal, two potential ways could be used:

1. **Design for Deconstruction (DfD)**

Design for deconstruction is a way of thinking and designing a building to maximize its flexibility and adaptability (to cater to multiple owners and avoid wasteful renovations) and ensure that a building can be easily disassembled after becoming obsolete.
This emerging concept has the goal to reduce pollution impacts and increase resource and economic efficiency in the adaptation and eventual removal of buildings, and recovery of components and materials for reuse, re-manufacturing and recycling. In short several environmental and economic benefits derived by DfD.

Thanks to this new concept the whole life-cycle of the building is really considered, not just construction and operation, and maintenance and repair, but major adaptations, and eventual whole-building removal. In particular this latter point turns out to be fundamental in the light of resource-efficiency. The ultimate goal of DfD study is to responsibly manage end-of-life building materials to minimize consumption of raw materials. By capturing materials removed during building renovation or demolition and finding ways to reuse them in another construction project or recycle them into a new product, the overall environmental impact of end-of-life building materials can be reduced.
The real benefit of deconstruction is about closing the loop of resource use. It is about reusing these “waste” resources to avoid logging or mining new virgin resources from our ecosystems. Designing for Deconstruction means to design in such a way that these resources can be economically recovered and reused. In contrast to the conventional linear model of extraction, use and landfilling, DfD envisions a closed cycle of use and reuse (Fig. 22).

Some building materials are often difficult to separate, and many are not readily recycled. For example concrete can be “recycled”, but only as low value aggregate, wood debris can be ground up for wood fiber or mulch, but thereby loses its most valuable properties. On that basis, recycle could be actually considered the down-cycling of a material to a lower grade use.
In that light, DFD becomes a method that allows recycling of materials to be considered as a secondary option, if reuse is out of the question. DFD allows materials and components from building to be recovered for re-use, eliminating additional inputs resources such as energy, transportation, or additional materials, necessary for each resource flow steps. In particular,

materials recycle also uses more embodied energy in transportation and manufacturing than reusing materials, which tends to only use energy for transportation.

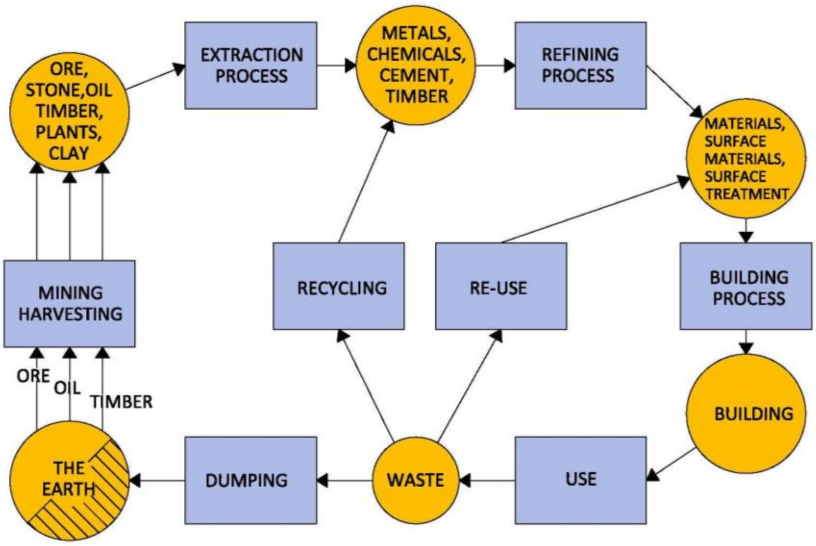


Figure 22_Resource flow, considering Design for Deconstruction concept
(Source: Bjorn Berge - The ecology of building materials)

In order to Design for Deconstruction, it is worth considering following concepts:

- Select materials with high-value, feasibility for reuse, and/or recycling.
- Design connections that are accessible visually, physically, ergonomically, and without expensive equipment needs or hazards to workers.
- Use simple, open-span structural systems, simple forms, and standard dimensional grids that allow for ease of additions and subtractions and deconstruction in increments without impinging upon the whole.
- Use materials and systems that exhibit principles of inter-changeability, i.e. modular, self-supporting, standardized and homogenous.

2. Economic instruments

It would seem that the use of landfill taxes (adapted to the conditions in each Member State) can help to shift waste into recycling options, with progressively higher taxes generating higher performance.

The sum of the landfill tax (a levy charged by a public authority for the disposal of waste) and the gate fee (a charge set by the operator of the landfill for the provision of the service) represent the total charge for the disposal of waste in a landfill.
A fairly clear and linear correlation was observed between the total landfill charge and the percentage of municipal waste recycled and composted in EU Member States. The MS that charge more for landfilling show a higher percentage of MSW recycled and composted.
That means that low landfill taxes can provide a disincentive to recycling.

Data was gathered for a smaller number of Member States on the landfill tax rates for inert waste, including Construction and Demolition (C&D) waste. In the majority of Member States where data was collected on the cost of both municipal and inert/C&D waste, the cost of landfilling inert/C&D (Fig. 23a) waste appears lower than that of municipal waste (this is not the case in DK where no distinction is made between the two types of waste for tax purposes, nor in EE and LV where inert/C&D waste is subject to a higher landfill tax than municipal waste).

The two Member States with the highest landfill taxes for inert/C&D waste (DK and NL) (Fig. 23b) demonstrate the highest levels of recycling of such waste. In spite of that, there is a wide range of recycling performance amongst the other Member States which makes it difficult to infer any significant correlation between the rate of landfill tax and the recycling of C&D waste.

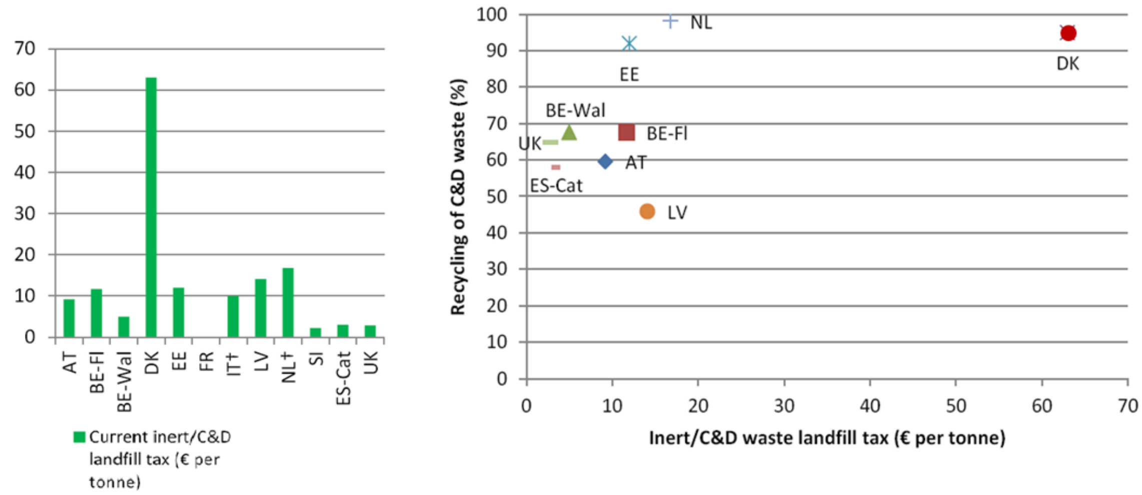


Figure 23_ (a) – Overview of landfill tax for inert/C&D waste (selected MS), (b) – inert /C&D waste landfill tax and percentage of C&D waste recycled

Additional reductions in landfilling can be achieved using landfill restrictions or bans, but these have to be deployed carefully to ensure that the waste management system does not become over-reliant on residual waste treatment at the expense of further progress in recycling.
These instruments seem to be indispensable (in combination with other policies) to meet the existing minimum EU targets and furthermore to ensure Member States progress towards the goal of the Resource Efficiency Roadmap to achieve zero residual waste.

One policy which may (in conjunction with landfill taxes and taxes on primary aggregates, analysed in the previous section) have a useful role to play in increasing recycling rates for C&D wastes is an approach using refunded compliance bonds.
Under this arrangement, contractors would be required to pay a financial sum to the relevant regulatory land-use planning authority, related to the size of the project at its commencement, plus a small administrative fee (to cover the administrative costs of the system). The financial sum would be retained as a bond to ensure that the project exceeded a specified recycling rate, which could be set higher for public sector projects
The size of bond paid would vary by project size, and all of the bond, excluding the administrative fee, would be returned at the end of the construction process on demonstrating achievement of the desired recycling rate.

Focus on Resource efficiency in construction sector

Resource efficiency is an important topic in the light of the sustainable construction sector that can not be anymore omitted, considering that building sector accounts for 50% of raw materials consumption. In order to underline the importance of this issue, a list of raw materials subject to risk of supply chain interruption has been presented, showing that some elements included in this list are largely used in sustainable constructions. In that context, Europe has launched several initiatives and strategies to reinforce the sustainable use of natural resources, highlighting that a change of direction is needed otherwise the environmental, social and economic systems will collapse in short time. Moreover resource efficiency can favour the achievement of EU objectives in terms of CO_2 reduction for 2050 and can improve EU economy, creating new markets and jobs. Indeed according to eco-innovation, the development of new technologies, such as green products could enhance resource efficiency, as well as the promotion of recycling and re-use of materials. All this considered the challenge to include also this aspect in the sustainable structural design methodology has to been analysed, considering a way to quantitatively measure resource efficiency. A recent study conducted by the University of Dundee shows the possibility to use a *Current Scarcity Score (CCS)* indicator to reach this goal.

Even if steps to seriously consider this theme in the sustainable construction sector are increasing, further needs have to be developed. Potential options could be considered to promote an 'optimal' use of resources in construction sector:

1. **Economic dimension of resources:** an effort to assess the economic dimension of this issue should be done, in order to include this aspect in the proposed SSD methodology. In such a way, once the resource price has been defined, the true cost of resource use could be combined with environmental and structural results thanks to the third step of the proposed SSD methodology. In that line, taxes on raw materials should be taking into account, encouraging in such a way the resource efficiency achievement.
2. **Satisfying waste and recycling targets:** re-use and recycling of building materials should become a normal practice. According to Waste Directive, 70% of C&D waste should be reused and recycled by 2020. This target could be ensured in two ways:
   - *Design for Deconstruction.* This emerging concept allows building materials and components to be easily disassembly, favouring their second life. In such a way, this way of designing constructions helps to reduce demands on virgin and natural resources, and minimizes pollution. All these aspects help to "close the loop" on construction waste by turning waste into resources.
   - *Economic instruments.* It would seem that a correlation between landfill taxes and increasing of C&D waste recycling exist. In spite of that, poor data do not allow to consider a significant link, but this economic instrument seem to be essential (in combination with other policies) to meet the existing minimum EU targets and ensure the goal of zero residual waste.

CONCLUSIONS

This study demonstrates that a holistic view is the key of the sustainability in the construction sector.
A new way to conceive the structures is needed in order to reduce the environmental impacts above all in terms of equivalent CO_2 emissions and energy consumption and to guide the sustainable construction sector toward a multi-performance, life-cycle oriented approach, as European objectives require.
A framework for a possible Sustainable Structural Design (SSD) methodology has been presented, as an integrated approach, able to include environmental performance in structural design.
The three main steps of this methodology have been discussed. In details, the first step the environmental performance assessment could be carried out through the use of LCA methodology, allowing CO_2 emissions and energy consumption to be quantified in equivalent quantities of CO_2 and energy. Considering that the environmental and structural results are expressed in different units of measure, a way to combine these two aspects has been conceived thanks to the second and the third step of the proposed methodology. The second step allows structural behaviour to be assessed in economic terms, considering monetary loss in relation to the damages to which a structure could be subjected throughout its entire life-cycle. The third step, finally, describes how to define a global assessment parameter: a way to convert environmental results in monetary units has been proposed. In such a way the ecological performances can be combined with the structural ones, obtaining an unique result.
Although the environmental preservation is one of the most discussed topics of the last years, a low reference value of CO_2 emissions is still maintained. Moreover, the big difference between the values of energy and CO_2 depends on taxes considered for the energy. In particular, in order to understand the importance of externalities in the construction sector, the reference value of CO_2 emissions should change to better reflect the environmental and social costs.
The importance of considering resource efficiency in the construction sector has been highlighted, analysing a procedure to measure in quantitative way it through a scarcity indicator. In addition potential options have been considered to promote an optimal use of resources in the construction sector, focusing on the possibility to define the economic dimension of resources and to respect reuse and recycling targets. For the latter point the concept of design for deconstruction and economic instruments such as landfill taxes turn out to be potential issues to favour resource efficiency.
In order to develop this aspect further research is required.

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Abstract

Sustainability has become one of the most ambitious challenges for Europe growth, according to *2020 Europe Strategy*. This high-priority theme braces a lot of industrial sectors. In particular the construction sector bears a huge responsibility in relation to sustainable development because of several impacts produced on its three dimensions: environment, economy and society. A building has to fulfill its own performance not only in the abovementioned common triple-bottom line of sustainability, but also in usability, capacity, reliability, safety and comfort. In that context, designing a sustainable construction turns out to be a very complex issue, so a holistic view is the key of sustainability in the construction sector. Furthermore, buildings should be designed and assessed in the light of time with a future in mind which can be predicted only in probabilistic terms, so an integral life-cycle approach is required.

This report emphasizes the present need for the construction sector to develop a new way to conceive structures, with the aim to develop a competitive sustainable construction sector. In order to obtain this European objective a new design methodology is needed, focusing on a multi-performance, life-cycle oriented approach.
A potential *Sustainable Structural Design (SSD)* methodology with its three main steps is presented, addressing the possibility to include environmental aspects in structural design, in order to obtain a global assessment parameter in monetary terms. In details, the building environmental analysis in terms of CO_2 emissions and energy consumption, carried out by the LCA methodology, should be combined with the structural analysis. For this reason environmental results have to be transformed in costs in order to be summed with structural results, expressed in economic terms thanks to the simplified Performance Based Assessment (sPBA) methodology.
Finally the importance of considering the resource-efficiency in construction sector is discussed, highlighting a possible way to measure it. The necessity to develop a research programme to consider the economic dimension of this aspect in order to include it in the SSD methodology is considered. Other possible options to ensure resource-efficiency in the construction sector through the re-use of building materials and the recycle of construction and demolition waste or the reinforcement of economic instruments are underlined.

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