Matching safety and sustainability: the SAFESUST approach

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Abstract. The construction industry, as a main energy consumer and a foremost contributor to greenhouse gas emissions, has been undergoing a "green revolution" in the recent years. Sustainability has become a prominent issue, and environmental methods such as footprint schemes and Life Cycle Analysis approaches are being considered in the design and in the rehabilitation of buildings. However, all environmental assessment methods are applied at a later design stage, to provide a final indication of the life cycle environmental performance. A more effective way would be to consider the environmental issues in the early design stage, along with structural reliability and safety, and the global performance indicator should be expressed in economic terms. The need for an integrated design approach, to tackle safety and sustainability together has been the object of a recent workshop, in which the acronym SAFESUST was introduced. SAFESUST is an acronym to mean SAFEty and SUSTainability. It also identifies a research work-package on impact of sustainability and energy efficiency requirements on building design and retrofit, being conducted by the European Commission - Joint Research Centre, as a part of the project Safe and Cleaner Technologies for Construction and Buildings. The SAFESUST approach has been implemented into a Sustainable Structural Design (SSD) method, which considers both environmental and structural parameters in a life cycle perspective. The integration of environmental data in the structural performance is the focus of the method. Structural performances are considered in a probabilistic approach, through the introduction of a simplified Performance Based Assessment method.

Keywords: Building Sustainability; Sustainable Structural Design; Performance Based Design; Building Rehabilitation

1. The SAFESUST approach

The global population now exceeds seven billion. This means that during the past 250 years or so, it has increased tenfold that of the Industrial Revolution in the mid-18th century, which is believed to have been 700 million. Eighty percent of the global population lives in developing regions, which means that the consumption of resources and energy will increase enormously in the future. Resources and energy are some of the most fundamental elements for the daily life of humankind. In recent years, it has been recognised that increasing fossil energy consumption could even change the global climate. It is anticipated that global warming will cause extremely serious problems in the future, in fact, climate change driven by global warming has already increased the intensity and frequency of weather action such as typhoons/hurricanes and torrential rainfalls, causing enormous damage; in addition, the frequency or intensity of heavy precipitation events has likely increased in North America and Europe [1]. On the other hand, developed countries, such as EU, have accumulated a

huge amount of infrastructure and building over a long time. It means that these structures have to be properly maintained by taking cost, natural resources consumption, and more severe loading and environment into consideration. In other words, it is very important how to incorporate sustainability concepts into construction industry.

SAFESUST is an acronym to mean SAFEty and SUSTainability. It identifies a research work-package on Impact of sustainability and energy efficiency requirements on building design and retrofit, being conducted by the European Commission - Joint Research Centre as a part of the project: Safe and Cleaner Technologies for Construction and Buildings. The acronym appeared in the title of the workshop: A roadmap for the improvement of earthquake resistance and eco-efficiency of existing buildings and cities, and the word soon during the discussions which took place, became a neologism. Expressions such as "SAFESUST concept", "SAFESUST problem" and "SAFESUST approach" were commonly used. For this reason, in this freshly created word, possibly remains the essence of the roadmap which has been started to be drawn at the workshop: SAFEty and SUSTainability.

There is sufficient evidence of the fact that there could be not anymore safety without sustainability. This evidence underpins actions to mitigate what could be the most difficult problem mankind have faced since ever: saving our only planet and this was not to be discussed at the workshop. What became soon evident during the discussion is that there can be no sustainability without safety, in tackling the improvement of the existing building heritage.

2. Why a Roadmap?

Today, more so than ever before, global issues such as the climate change are overlapped to local crises like the shrinkage of the construction sector, which followed the economic and financial crisis in EU [2]. On one hand this scenario is a nightmare for stakeholders involved in the building process, but - on the other hand - it represents a good chance to create the technical conditions for a deep and lasting urban transformation. This is a stimulating challenge that the construction chain will face in the coming decades.

The destinations of this route are smart, resilient and sustainable cities and the starting point is the present building stock. The path is made by the innovation of products and processes and the basic tools to have a coherent and safe travel are a compass and a map to guide the action. Without a roadmap, all efforts would lack direction and thus could easily be inefficient. The age profile analysis of the EU's building heritage [3] reveals that only the minority of these 27 billion m^2 is recent, namely built after 1991: the main part of the stock was built between 1961 and 1990 and a significant percentage before 1960. This means that those buildings are likely to have poor thermal and environmental performances and, in addition, they were built without modern structural design codes and often without seismic prescriptions.

Any actions aimed at improving energy and environmental efficiency without addressing safety at the same time is bound to failure. No seismic provisions were considered in the construction of very old buildings, and those enforced at the time of the construction of more recent ones are typically considered to be insufficient. The problem of seismic safety is being considered also in those regions which were not considered as affected by the earthquakes in the past and, sometimes, it is technically more severe there. The improved knowledge of the seismicity of Europe has significantly increased the areas for which at least some seismic provisions should be enforced.

Other dynamic actions, e.g., traffic disturbances, industrial or mining activities, pose similar problems. In more general terms, requirements for service loads are nowadays more stringent than those considered in the design and construction of old buildings, as well as for the deformability requirements. Ageing of materials, poor maintenance and corrosion also affect the resulting structural safety of existing buildings.

The need to pursue is the integrated renovation/reconstruction with the SAFESUST approach: to tackle the problem of the improvement of the structural safety at the same time of the energy and environmental performance in a Life Cycle (LC) perspective should then be kept in mind.

3. Who's game?

In defining a roadmap, those who will have to follow it have to be identified. To this extent, the experience of the SAFESUST workshop has been instrumental. Many individuals from the scientific committee have expressed doubts and concern about the format of the workshop. The idea of mixing traditional sessions based on oral presentations, open discussions and take-home assignments to be left with the rapporteurs was seen as rather uncommon, however, it worked well. What was seen as rather bizarre, and possibly unprecedented as for this topic, was to ask for the participation of experts from differing disciplines. The workshop was intended to bring in the same room experts on structures, architecture and city planning, materials, energy and finance, so that they could learn from each other, discuss and seek synergies and possible agreed priorities. From one side it might have been difficult to identify the leading experts from all disciplines, and convince them that it might have been worth playing that game. From the other, somebody was preoccupied because the disciplines were seen as too far apart to speak the same language, or too close to reach a common view.

The workshop was unanimously seen as a success by the participants, and the main lesson learnt from this success is profound: a solution to the problem of the improvement of safety and eco-efficiency of existing buildings can be found only in a multidisciplinary perspective. Defining the rules of the game calls for the participation of all technical experts.

Any solution conceived having in mind only one aspect of the problem is bound to failure. The need for new, interdisciplinary, expertise was expressed. Different roles will continue to be necessary; at the same time, a new approach calls for a common language as well as shared rules. This is best expressed by the need for new taxonomy, semantic and metric. Moreover, it became evident from the presentations, as well as during the discussions, that not all the players were indeed in the room: other actors have to be involved, such as local authorities and communities, owners and investors; to that extent, another issue has to be included to the roadmap. The SAFESUST approach will from now on also refer to the involvement of all experts and stakeholders, sharing the new common language.

4. The circle game

Circular economy: Cradle to grave (or Cradle to cradle?). Prevent, reduce, reuse, recycle... Where is the starting point?

Figure 1. The virtuous circle.

Everybody would agree that there is no starting point in circle. There has been a strong agreement at the workshop: it is not effective to just check the safety requirements of a satisfactory design in terms of eco-efficiency, as well as it is not effective to check the level of eco-efficiency of a compliant

safety design. Safety and eco-efficiency should be addressed together, at the same time, and this should be done in the design phase.

At the moment, design norms just relate to safety performance, and eco-efficiency can just be checked afterwards. Design norms should be extended to include eco-efficiency. Speaking about safety, the neighbors' safety is equally important than ours. In case of accident, especially in historic town centres, the fire propagation, or the seismic interactions among buildings, can affect also inherently safe buildings. In addition, to preserve one property is not enough if the surrounding is injured. For all these reasons, an innovative approach must be developed at urban scale to improve the city resilience.

5. The rules

He/she who moves first loses. There seem to be a first move advantage in chess, for sure not in addressing the improvement of safety and eco-efficiency of buildings. If one tries to improve the energy efficiency of a building, without making adequate structural safety, loses. No point in having your old car repainted, if the engine has not been fixed!

Who holds the starting pistol? Typically, owner/investor and architect initiate the game. However, in a circle game, moving first does not make sense if the others remain still, therefore each actor should be encouraged to move. The architect is often the first technical interface with the owners/investors, his/her role is crucial at the beginning, to collect and represent the requirements from the other experts and stakeholders since the first project stage. The architect must define, together with his/her counterparts the main aspects of the building in terms of cost and general layout.

A rational and collaborative pre-design analysis should prevent jeopardising the integrity of the project at later stages. For this purpose, rules should be known in advance, so that whoever moves does that without preventing the others from setting their objectives and applying their methods. SAFESUST objectives should be put forward from the beginning, so that they can be defined in economic terms and be considered by all the experts who intervene in the design. A specific training might be required, and possibly a new coordinated expertise should take the lead: a SAFESUST expert.

6. Good and bad players

Eco-efficiency is a challenge, but it can also be an opportunity. When the opportunity is addressed in economic terms, players try to demonstrate that their products are superior to the others'. There are no doubts that industrial competition harvests innovation; however, a general consensus was soon reached about the fact that there is no good, or bad, material. The use of structural materials is responsible for a huge fraction of the global CO_2 production; however, there is no alternative to the current wide use of steel and concrete. No material is *per se* better performing in environmental terms, the best solution can be identified only when the environmental performances, together with the safety performances, are defined for the building, in a life cycle perspective: the SAFESUST approach.

Technical advances could help to give the start. For instance, it is much easier to recycle materials which have been designed for recycling, whereas reusing normal scrap might be difficult or even impossible. To that extent, new technologies to ensure the possibility to completely recycle the construction materials have been developed. It is for instance possible to produce concrete from which aggregates can be fully recovered at the end of its life. Adopting such technologies would for sure help in starting the game.

7. Pay to play

It's a long way. In each technical session, many needs were identified as for research and innovation, awareness increase, education, training, barrier breaking, integration... The main obstacle to enter the virtuous cycle is economic.

From one side, it should become evident that the cost increase for buying a better performing, more efficient and safer building corresponds to an investment with a high return. The investor should be made fully aware of this, as well as of the importance of preserving the resources and ameliorating the quality of his life and the life of his community. Moreover, the figures shown at the workshop seem to indicate that the cost for design is a small percentage of the total cost of the building (and it might become negligible if compared to the cost of operating the building). It was also shown that in recent years, as an effect of energy efficiency regulations, the building's price index has increased, but it has much less than constructions cost: the owner should realise that investing in safety and eco-efficiency is a good business. Education and public awareness play an important role, to this extent.

On the other hand, the fact that the increase in the costs associated to new eco-efficient construction is not reflected by the increase in retailing prices of new buildings might not be good news for the construction industry. The advantages for the community should govern over those of the owner or of the single investor, and this could be enforced by means of regulations and incentives.

Figure 2. The economy circle.

In a roadmap, the most urgent need should be identified, and a consensus was soon reached about the importance of adequate investments in research and innovation. And also in this case, a specific, SAFESUST, approach was said to be needed: the current lines of funding for research and innovation are focused on eco-efficiency, but seem to forget the problem of the improvement of safety of existing buildings.

In the last resort, citizens pay for the game. They do it indirectly – as taxpayers – fostering studies/research/policies, and they do directly, incurring higher prices to buy or rent buildings with better performances. If people are not aware of these technical advances, and even more if safety and sustainability are not recognised as crucial for their lives, how is it possible to call for resources on this? In other words: who will pay for a show no one has ever heard of?

8. Sustainable Structural Design

To reach all the targets stated above, a new way to conceive structures is needed. The design process should concern the whole life cycle of structures and their components, in order to reduce environmental impacts and increase the durability of structures. In this light, the *Sustainable Structural Design* (SSD) method hereinafter presented could be the solution to design constructions, considering all buildings requirements in a holistic way.

The SSD method is conceived as a supporting tool for the building design process. It takes into account technical-structural aspects along with environmental ones during the entire LC. It tends to optimize the building design in terms of structural and environmental performance, configuring a design method both for safety and sustainability [4] [5].

The framework of the SSD method is based on three main pillars, corresponding to the three evaluation steps: *Energy Performance Assessment; Life Cycle Assessment and Structural Performance Assessment*. The following sections describe the details of each component. Finally, a *Global Assessment Parameter*, expressed in monetary terms, is obtained, to make the necessary design decisions.

9. Energy performance assessment

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

The main reason for this decision is the fact that the cost of energy typically includes a tax that is intended to represent the environmental impact corresponding to the production and use of the energy, from whatever source the energy is produced. Such tax, which is fixed by the relevant authorities, is in principle accounting for the full environmental impact and therefore it should not be included in the LCA.

10. Life cycle assessment

The life cycle assessment is performed according to the standard cradle to grave approach. The contribution of the operating phase will be determined using the results of the first step and the output of this phase will be expressed in terms of total equivalent CO_2 emissions.
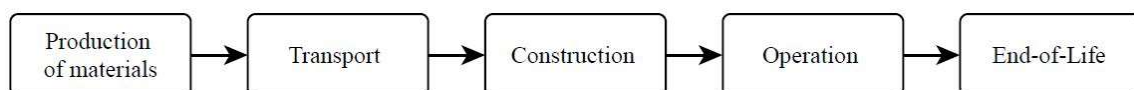

Figure 3. Flowchart of the LCA of a building.

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

11. Structural performance assessment

The third step of the SSD method deals with the structural design using a Performance-Based Assessment (PBA). In other terms, the design process should not be seen in the sole aspect of structural response but also in the aspect of structural performance [6] is expressed in predefined design targets that the structure is required to meet over its design life [7].

The structural PBA consists in the implementation of probabilistic scenarios that can occur during the lifespan of the structure in terms of uncertainties [8]. Therefore, not only loads imposed on the structure but also uncertainty and probabilistic response should be taken into account in the structural analysis [9]. The uncertainties are grouped into three main categories namely hazard uncertainty (e.g. earthquakes, winds), structural uncertainty (e.g. stiffness, material properties) and interaction mechanism uncertainty (e.g. pressure duration) [8] [10]. To this regard, the PBA allows structural systems to be designed in a way that meets performance targets in terms of capacity, safety and quality [7].

The final results of the structural PBA are presented in economic context by evaluating all the costs associated with a structural solution, as well as the expected losses that may occur to the building during its life for all the design targets.

The development of PBA methods is gaining big interest in the field of structural engineering. This interest originates from the successful implementation of the Performance-Based Earthquake Engineering (PBEE) method from the Pacific Earthquake Engineering Research (PEER) Center [11]. The PEER's PBEE method has been fundamental in addressing the importance of integrating loss-assessment within structural design. However, such method seems too complicated to be applied to ordinary projects due to complex probabilistic relations and high number of parameters [4] [5]. Considering the latter, a simplified Performance-Based Assessment (sPBA) method has been introduced by Safety & Security of Buildings Unit of the Directorate Space Security & Migration – European Commission, Joint Research Centre (JRC) [4] [12]. The framework of the sPBA method aims at reducing the complexity and the amount of data needed as well as simplifying the procedure of estimating losses due to uncertainties. The method has been developed for seismic actions, but the same approach could, *mutati mutandis*, be applied to other actions on the structure.

The output of the analysis determines the cost of the structure together with expected losses for each defined limit state, corresponding to different Peak Ground Acceleration (PGA) and Inter-storey Drift Ratio (IDR) [13]. The steps of the sPBA method are detailed in the following.

11.1. Limit States Definition

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

11.2. Structural Analysis

The structural analysis step consists in the calculation of the PGA values that cause the IDR values defined in the previous step. This correlation is defined through skeleton curves that may be obtained from the Incremental Dynamic Analysis (IDA), according to the FEMA-350 guidelines [14] or simply from a standard pushover analysis. After performing this analysis to a structural system, the PGA versus IDR can be defined for each configuration of damage state.

11.3. Hazard Analysis

In the hazard analysis, the output of the structural analysis is used to estimate the probability of exceedance. Modern seismic codes provide the relation between the Return Period (T_R) and the PGA [15]. For example, the Italian seismic code [16] provides a set of values of PGAs for nine return

periods (30, 50, 72, 101, 240, 201, 475, 975 and 2475 years) along with the interpolation formula for values in between:

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

where:

a_g is the PGA calculated for a defined damage state,

T_R is the return period which corresponds to that state,

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

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

After determining a_g from the previous step, the return period T_R can be defined for each damage state. The probability of exceeding R_N in N years is expressed from the following equation [16]:

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

11.4. Cost Analysis

The total cost of the building C_{TOT} is the sum of the initial construction cost (investment: I) and the expected total loss (L) over the project's life cycle. While the initial cost includes the expenses related to the initial establishment of the facility, the estimation of expected total loss is more complex and involves different stakeholder categories [4] [5].

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

More specifically, the contractor estimates in advance the time needed to repair the damages of each limit state. This information about time, needed for each limit state, is associated with the downtime loss. Downtime refers to the period of time in which the system fails to provide its primary function and therefore downtime loss expresses the amount of money that will be spent (lost) while the building is not used. Later, for each state, the structural engineer calculates the cost of repair of the damages [4] [5]. Therefore, the expected loss C_i for each limit state i is expressed as the sum of monetary loss (the amount of money needed to repair the damaged building) and downtime loss (the amount of money spent during the repairing actions e.g. for rent, removal, etc...).

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

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

12. Global Assessment Parameter

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

12.1. Energy performance into monetary units

The calculated amount of energy corresponds to energy consumed during the use phase and usually it is expressed in kilowatt-hour (kWh) or in cubic metres of natural gas (m^3 gas) [17]. The price for gas and electricity in Europe can be determined using the data of the Statistical Office of the European Union (Eurostat) [18] for each member state or the average price of all the Union in the household or

industrial category. Therefore the total energy price $R_{E(Energy)}$ can be calculated for a specific country or using the average price by the following equation:

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

where:

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

P_{Energy} is the price of one kWh or m3 of gas (€/kWh or €/m^3 gas).

12.2. Environmental performance into monetary units

Until today in Europe there are market prices only for the carbon dioxide (CO_2), therefore only the environmental impacts associated with the global warming potential (carbon footprint) can be converted into economic costs [4] [5]. To this end, ILCD is a crucial element to convert all the considered burdens into a CO_2 equivalent amount, and from this calculate an equivalent economic impact [19].

Carbon footprint is defined as the total amount of greenhouse gases (GHG) emissions caused by building life cycle phases, usually expressed in equivalent tonnes of carbon dioxide (CO_{2eq}). Otherwise, the embodied energy includes the energy consumed by processes associated with the production, use and demolition of the building, usually expressed in MegaJoule (MJ), kiloWatt-hour (kWh) or cubic metres of natural gas (m^3 gas) [17]. The conversion of the results into monetary unit can be done following the EU directives.

The carbon dioxide price per tonne is linked with the European Union Emissions Trading System (EU ETS). According to the EU ETS, each member state agrees on maximum national emission limit that should be approved by the European Commission. Then the Union countries allocate allowance values to their industrial operators, who are able to buy or sell such allowances named European Emission Allowances (EUA) [20]. The total number of permits issued, either auctioned or allocated, defines the price per carbon which is therefore, determined by stock exchange rules.

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

$$R_{E(CO_2)} = Q_{(CO_2)} \cdot P_{(CO_2)} \tag{7}$$

where:

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

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

12.3. Equation of the Global Assessment Parameter R_{SSD}

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

$$R_{SSD} = R_{E(CO_2)} + R_{E(Energy)} + C_{TOT} \tag{8}$$

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

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

13. Conclusions

The outcome of a recent workshop on the renovation of existing building heritage has been summarized. The main conclusion of the workshop, in which experts from many disciplines (structural engineering, architecture, city planning, finance) participated was that in the renovation of existing

buildings, as well as in the design of new ones, a method to account for safety and sustainability in recent years is needed. The acronym SAFESUST (SAFEty and SUSTainability) was introduced.

A possible way to implement the SAFESUST requirements is represented by the Sustainable Structural Design method. The method is based on the independent evaluation of Energy, Life Cycle and Structural performances, which are finally combined into a Global Assessment Parameter, expressed in economic terms.

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