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Recommendations and guidelines to foster sustainable design

EFIResources: *Resource Efficient Construction towards Sustainable Design*

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Authors

Helena Gervasio

Abstract

The research project *EFIResources*: *Resource Efficient Construction towards Sustainable Design* was developed in order to support European policies related to the efficient use of resources in construction. Its major goal was the development of a performance based approach for sustainable design, enabling to assess the resource efficiency throughout the complete life cycle of buildings.

The proposed approach aims at the harmonization between structural design and sustainability design of buildings, to enable an easier integration of structural and sustainability criteria in the design process, thus coping with the essential requirements for construction works of the Construction Products Regulation.

The development of this approach was made in different steps. The first step consisted in the development of a consistent model to assess the life cycle performance of buildings, to enable comparability and to support the quantifications of benchmarks. All buildings considered in this project were assessed based in this model.

Then, a graduated approach was adopted for the development of benchmarks, starting on a simple basis and improving in accuracy over time. Two sets of benchmarks were quantified for residential and office buildings.

The last step consisted in the presentation of the performance based approach for sustainable design, which is based on the definition on benchmarks to strive to a reduction of the use of resources in construction. The limit state of sustainability was introduced that aims to complement the limit states for structural performance.

This last report of the project *EFIResources* aims to summarize the main achievements of the project but also to emphasise some limitations of the developed approach. Hence, at the end of the report, the main achievements and limitations of the proposed approach are discussed and recommendations for future research work are provided.

1 Introduction

The built environment has a huge responsibility on the way natural resources are consumed and on the production of a major waste stream, thus being responsible for a high share of the corresponding environmental problems. Aiming to revert this situation, the research project *EFIResources*: *Resource Efficient Construction towards Sustainable Design*, focussed in the development of a performance based approach for sustainable design, enabling to assess resource efficiency throughout the complete life cycle of buildings.

The proposed approach aims for a generalized application, avoiding the need of extensive expertise in the field of sustainability assessment of buildings. Building designers should have the opportunity to assess the environmental performance of their projects, together with other mandatory criteria of safety and economy, in the early stages of the design process, when the potential to positively influence the lifetime behaviour of buildings is higher [1].

To comply with the above goal, the proposed approach is based on the harmonization between structural design and sustainability design of buildings, ensuring that architects and engineers are familiar with concepts and procedures.

In the structural design of buildings, the effect of loads on a structural member is compared with a reference value, in terms of either ultimate resistance or admissible deformation, and safety is ensured when the load effect is lower than the reference value.

On the other side, in the proposed approach for sustainable design, the life cycle environmental performance of a given building is compared against a benchmark, represented by the average value, in a given area, of the environmental performance of the buildings with the same typology. Analogously, the environmental performance of the building being assessed should be lower than the reference value to ensure a better environmental solution.

The approach is limited to the structural system of buildings. One of the reasons for this limitation is due to the lack of environmental data to enable an accurate life cycle analysis of the full building [2], particularly on the early stages of design. Hence, hereafter, when reference is made to building(s), it should be interpreted as the structural system of building(s).

However, the scope of the approach is open and when appropriate data becomes available, it may easily be extended to account for other building components.

To enable the development of the above approach, two previous major steps were required. The first was the development of a consistent LCA model to support all building assessments and to ensure comparability. The adopted model is based on the standardized framework developed by CEN-TC350 for the life cycle assessment of construction works, provided by EN 15804 [3] and EN 15978 [4]. All details about this model are given in [2].

The second step consisted in the adoption of a methodology for the quantification of benchmarks, which is fully described in [5].

The last step of the project entailed the development of the performance based approach for sustainable building design. The approach was introduced in [6], together with two sets of benchmarks for residential and office buildings.

This report briefly summarizes this last part of the project, although references will be made to other parts of the work carried out in the development of the project.

Furthermore, in the last part of this report, the main achievements and the main limitations of the project are discussed, followed by some recommendations for future research work in the context of sustainable building design.

2 Sustainable design of buildings

2.1 Harmonization with structural safety

In the structural design of buildings, the effect of loads on a structural member (S) is compared with a reference value (R), in terms of either ultimate resistance or admissible deformation and safety is ensured when the load effect is lower than the reference value ($S \leq R$). The function G ($G = R - S$) is called a limit state function and separates satisfactory and unsatisfactory states of a structure.

Each limit state is associated with a certain performance requirement imposed on a structure and generally two types of limit states are recognized [7]: Ultimate Limit States (ULS) and Serviceability Limit States (SLS). The former are associated with the collapse or other identical forms of structural failure; while, the latter correspond to conditions of normal use, as well as the comfort of people, and usually do not lead to structural failure. The European standards for structural design, the Eurocodes, are based on this limit state concept.

The proposed approach for sustainable design of buildings, follows a similar methodology. In this case, a new limit state was introduced, the limit state of sustainability, in which the environmental performance of the building is compared with a reference value or benchmark, given by the average life cycle environmental performance of a set of buildings with the same typology, in a reference area [6].

It is noteworthy that the compliance to the Eurocodes allows to satisfy the first essential requirement of 'mechanical resistance and stability' of the Construction Product Regulation [8]. This regulation, which repealed the original directive, introduced an additional essential requirement addressing the 'Sustainable use of natural resources'. In this case, the regulation states that '*construction works must be designed, built and demolished in such a way that the use of natural resources is sustainable* (…)'.

Currently, there is not a specific methodology allowing to comply with this new requirement.

Therefore, the proposed approach for sustainable design allows to satisfy this new essential requirement, thus providing the possibility to fill the gap of the present regulation.

2.2 Limit state of sustainability

As described above, the structural design of buildings according to current European standards is based on the limit state concept, which consists on the definition of structural and load models for relevant ultimate and serviceability limit states.

With the aim to harmonize structural design and sustainable design of buildings, a performance-based approach for sustainable design was proposed, which enables to assess the efficient use of resources throughout the complete life cycle of buildings, and complies with the design rules and reliability provisions of the Eurocodes [6].

Following this performance-based design, a structure shall be designed in such a way that it will with appropriate degrees of reliability, in an economical way and with low environmental impacts, attain the required performance. Therefore, the aim of the proposed approach is the pursuit of a building design with lower environmental performance than the reference value, representing the average performance of the same type of buildings, in a given area.

Hence, in this model two variables are defined: (i) the environmental performance of the building being assessed (E) and (ii) the reference value of the environmental performance of a set of buildings (R), with the same typology, in a given area.

In this case, taking into account the goal of the approach, the condition that should be satisfied is given by expression (1)

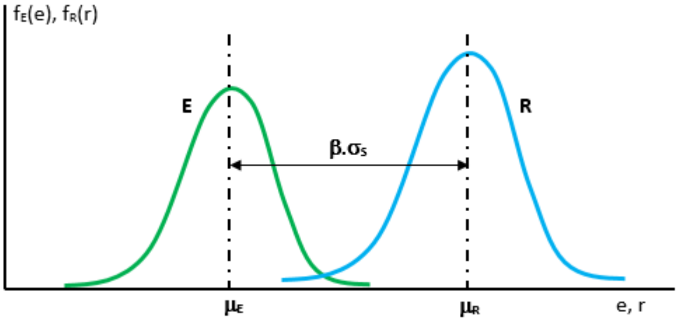
$$E \leq R \tag{1}$$

In this case, a limit state function may be defined by $S = E - R$, and therefore

$$S = E - R \leq 0 \tag{2}$$

Variables E and R are both quantified based on a life cycle approach and therefore, they are subjected to a high degree of uncertainties and variabilities, not only due to the long life span of buildings but also due to the inherent uncertainties in life cycle approaches [6]. These uncertainties should be taken into account in the analysis and hence, both variables are defined by vectors of basic random variables with respective probability density functions, as represented in Figure 1.

Figure 1. Probability density functions of the design environmental performance [$f_E(e)$] and of the reference environmental performance [$f_R(r)$]



In this case, the probability of achieving a good environmental performance, i.e. the probability of achieving an environmental performance lower than the reference one, is given by,

$$P\{f(S) \leq 0\} \tag{3}$$

This new limit state, denominated 'sustainability limit state', is complementary to the ultimate and serviceability limit states referred in the previous paragraphs.

The determination of the probability above may be solved by any of the methods described in [6] for the determination of the probability of structural failure, namely by the use of the reliability index, as described in the following paragraphs.

The limit state function $S = E - R$ is given by the sum of two variables and therefore, is also a variable. When the variables E and R are normally distributed, the variable S is also normally distributed.

The first two moments of S can be determined from the mean and standard deviations of E and R:

$$\mu_S = \mu_E - \mu_R \quad \text{and} \quad \sigma_S = \sqrt{\sigma_E^2 + \sigma_R^2} \tag{4}$$

In this case, the reliability index (β^*) is given by expression (5) and is illustrated in Figure 1.

$$\beta^* = \frac{\mu_S}{\sigma_S} \tag{5}$$

In this case, the probability of achieving a good environmental performance can be provided by the tables of the standard normal distribution:

$$P(E - R < 0) = \Phi(-\beta^*) \qquad (6)$$

where, Φ is the cumulative distribution function of the standardised normal distribution.

The distributions resulting from the uncertainty analysis of each building were found to have a shape close to a normal distribution but the resulting distribution of the set of buildings (either residential and office buildings) was not normal distributed [6]. The lack of statistical information for the buildings is currently a limitation in the application of the reliability index. Nevertheless, this limitation should be reduced by increasing the number of buildings in the sample and consequently, improving the statistical evaluation of the sampling distribution, which would then tend to be normal distributed.

The calculation of the probability given by (6) leads to an additional problem, which is the definition of an acceptable level of occurrence.

In terms of the structural safety of buildings, the target reliability index (β) for the ultimate limit state is based on an accepted fatal accident rate of 10^{-6} per year, leading to a reliability index of 4.7 [6].

However, in the case of the limit state of sustainability, a much higher probability may be acceptable since there is no direct association with fatalities. The definition of an acceptable order of magnitude is beyond the scope of this report. However, the proposed methodology can provide a sound basis for this discussion so that, in the near future, target reliability indexes (β^*) may be defined for buildings and other construction works.

2.3 Benchmarks for residential and office buildings

The calculation of benchmarks was based on the statistical analysis of buildings collected from design offices, building promoters and research centres. All collected data is referring to recent buildings, the oldest BoM refers to year 2006.

It is important to highlight that the quality and robustness of benchmarks, based on a statistical analysis, is strongly dependent on the quality and representativeness of the sample in relation to the ‘basic population’. However, the number of buildings collected in this project was not enough to enable a proper statistical analysis. In spite of this limitation, the set of values provided in the following paragraphs are used to demonstrate the approach for sustainable design described above.

The evaluation of the life cycle performance of each building was based in the LCA model described in [2] and carried out with the software GaBi (version 8.1.0.29) [9].

Benchmarks for the environmental performance of buildings are provided at different levels as indicated in Table 1. This scheme enables to include other construction works at Tier 1, such as bridges or other infrastructures, and additional building typologies at Tier 2 (e.g. industrial, educational buildings, etc.). The volume of the building is considered in Tier 3. For residential and office buildings, 4 main types of buildings are considered taking into account the number of floors of the building, as indicated in Table 1.

Tier 4 is a cross-cut level and represents the type of the structural system of the building, in terms of the main materials used in structural components and elements. The characterization of buildings at this level may not be easy, as a structural system may be composed by different materials. For example, a building with a steel-framed structure may have a significant amount of concrete in the foundations and in the horizontal structural components (slabs); while, a building with a concrete frame usually requires a considerable amount of steel for reinforcement. Hence, this classification level aims to classify the structural system taking into account the material(s) with higher mass and with higher importance in the structural performance.

Table 1. Types of buildings and classification levels

Tier 1	Tier 2	Tier 3		Tier 4	
					Reinforced concrete structure
Buildings	Residential buildings	SF	Single-family houses (SF)		
		MF	Multi-family houses (≤ 5 stories)		Steel structure
		MR	Medium rise buildings (5 – 15 stories)		Composite structure
		HR	High rise buildings (> 15 stories)		Wood structure
	Office buildings	LR	Low rise buildings (≤ 5 stories)		Masonry structure
		MR	Medium rise buildings (5 – 15 stories)		Hybrid structure
		HR	High rise buildings (> 15 stories)		Others
		TB	Tall buildings (> 60 stories)		

This project focussed on two building typologies (Tier 2): residential and office buildings. The results summarized in the following paragraphs are normalized by the Gross Floor Area (GFA) of the buildings and per year [2].

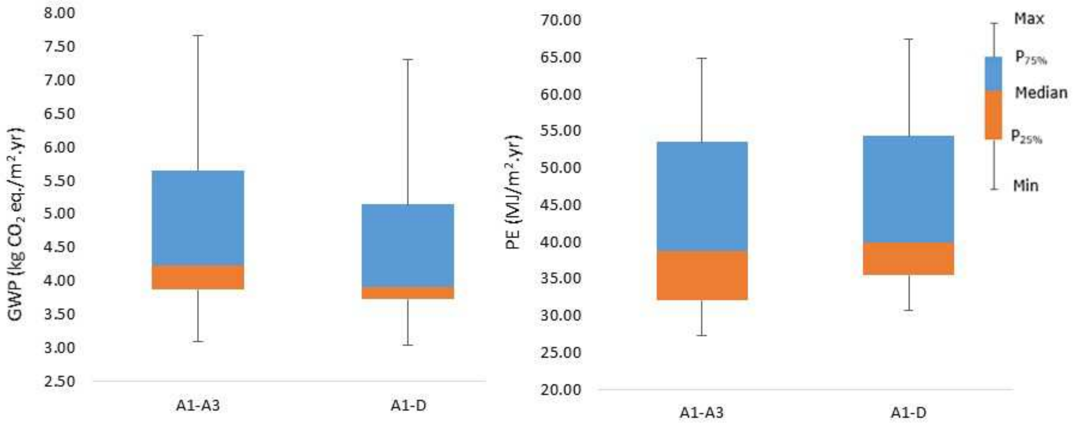
2.3.1 Residential buildings

The calculation of benchmarks for residential buildings was based on data collected for eight medium-rise buildings and a single family house.

All data collected is referring to the design stage of the buildings and to the reference period of 2006 - 2017. The BoM of the main materials used in the structural system, including the foundations, and detailed LCA calculation for each building, are given in [6]. This set of buildings may be classified in Tier 4 as reinforced concrete buildings.

A statistical analysis was performed, based on the outcome of the LCA of the buildings. Focussing on the results of the initial sages (modules A1-A3) and the results of the complete life cycle (A1-D), the respective range of values are indicated in Figure 2 for the impact categories of GWP and PE. These results are relative to Tier 2 in Table 1.

Figure 2. Range of values for GWP and PE in A1-A3 and A1-D

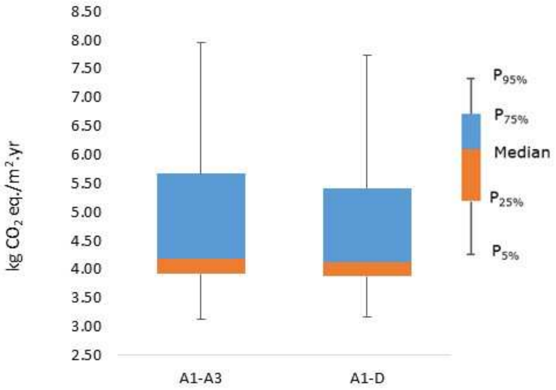


As explained in [6], uncertainties are unavoidable in a life cycle approach and neglecting them in the outcome of the analysis might lead to incorrect or biased conclusions. In relation to buildings and other construction works, this problem is even more relevant due to the usual long period of time considered in the analysis and to the complexity of this type of systems.

Hence, an uncertainty analysis of each building was carried out by Monte Carlo Simulation, Latin Hypercube sampling, considering 5000 iterations, and LCA software GaBi [9].

The resulting distribution of values for the set of buildings considered in the analysis, given by the 90% interval of confidence, is illustrated in Figure 3, for the impact category of GWP.

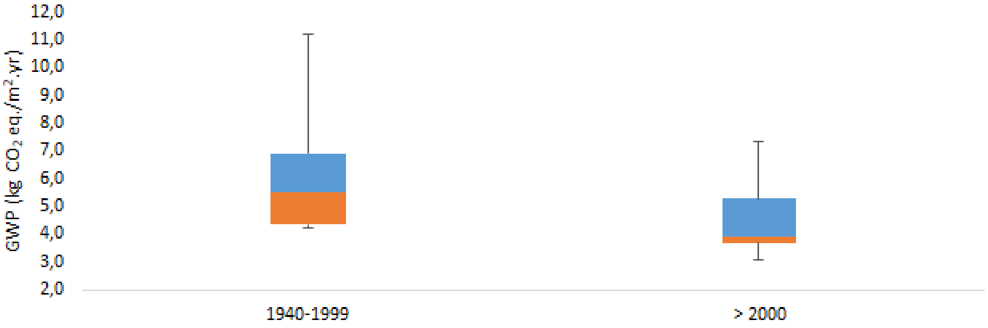
Figure 3. Distribution of values for residential buildings, in terms of GWP



It is observed that this resulting distribution is not normal distributed, in spite of the distributions resulting from the uncertainty analysis of each building have a shape close to a normal distribution (see [6]). This was already expected as the number of buildings considered in the analysis is reduced. However, it is foreseen that the resulting distribution will become normal distributed with a higher number of buildings [6].

The set of values indicated in Figure 2, which corresponds to recent buildings, is compared in Figure 4 with a preliminary set of benchmarks for residential buildings that was provided in a previous report [5]. This latter set of values was based on data representative of the existing building stock in the EU-25, retrieved from the *IMPRO-Building* project [10]. In this case, data was mostly referring to buildings from the second half of the 20th century.

Figure 4. Comparison of values (in terms of GWP and modules A1-D) referring to building data from different periods of time



As observed from Figure 4, there is a clear reduction of the values found from the two sets of buildings, in terms of median values and scatter of values. Regardless of the limitations of the analysis, this optimistic trend may be representative of some improvement over the years on the way buildings are designed, with more efficient materials and structural systems.

2.3.2 Office buildings

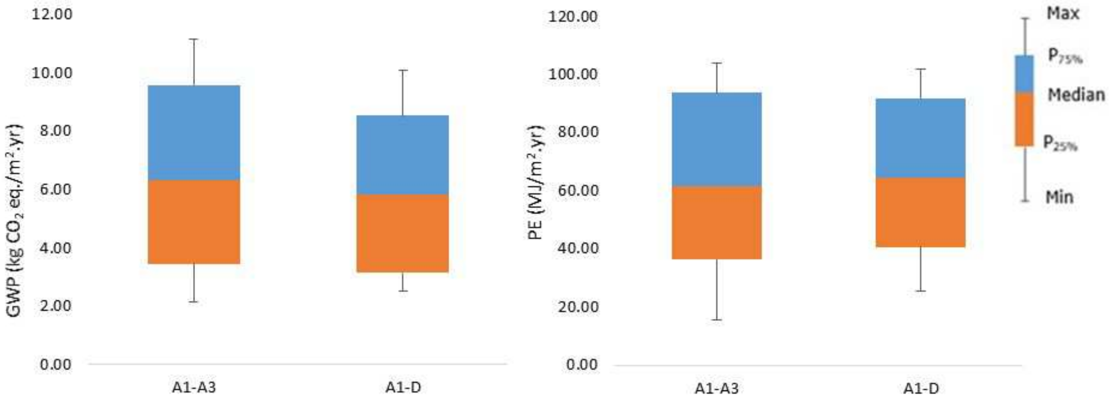
In the case of office buildings, two different types of analyses were performed. The first was based on data collected for ten buildings (two buildings were classified as medium-rise buildings and the remaining buildings fell into the category of low-rise buildings, according to Table 1); while, the second type of analysis was performed based on literature data for tall buildings.

In the first analysis, benchmarks were calculated based on the statistical evaluation of the outcome of the life cycle performance of each building, similar to the procedure for residential buildings. The BoM of the main materials and detailed LCA calculation for each building are given in [6]. Since the bill of materials for some buildings did not include the foundations, the LCA and the following statistical analysis were made considering the structural system of each building, excluding the foundations.

In relation to Tier 4, four buildings are classified as reinforced concrete buildings and the other six are classified as composite (concrete and steel) buildings.

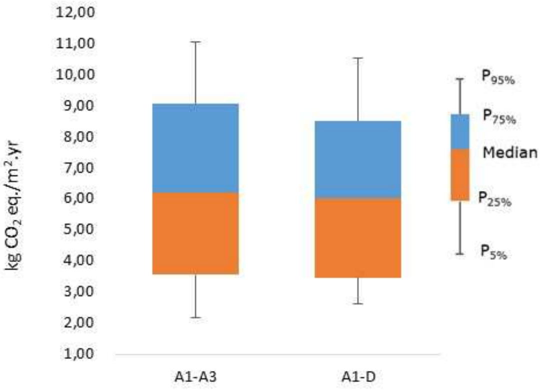
Focussing on the results of the initial sages (modules A1-A3) and the results of the complete life cycle (A1-D), the respective range of values are indicated in Figure 5 for the impact categories of GWP and PE. These results are relative to Tier 2 in Table 1.

Figure 5. Range of values for GWP and PE in A1-A3 and A1-D



Taking into account the uncertainties in the life cycle analysis of each building, the resulting distribution of values for the set of buildings considered in the analysis, given by the 90% interval of confidence, is illustrated in Figure 6, for the impact category of GWP.

Figure 6. Distribution of values for office buildings, in terms of GWP



Likewise, the resulting distribution is not normal distributed, in spite of the distributions resulting from the uncertainty analysis of each building have a shape close to a normal distribution. Nevertheless, as already referred, it is foreseen that the resulting distribution will become normal distributed by increasing the number of buildings considered in the analysis [6].

2.3.3 Synopsis of benchmarks for residential and office buildings

The benchmarks for residential and office buildings are summarized in Table 2 for the environmental category of GWP, in terms of mean/median values and percentiles (25% and 75%). These results are relative to Tier 2 level in Table 1.

Table 2. Summary of values of GWP (kg CO_2 eq./m^2.yr) for Tier 2

		A1-A3	A4-A5	C1-C4	D	A1-D
Residential buildings	Mean	4.84	0.23	0.25	-0.78	4.53
	Median	4.24	0.22	0.23	-0.78	3.91
	$P_{25\%}$	3.87	0.20	0.21	-1.07	3.73
	$P_{75\%}$	5.65	0.26	0.30	-0.51	5.15
Office buildings	Mean	6.37	0.52	0.23	-1.30	5.82
	Median	6.34	0.52	0.24	-1.26	5.85
	$P_{25\%}$	3.45	0.48	0.12	-1.94	3.15
	$P_{75\%}$	9.57	0.55	0.35	-0.87	8.53

Taking into account the volume of the building (Tier 3), the minimum and maximum values are indicated in Table 3, for each building type.

In this case, the values obtained for tall buildings are also indicated in this table. These values are normalized by a period of time of 50 years, for consistency with the other results.

Table 3. Summary of maximum and minimum values of GWP (kg CO_2 eq./m^2.yr) for Tier 3

		A1-A3	A4-A5	C1-C4	D	A1-D
Residential buildings	SF	5.61	0.12	0.26	-1.12	4.87
	MR	3.10/7.68	0.21/0.30	0.18/0.40	-1.09/-0.43	3.05/7.32
Office buildings	LR	2.14/11.16	0.47/0.60	0.08/0.47	-2.13/-0.26	2.50/10.09
	MR	4.40/6.07	0.47/0.52	0.08/0.23	-1.22/-1.12	3.83/5.61
	TB 60 floors	2.84/4.44	0.01/0.03	0.07/0.16	-1.24/-0.65	2.13/3.88
	TB 120 floors	3.81/7.44	0.02/0.04	0.05/0.20	-2.62/-0.93	3.05/5.22

In relation to Tier 4, the minimum and maximum values for each structural system are given in Table 4.

Table 4. Summary of maximum and minimum values of GWP (kg CO_2 eq./m^2.yr) for Tier 4

			A1-A3	A1-D
Residential buildings	SF	Reinforced concrete structure	5.61	4.87
	MR	Reinforced concrete structure	3.10/7.68	3.05/7.32
Office buildings	LR	Reinforced concrete structure	2.14/7.15	2.50/6.45
		Steel structure	3.68/11.16	3.26/10.09
	MR	Reinforced concrete structure	6.07	5.61
		Steel structure	4.40	3.83
	TB 60 floors	Steel frame and concrete core (1a, 1b)	3.01/3.50	2.16/2.54
		Reinforced concrete structure (2a, 2b)	2.84/4.44	2.37/3.38
		Steel structure (3a, 3b)	3.72/4.18	2.53/2.83
		Composite frame (1c, 3c)	2.96/3.85	2.13/2.69
	TB 120 floors	Steel frame and concrete core (4a, 4b)	5.56/5.78	4.00/4.15
		Reinforced concrete structure (5a, 5b)	3.81/4.83	3.05/3.93
		Steel structure (6a, 6b)	6.47/7.74	4.73/5.22
		Composite frame (4c, 6c)	4.43/4.84	3.20/3.61

As previously emphasized, the values provided in the above tables cannot be considered as representative of the building stock in the EU, as major limitations were found in terms of the availability of consistent building data and in terms of data collection. In fact, the sample used for the evaluation of such values is reduced and, *per se*, do not enable a proper statistical evaluation.

However, these values were used to illustrate the approach for sustainable design and may serve as reference for future research work.

Finally, it is observed that the values provided in Table 2 to Table 4 are limited to the structural system of buildings but it is expected that in the near future, similar values will become available for the full building, thus enhancing the efficiency of the global building sector.

3 Major achievements and limitations

The performed-based approach for sustainable design summarized in this report is freely accessible and aims for a generalized applicability. The approach is in line with current standards for structural design and relies in a 'limit state of sustainability', which is a concept familiar to engineers and architects. Hence, it fosters the use of sustainability criteria, side by side with the mandatory safety criteria.

The proposed approach has the potential to effectively improve the way buildings are currently designed by raising the attention of the professionals that have the responsibility and the power to take the right decisions at the appropriate stages of building design: the early stages. Decisions taken in these stages will affect decades in the future. The ability to positively influence the life cycle performance of the building dramatically drops as the life cycle progresses.

The stronger achievements but also the major weaknesses of the proposed approach are summarized in Table 5.

Table 5. S.W.O.T. matrix of the developed approach

Strengths	**Weaknesses**
• Sustainability design is freely accessed to all professionals and is not a privilege of a few; • Sustainable design goals may become part of the daily practice of engineers and architects and will be handled together with mandatory safety criteria; • Benchmarks provide a transparent yardstick to measure the environmental performance of buildings, striving towards an effective reduction of the use of resources and relative environmental impacts in the building sector; • Supports EU policies of resource efficiency and circular economy and EU tools (e.g. Level(s)).	• The lack of building data do not enable a proper quantification of benchmarks; • The environmental data available is still very reduced. EPDs are produced on a voluntary basis; • General community is still lacking credibility in life cycle approaches and other similar tools.
Opportunities	**Threats**
• The design of buildings will have the chance to be continuously improved and new targets may be set to reduce the use of resources in construction; • Raise the global awareness for sustainability goals; • Call for other criteria to be integrated as well (e.g. social criteria); • Development of digital platforms for data collection, supported by BIM and/or similar tools, to enable the flow of information among stakeholders.	• The lack of data related to the lifespan of buildings do not allow for proper life cycle approaches; • In general, the different professionals involved in the construction sector are not aware of the benefits of sustainable practices and are not motivated to implement such practices in the daily activity; • The lack of public demand for buildings with lower embodied energy, i.e. lower use of resources and related impacts.

The definition of benchmarks in every stage throughout the building life cycle provides a yardstick to measure the environmental performance of buildings in each stage and to pursuit measures and strategies to reduce the respective potential environmental impacts. Moreover, this provides the opportunity not only to building designers but also to all the professionals involved in the long chain of the building process (e.g. construction and demolition contractors), to benchmark the respective activities, thus improving the performance of the sector as a whole and leading to a higher competitiveness of construction related activities.

The proposed approach supports current European Policies. It ensures the full implementation of the Construction Products Regulation and complies with the strategies for resource efficiency and circular economy. The use of benchmarks for the environmental performance of buildings allows to effectively reduce the potential environmental impact of the building stock, so that the targets foreseen by the EU may become tangible in a realistic horizon of time.

The adopted life cycle approach uses the same environmental indicators as EU-*level(s)* [11], the new EU tool for reporting the sustainable building performance, and therefore, both tools are compatible. Furthermore, the developed benchmarks provide a consistent basis for interpretation of the indicators reported in EU-*level(s)*.

This project is focussed on the structural system of buildings, which is the part of the building design that civil engineers are directly involved. This limitation was mainly due to the lack of environmental data to cover the remaining building components. However, the proposed model is open and can be easily extended to include other buildings components and even other criteria (e.g. social and economic criteria).

In fact, the lack of environmental data for materials and construction related processes, and the lack of data related to the building design, construction and demolition activities, are major limitations in LCA and consequently, in the development of benchmarks based on such approaches.

Moreover, the lack of consistent and reliable data to enable a proper LCA of buildings or any other construction work, is maybe one of the reasons why the use of LCA is faced with scepticism, in particular, from the professionals outside the academic field.

Therefore, the production of EPDs or any other type of environmental data from local manufacturers is a crucial step. The information contained in an EPD provides the potential impacts of materials throughout the life cycle and therefore, it enables the calculation of the environmental impacts of buildings. The production of EPDs should be stimulated and this type of data should be promoted not only by green public procurement but also by similar initiatives in the private sector.

On the other hand, over the long life span of a building, a huge amount of data is produced in every stage. This data usually comprehends the BoM, plans and other details that are produced during the design stage; all data related to construction activities (such as the use of equipment, consumption of energy, waste produced, etc.) that take place during the erection of the building; the consumption of energy, water and materials required during the use stage of building; and finally all data related to the deconstruction of the building and management of waste.

All the above data are available at a certain point in time, but is usually lost over the lifespan of the building. In fact, the long life span of buildings and the involvement of multiple stakeholders are major constraints faced by the building sector, and are a barrier to the flow of information among stakeholders.

Among all obvious advantages that would result from the availability of such data in terms of the LCA of buildings, there are additional advantages related to the actual life cycle performance of the building. For instance, the loss of information related to the materials and type of structural system adopted in the building may prevent the optimum recovering of materials and/or other buildings components, in the end-of-life of the building.

Therefore, the development of a platform to collect all data related to the different stages over the lifespan of buildings, supported by the use of tools such as Building Information Modelling (BIM), would allow to provide a solid basis for the quantification of all types of indicators that are currently used for the assessment of the sustainability of buildings and obviously, for the quantification of consistent benchmarks.

The development of such a platform could also represent an opportunity for the building sector to overcome some of the constraints referred above and become a more integrated and competitive sector.

Over the last years a strong emphasis has been given by the EU, supported by the scientific community, to the development of approaches and tools for the sustainable assessment of buildings and other construction works. The primary focus was given to the consumption of energy during the operation stage of the building, and successful initiatives are being taken to reduce the bill of energy in buildings.

The successful achievements in reducing the operation energy of buildings made the share of embodied energy more relevant than ever.

Unfortunately, in this case, the problem is more complex, as embodied energy and related impacts are not reflected into the bill of energy paid every month by consumers. Therefore, there is a need for stronger incentives and legislative initiatives to raise the awareness of professionals to life cycle impacts of buildings and simultaneously, to raise the public demand for lower-impact buildings.

4 Conclusions

The main achievement of the project *EFIResources*: *Resource Efficient Construction towards Sustainable Design* was the development of a performance based approach for sustainable design, enabling to assess resource efficiency throughout the complete life cycle of buildings.

The proposed approach fosters the harmonization between environmental criteria and structural criteria in the design of buildings, thus leading to an enhanced building design, coping with the required safety demands but with lower pressure on the environment and on the use of natural resources. Moreover, it provides the chance for structural engineers to include environmental criteria in the decision making process of building design, thus promoting a more efficient use of resources throughout the life cycle of buildings and reducing the environmental impacts of construction works.

The approach provides major innovations with respect to other available methodologies:

- The model for the assessment of buildings is based on a standardized procedure for LCA that was developed specifically for the assessment of construction works (provided by the series of CEN TC 350 standards); thus enabling comparability and benchmarking;
- The approach is meant to be used in the early stages of design so that proper decisions, with regard to design options, can be made in the most influential stages of design;
- The methodology enables a widespread application among building designers, without the need of a great level of expertise;
- The approach for sustainability design complies with the design rules and reliability provisions of the European standards for structural design (the Eurocodes), thus enabling the harmonization between structural safety and sustainability in the design process;
- The approach addresses the new essential requirement of ‘sustainable use of natural resources’ of the Construction Products Regulation, thus ensuring full compliance with the regulation;
- The definition of benchmarks in every stage throughout the life of a building provides a yardstick to measure the environmental performance of buildings in each stage and therefore, it enables the chance for every professional involved in the building process to improve the respective activities;
- Finally, the development of benchmarks for the environmental performance of buildings will enable to establish reliable targets for the consumption of resources and other environmental goals.

The results of this project will facilitate the incorporation of sustainability criteria in construction practices consistent with the safety requirements of the design standards, thus providing building designers with an approach for safe and clean construction.

During the development of this project a major limitation was identified: the lack of environmental data relative to materials and construction processes and data related to the building design, construction and demolition.

The production of Environmental Product Declarations (EPDs) or other type of environmental data from manufacturers is a step forward. The creation of EPD databases should be stimulated and this type of data should be promoted not only by green public procurement but also by similar initiatives in the private sector.

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List of abbreviations

BoM	Bill of Materials
EDP	Environmental Product Declaration
GFA	Gross Floor Area
GWP	Global Warming Potential
LCA	Life Cycle Analysis/Assessment
LR	Low rise buildings
MCS	Monte Carlo Simulations
MR	Medium rise buildings
PE	Primary Energy
$P_{25\%}$	25th percentile
$P_{75\%}$	75th percentile
SF	Single family houses
TB	Tall buildings

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