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To cite this article: Helena Gervasio 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **225** 012057

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 642384.



The role of resource efficiency towards circular economy

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Abstract. The use of natural resources for building construction represents, in terms of mass, one of the biggest challenges in resource consumption. On the other hand, construction and demolition waste is one of the most important waste streams generated in the EU, about 25% - 30% of all waste generated in the EU, and consists of numerous materials with potential for recycling. Recently, a research project *EFIResources* was completed, which focussed on the development of a performance based approach for sustainable design, enabling to assess resource efficiency of buildings, in the early stages of building design, and supporting European policies related to resource efficiency and circular economy. Therefore, the main aim of this paper is to present the developed approach, which is based on the benchmarking of the environmental performance of buildings, in a life cycle perspective. Moreover, this paper includes a discussion of the different methods that are available for the allocation of credits and/or debits due to the recycling process, between the system producing the secondary materials and the system receiving them, in line with current EU policies.

Keywords: LCA, buildings, allocation, resource efficiency, benchmarks, circular economy.

1. Introduction

The project *EFIResources: Resource Efficient Construction towards Sustainable Design*, focussed on the development of a performance based approach for sustainable design, enabling to assess resource efficiency throughout the lifetime of buildings. In this project, resource efficiency is understood as a reduction of the consumption of natural resources and the production of waste against current values, throughout the life cycle of the building. Therefore, resource efficiency is directly linked to the life cycle environmental performance of buildings and thus, by reducing this, it will ensure a better use of resources and a better management of waste.

The proposed approach aimed at 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].



Furthermore, the proposed approach aimed for 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 with a reference value or benchmark, represented by the average value of the life cycle environmental performance of buildings with the same typology, in a given area.

Analogously, to comply with the goal of the proposed approach for sustainable design, the environmental performance of the building being assessed should be lower than the reference value to ensure a better environmental solution.

Furthermore, besides supporting the EU policies related to resource efficiency [2][3] and circular economy [4], the proposed approach complies with the new EU tool level(s), for reporting the sustainable building performance [5], by providing a valuable aid in the interpretation of the indicators addressing the life cycle environmental performance of buildings.

The main aim of this paper is to present the developed approach. However, first the adopted model for life cycle assessment (LCA) of buildings is briefly described, which is based on the standardized framework for LCA developed by CEN TC 350 to ensure comparability and benchmarking. In addition, this first part of the paper includes a discussion of the different methods that are available for the allocation of credits and/or debits due to the recycling process, in line with current EU policies.

Then the second part of the paper, introduces the performance based approach for sustainable design that is in line with current standards for the structural design of buildings. This part includes two sets of benchmarks for residential and office buildings, which were calculated based on the statistical analysis of real building data collected from design offices building promoters and research centres.

Final conclusions are drawn in the end of the paper.

It is observed that the approach for sustainable design presented in this paper is limited to the structural system of buildings. However, the scope of the approach is open and may easily be extended to account for other building components. Hence, hereafter, for simplification, when reference is made to building(s), it should be interpreted as the structural system of building(s).

2. Life cycle assessment of buildings

2.1. Goal and scope of the model

The development of benchmarks for the life cycle performance of buildings should rely on a consistent model, ensuring comparability between the assessments of different buildings [6].

Hence, the adopted model for the Life Cycle Assessment (LCA) of buildings is based on the standardized framework for LCA developed by CEN TC 350 for the sustainability assessment of construction works, provided by EN 15804 [7] and EN 15978 [8]. The adoption of a standardized procedure ensures comparability between different building assessments and benchmarking.

All details about this model and all the assumptions and scenarios that are required to perform the life cycle analysis of buildings, are provided in [6]. In the following paragraphs, a brief summary of the model is provided, focussing on the most relevant aspects.

The functional equivalent considered in the model is the structural system of a building, designed to fulfil the specific safety requirements of residential or office buildings, during the period of time considered in the analysis. The results of the life cycle analysis, for each environmental category, are provided for the functional equivalent, which is normalized by the Gross Floor Area (GFA) of the building and per year, as given by the following expression [6]:

$$\text{Building performance for environmental category } i = \frac{\text{Environmental result } i}{\text{GFA} \times \text{Ref. period of time}} \quad (1)$$

The scope of the analysis takes into account the complete life cycle of the building, from the product stage (Modules A1-A3) to the end-of-life stage (Modules C1-C4 and D). Modules B6 and B7, which are related to the operation of the building, are not included in the analysis.

Module D, which allocates net benefits due to recycling and/or recovery processes, is required to close the loop of materials and building components, as envisaged by current EU policies. Therefore, in the adopted model, Module D is considered a mandatory stage in the life cycle analysis of buildings. This is a deviation from CEN TC 350 standards, which consider Module D an optional stage in the LCA of buildings. Module D is further discussed in the following sub-section of the paper.

The aim of the proposed approach for sustainable design is to make a more efficient use of natural resources in buildings and other construction works. However, no single indicator is currently appropriate to represent the burdens associated with the use of resources in construction systems [1]. Instead, the extraction, production, use and waste of resources are better assessed by a set of indicators describing the different environmental problems linked with these activities.

Hence, the environmental indicators adopted from the life cycle analysis are based on the set of environmental categories provided by EN 15804 and EN 15978, which include indicators focussing on impact categories using characterisation factors and indicators focussing on environmental flows.

In the calculation of the benchmarks, the indicators describing environmental impacts considered for the performance of buildings are listed in Table 1.

Table 1. Indicators describing environmental impacts

Indicator	Abbreviation	Unit
Global Warming Potential (excluding biogenic carbon)	GWP _{exc}	kg CO ₂ eq.
Global Warming Potential (including biogenic carbon)	GWP	kg CO ₂ eq.
Depletion potential of the stratospheric ozone layer	ODP	kg CFC 11 eq.
Acidification potential of land and water	AP	kg SO ₂ - eq.
Eutrophication potential	EP	kg PO ₄ ³⁻ eq.
Formation potential of tropospheric ozone photochemical oxidants	POCP	kg C ₂ H ₄ eq.
Abiotic Resource Depletion Potential of fossil fuels	ADP _f	MJ, n.c.v. (*)

(*) net calorific value

It is noteworthy that the impact category of ADP based on ultimate reserve (as given in EN15804 and EN15978) is not considered in the analysis. The main reason for this is due to the lack of characterization factors for most common raw materials required for the production of construction materials leading to bias results, particularly in comparative assertions [6].

Nevertheless, it is observed that the above LCA model is open and additional indicators can be added whenever relevant.

2.2. Allocation procedure for recycling materials

Recycling plays an important role towards the efficiency of resources in construction. In this case, an allocation procedure is required to allocate the burdens and credits due to recycling processes between the primary system and the secondary system.

In the literature, three different types of allocation procedures are generally considered [1]: (i) the recycled content approach; also known as the ‘cut-off’ rule or the 100:0 method; (ii) the avoided impact approach; also known as the substitution method or the 0:100 approach; and (iii) the 50:50 method, which may be considered as a compromise between the above approaches.

In addition, according to EN 15804, the net environmental benefits or loads due to recycling, reuse or energy recover are allocated in Module D. Net impact has a twofold meaning: (i) in relation to environmental impacts, net impact is the difference between the impacts due to the recycling process which substitutes primary production (E_R^*) and the impacts due to the production of the avoided primary material (E_V^*); and (ii) in relation to mass, net impact is the difference between the output of secondary material from the system (RR) and the input of secondary material to the system (R_C). It is noted that secondary material may only be considered as substituting primary production when it reaches the functional equivalence of the substituted primary material [7]. Hence, a value-correction factor (C_f) is adopted to reflect the differences in the functional equivalence of the secondary material in relation to the substituted primary material.

All the above procedures are summarized in Table 2 according to the modular concept of EN15804, where the E_V , E_R and E_D are the environmental burdens arising from the acquisition and pre-processing of virgin material, from the recycling process of the recycled material and from disposal of waste material at the end of life stage, respectively.

Table 2. Relation of other allocation approaches with Module D [6]

Approach	Modules A1 – A3	Modules C1 – C4	Module D
100% - 0%	$[(1 - R_C)E_V + R_C \times E_R]$	$[(1 - RR)E_D]$	-
50% - 50%	$\left[\left(1 - \frac{R_C}{2}\right)E_V + \frac{R_C}{2} \times E_R\right]$	$\left[\left(1 - \frac{RR}{2}\right)E_D\right]$	$\frac{RR}{2}(E_R^* - E_V^*)$
0% - 100%	E_V	$[(1 - RR)E_D]$	$RR(E_R^* - E_V^*)$
Module D ^(*)	$[(1 - R_C)E_V + R_C \times E_R]$	$[(1 - RR)E_D]$	$(RR - R_C)(E_R^* - E_V^* \times C_f)$

(*) Module D with a value-correction factor

The adoption of an allocation approach should be consistent with the goals and scope of the life cycle study. In the scope of the proposed approach, both the use of materials with recycled content and materials with potential for reuse, recycling or recover are encouraged. A sustainable design of a building should consider both types of materials. This means that both present and future impacts are important and neither should be neglected in a LCA, obviously avoiding the double counting of impacts.

As observed from Table 2, only Module D takes advantage of both the recycling content and the potential for recycling, simultaneously. Therefore, in the scope of the proposed approach, only Module D was considered to be appropriate for the allocation of credits and debits to the product system.

On the other hand, it is important to report the results in a transparent manner, both in terms of assumptions and results. Hence, the aggregation of results is not recommended and the results should be provided in relation to the stage they are related, which is the case of CEN standards.

3. Performance based approach for sustainable development

3.1. 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 [9]: 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 [10].

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 [11]. 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, described in the following paragraphs, allows to satisfy this new essential requirement, thus providing the possibility to fill the gap of the present regulation.

3.2. Limit state of sustainability

As described above, the structural design of buildings according to current European standards is based on the limit state concept.

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 [10].

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 (2)

$$E \leq R \quad (2)$$

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

$$S = E - R \leq 0 \quad (3)$$

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 [10]. 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.

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,

$$P\{f(S) \leq 0\} \quad (4)$$

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 [10] for the determination of the probability of structural failure, namely by the use of the reliability index, as described in the following paragraphs.

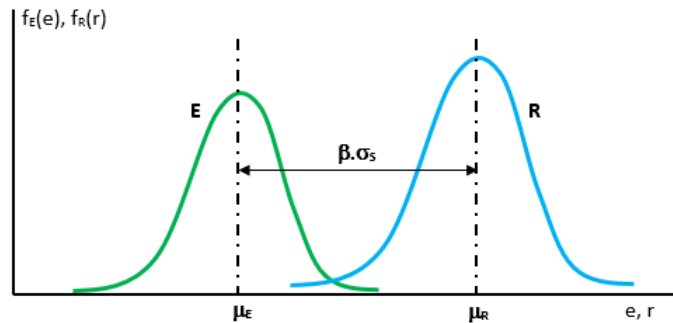


Figure 1. Probability density functions of the design environmental performance [$f_E(e)$] and of the reference environmental performance [$f_R(r)$] [10].

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 :

$$\mu_S = \mu_E - \mu_R \quad \text{and} \quad \sigma_S = \sqrt{\sigma_E^2 + \sigma_R^2} \quad (5)$$

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

$$\beta^* = \frac{\mu_S}{\sigma_S} \quad (6)$$

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

$$P(E - R < 0) = \Phi(-\beta^*) \quad (7)$$

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

The calculation of the probability given by (7) 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 [10].

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 project. 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.

3.3. Benchmarks for residential and office buildings

Benchmarks were calculated for residential and office buildings based on the statistical analysis of real building data collected from design offices building promoters and research centres [12]. All collected data refers to recent buildings as the oldest BoM corresponds to year 2006. It is observed that the number of buildings collected does not enable a proper statistical analysis. However, in spite of this limitation, benchmarks were calculated to illustrate the approach for sustainable design, described above.

The LCA of each building was carried out based on the model described in the first part of this paper.

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, a framework to deal with the uncertainties in the LCA of buildings was considered, aiming to address most types of uncertainties of buildings, over the different stages [10]. Probability distribution functions were assigned to the most relevant input parameters and the uncertainty propagation was carried out by the use of a sampling propagation method.

Therefore, the uncertainty analysis of each building was performed by Monte Carlo Simulation, Latin Hypercube sampling, with the LCA software GaBi (version 8.1.0.29) [13]. 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 2, for the impact category of GWP. The results are provided for the initial stages (modules A1-A3) and for the complete life cycle (A1-D).

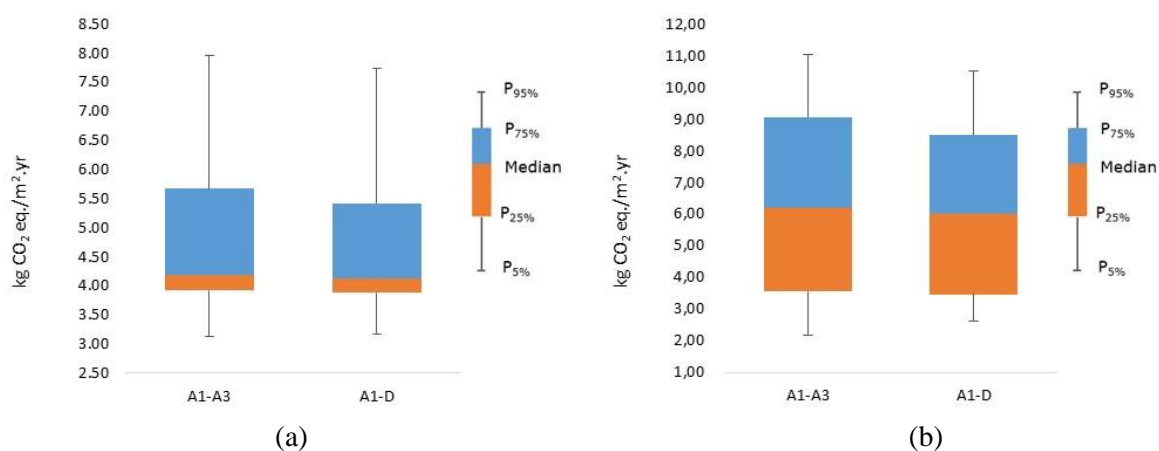


Figure 2. Distribution of values for GWP in (a) residential buildings and (b) office buildings [10]

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 [10]. The lack of statistical information for the buildings is currently a limitation in the application of the reliability index proposed above. 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.

4. Conclusions

The performance based approach for sustainable design developed in the project *EFIResources* enables to assess resource efficiency throughout the complete life cycle of buildings and aims for the harmonization between structural design and sustainability design of buildings.

The approach is based on 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.

The proposed approach has a twofold achievement. In one hand, by providing a reference value for the environmental performance of buildings, it enables an easier interpretation of the performance of any given building and the identification of best practices, thus motivating the pursuit of measures leading to an enhanced building performance. On the other hand, the introduction of benchmarks provides a transparent yardstick to measure the environmental performance of buildings and will allow 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.

Finally, it is observed that the values provided in this report cannot be considered as representative of the current 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. The lack of building data and environmental information about materials and processes are, in fact, the major limitations of the proposed approach. This emphasizes the need to promote the production of such data, to allow for the consistent implementation of LCA-based approaches.

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Acknowledgments

This research was supported by the European Union, under Marie Curie Individual Fellowship H20-20-MSCA-IF-2015, contract no. 707532.

A special acknowledgment to Dr. Silvia Dimova and Dr. Artur Pinto for their kind hospitality in JRC-Unit E.4, Italy, and support throughout the development of the work.