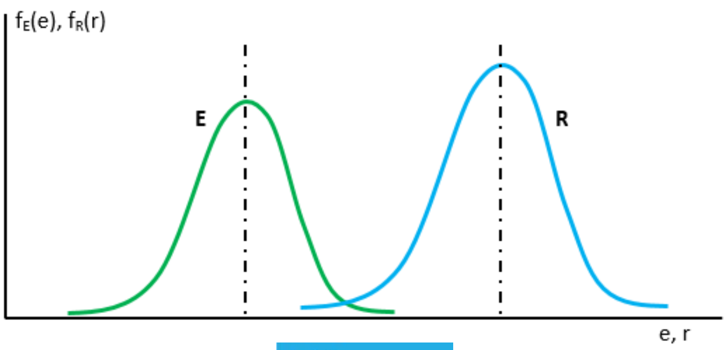
JRC TECHNICAL REPORTS

Sustainable design of buildings

***EFIResources**:*
Resource Efficient Construction towards Sustainable Design

Gervasio, H.

2018



EUR 29324 EN

This publication is a Technical report by the Joint Research Centre (JRC), the European Commission's science and knowledge service. It aims to provide evidence-based scientific support to the European policymaking process. The scientific output expressed does not imply a policy position of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use that might be made of this publication.

Contact information
Name: Silvia Dimova
Address: European Commission, Joint Research Centre, Directorate E, Unit E.4
Email: silvia.dimova@ec.europa.eu
Tel. : +39 0332 78 9063

JRC Science Hub
https://ec.europa.eu/jrc

JRC112808

EUR 29324 EN

PDF	ISBN 978-92-79-92882-6	ISSN 1831-9424	doi:10.2760/356384
Print	ISBN 978-92-79-92883-3	ISSN 1018-5593	doi:10.2760/353376

Ispra: European Commission, 2018

How to cite this report: Gervasio, H., Sustainable design of buildings , EUR 29324 EN, Publications Office of the European Union, 2018, ISBN 978-92-79-92882-6, doi:10.2760/356384, JRC112808.

Contents

Acknowledgements

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 and support throughout the development of this work.

In addition, the author would like to acknowledge Prof. Luis Simoes da Silva, from the University of Coimbra, for his professional guidance and constructive recommendations and Dr. Thierry Maras, from EC-JRC Unit I.1, for his valuable support in the development of this work.

The author would like to thank the following persons for the assistance and support in the development of this project (in alphabetic order):

Ms Athina Papakosta, Sturgis carbon profiling, UK;

Dr. Heiko Trumpf, bollinger-grohmann, Germany;

Prof. Jose Guilherme, University of Rio de Janeiro, Brazil;

Prof. Luis Costa Neves, STRUCAD, Portugal;

Ms Malgorzata Wrobel, EC-JRC, Italy;

Prof. Milan Veljkovic, University of Delft, the Netherlands;

Ing. Rijk Blok, University of Eindhoven, the Netherlands;

Prof. Viorel Ungureanu, University of Timisoara, Romania.

Author

Helena Gervasio

Abstract

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

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

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 (ultimate limit state) or admissible deformation (serviceability limit state) and safety is ensured when the load effect is lower than the reference value.

Analogously, 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 the stock of buildings, in a given area. In this case, the environmental performance of the building being assessed should be lower than the reference value to ensure a better environmental solution.

The proposed approach has a twofold achievement: (i) by providing a benchmark 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; (ii) the introduction of benchmarks for the environmental performance of buildings, which should to be updated over time, strives towards an effective reduction of the use of resources and relative environmental impacts in the building sector, so that the targets foreseen by the EU may become tangible in a realistic horizon of time.

The performance based approach for sustainable design is fully described in this report, including the definition of a set of benchmarks for residential and office buildings. At the end of the report, the limit state of sustainability is introduced, which aims to complement the limit states for structural performance that are provided in current standards and referred to in the text above

1 Introduction

The built environment has a huge responsibility on the depletion of natural resources and on the production of a major waste stream in the EU.

By 2020, it is expected that all buildings will be highly material efficient and 70% of non-hazardous construction and demolition waste (C&DW) will be recycled [1]. Complying with these targets requires that the extraction of natural resources for the production of construction materials and the production of C&DW are reduced against the current rates of 50% and 30% (in the EU), respectively. Moreover, to fulfil such expectations, it is required to take into account, on a routine basis, the use of natural resources and the production of C&DW in the design of buildings and to take the necessary steps to improve construction related activities over the complete life cycle of buildings.

Unfortunately, this is not a generalized practice in construction as the environmental burdens related to construction activities are usually neglected.

In spite of all available market-driven green-labelling schemes for buildings, this type of systems has not succeeded in achieving a generalized enhancement of the built environment [2]. Although such systems should be praised for raising the awareness of the general public to the environmental problems of buildings and other construction works, they have a limited influence on the sector and they are only accessible to a few privileged users.

However, to fulfil the above goals, the pursuit of a sustainable design should not be a privilege of a few but a commitment from all stakeholders in the construction sector.

The project *EFIResources*: *Resource Efficient Construction towards Sustainable Design*, focusses 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 aims 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 [3].

The proposed approach aims 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 the stock of buildings, 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.

Hence, 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. It is noted that the interpretation step is the last step of a life cycle analysis and without a benchmark and/or target value to enable a proper comparison, the interpretation is meaningless.

On the other hand, the introduction of benchmarks for the environmental performance of buildings, which should be updated over time, 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.

Furthermore, besides supporting the EU policies related to resource efficiency [1][4] and circular economy [5], the proposed approach complies with the new EU tool *level(s)*, for reporting the sustainable building performance [6], by providing a valuable aid in the interpretation of the indicators addressing the life cycle environmental performance of buildings.

This report focuses on the development of the performance-based approach for sustainable design. However, in order to enable the analogy between structural design and sustainable design, a brief introduction to the approach and concepts of structural design is provided in the following section of this report (Section 2).

The proposed methodology takes into account the complete life cycle of buildings. However, in a Life Cycle Analysis (LCA), uncertainties and variabilities are unavoidable. In relation to buildings and other construction works, this problem is even more relevant due to the usual long period of time considered for the analysis (usually above 50 years) and to the complexity of this type of systems. Uncertainties should be properly addressed in a LCA, otherwise the outcome of the analysis might lead to incorrect or biased conclusions. Therefore, a framework to address uncertainties in the life cycle analysis of buildings is introduced in Section 3.

The performance based approach for sustainable design is introduced in Section 4. In this section, apart from the introduction of a new 'limit state of sustainability', benchmarks are provided for residential and office buildings. The major achievements but also the main limitations of the proposed approach are discussed in the end of this section.

Final conclusions and other remarks are provided at the last section of the report.

2 Safety assessment of building structures

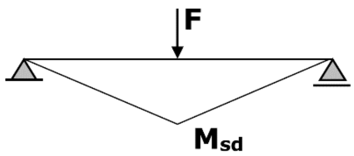
A detailed overview of the structural design of buildings is beyond the scope of this report. However, in the following paragraphs, the most important aspects of structural safety are briefly presented, to allow establishing the analogy between the structural design of buildings and the proposed approach for sustainable design, which will be provided in Section 4 of this report.

Therefore, the main goal of this section is to briefly introduce the general procedure for the structural assessment of construction works in the codes for structural design. Special emphasis is given to the European standards for structural design – the Eurocodes.

2.1 Limit state functions in structural design

Many problems in civil engineering can be described by the comparison of two variables: a variable representing the effect of an action (S) and a variable representing the capacity or resistance of a member (R). For example, a beam under the effect of a concentrated load applied at mid span leads to a triangular bending diagram as illustrated in Figure 1.

Figure 1. Bending diagram of a simple supported beam



Assuming that the cross-section of the beam is constant over the entire span, the safety of the beam, in terms of bending, is checked by comparing the bending moment at mid span (M_{sd}) due to the applied load, to the bending resistance of the beam (M_{rd}). In this case, the safety condition is satisfied when $M_{rd} \geq M_{sd}$.

Hence, in general, the safety condition is given by expression (1)

$$R \geq S \tag{1}$$

Defining the function G = R - S, failure occurs when,

$$G = R - S < 0 \tag{2}$$

Function G is called a limit state function and separates satisfactory and unsatisfactory states of a structure.

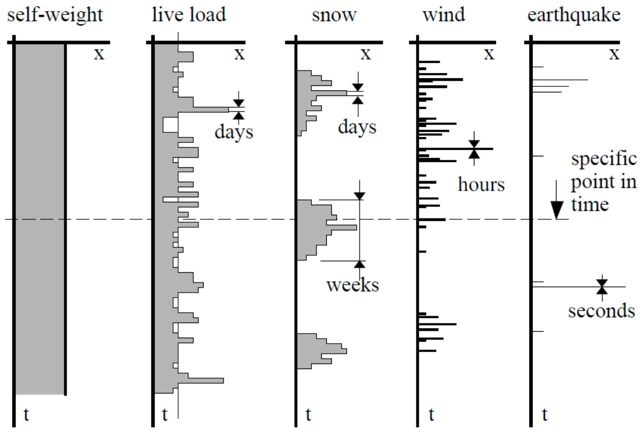
Each limit state is associated with a certain performance requirement imposed on a structure and generally two types of limit states are recognized [7]: Ultimate Limit States (ULS) and Serviceability Limit States (SLS). The former are associated with the collapse or other identical forms of structural 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.

In real life engineering problems, it is not possible to avoid uncertainties and therefore, design rules are calibrated so that the variability of the uncertainty incorporated in those rules leads to safe-sided results.

For instance, taking into account expression (2), the structural resistance (R) can be expressed by a combination of three different variables: (i) a variable addressing model uncertainties, which takes into account the deviations between analysis and experimental tests; (ii) a variable that considers the differences between the properties of the materials obtained by tests and the properties of materials when applied in a structure; and (iii) a variable that takes into account the variability in the measurement of the geometrical properties.

On the other hand, loads may in general be considered stochastic processes, as illustrated in Figure 2.

Figure 2. Different actions for structural design (extracted from [8])



Apart from the self-weight, which may be regarded as constant over time, all the other loads vary over time with different characteristics. For example, short term live loads have a duration of hours or days; while, earthquakes have a period of strong motion in the order of several seconds. Moreover, the effect of actions upon a structure (S) is usually determined by the combination of different simultaneously actions and different rules are used to determine this effect [8].

Hence, all variables included in the design of structures may be considered as random variables and therefore, the limit state condition, separating the acceptable region from the failure region, can be formulated by the following equation:

$$G(a_0, X_1, X_2, \dots, X_n) = 0 \tag{3}$$

where X_i represent the random variables describing the problem and the requirements for the basis of assessment.

In this case, failure is given by

$$G(a_0, X_1, X_2, \dots, X_n) < 0 \tag{4}$$

and the probability of failure (p_f) may be determined by

$$p_f = P[G(X_i)] \leq 0 \tag{5}$$

The methods available for the determination of the probability of failure may be split into three levels, each method having its own level of sophistication. Starting from the lower level of sophistication:

- Level I – In this case, each variable is introduced by a single value, the so-called design value, which is obtained by the use of partial factors. In this case, the probability of failure is not calculated and only some defined target level is checked;

- Level II – Approximate analytical methods such as First Order Reliability Method (FORM);
- Level III – Limit state functions and distribution functions for the random variables are introduced without any approximation; calculations are made directly by numerical integration or are based on Monte Carlo simulations.

Level I method is the basis for most design and assessment procedures, in every day practice, and is usually referred to as the semi-probabilistic level. In this case, partial safety factors are determined either by statistical evaluation of experimental data or by a calibration based on experience derived from a long building tradition [9]. The approach considered in the European codes for structural assessment (the Eurocodes) falls under this category of methods and further details are provided in Sub-section 2.3. However, it is noted that additionally, the Eurocodes allow to take a full probabilistic approach for the verification of the structural reliability.

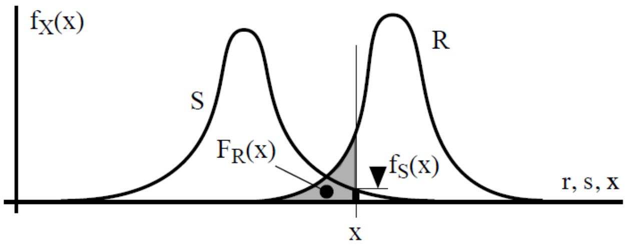
Moreover, the calibration of partial factors can be performed based on full probabilistic methods or on First Order Reliability Method (FORM) [9]. The next sub-section focusses on these approaches.

2.2 Reliability-based analysis

2.2.1 Level III approaches

In a full probabilistic approach, the variables in expression (2) are considered with their distribution types and their respective parameters, as illustrated in Figure 3.

Figure 3. Probability density functions of R and S (extracted from [8])



The classical solution for the determination of p_f is provided by numerical integration:

$$p_f = \int_{-\infty}^{+\infty} f_S(x). F_R(x). dx = 1 - \int_{-\infty}^{+\infty} F_S(x). f_R(x). dx \quad (6)$$

This integral, known as the 'convolution integral' can only be solved for certain simple cases.

As an alternative, Monte Carlo simulations (MCS) may be used. MCS replace the exact or approximate calculation of the probability density of an arbitrary limit state function by the statistical analysis of a large number of individual evaluations of the function using random realisations (x_{ik}) of the underlying distributions (X_i).

Each set of k realisations introduced into the limit state function leads to a number,

$$g_k = G(a_0, x_{1k}, x_{2k}, \dots, x_{nk}) \quad (7)$$

The resulting z numbers g_k are evaluated statistically and the number of failures (z_0) is counted. Hence, the probability of failure is given by,

$$p_f = \frac{z_0}{z} \tag{8}$$

It is noted that the greater the number of z, the more reliable is the value of p_f.

Hence, MCS usually require a huge computational effort. In order to reduce this effort, a number of methods may be used (e.g. Latin Hyper cube) to reduce the dimensions of the sample, by focussing on the area of the limit state function where failure is most likely to occur.

Full probabilistic methods are increasingly used in the calibration of design codes as statistical characterization of the basic random variables (e.g. material properties, geometry, etc.) becomes available [10][11].

2.2.2 Level II approaches

In level II approaches, an alternative measure of reliability is defined by the use of the reliability index (β), as described in the following paragraphs.

The limit state function G = R – S is also called the safety margin (M). Hence, considering M = R – S, the safety margin is given by the sum of two variables and therefore, is also a variable. When the variables R and S are normally distributed, the variable M is also normally distributed.

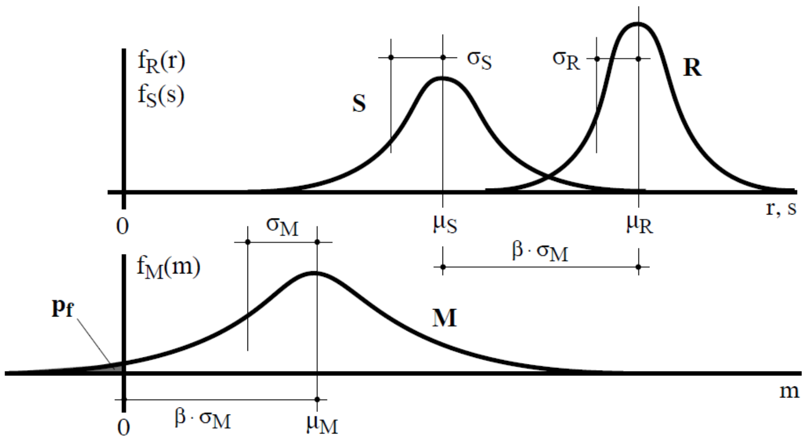
The first two moments of M can be determined from the mean and standard deviations of R and S:

$$\mu_M = \mu_R - \mu_S \quad \text{and} \quad \sigma_M = \sqrt{\sigma_R^2 + \sigma_S^2} \tag{9}$$

The reliability index is given by expression (10) and is illustrated in Figure 4.

$$\beta = \frac{\mu_M}{\sigma_M} \tag{10}$$

Figure 4. Safety margin M and reliability index β (extracted from [8])



From Figure 4, it is observed that the reliability index (β) indicates how often the standard deviation of the random variable M may be placed between zero and the mean value of M. Assuming normal distributed variables, the probability of failure can be provided by the tables of the standard normal distribution:

$$p_f = P(M = R - S < 0) = \Phi(-\beta) \tag{11}$$

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

The definition of the acceptable or target reliability index is provided in the following paragraphs.

2.3 Partial factor method

Following the treaty of Rome, the European Commission took the initiative to establish a set of harmonized technical rules for the structural design of buildings and other civil engineering works. The main aim of these harmonized codes, the Eurocodes, was to eliminate technical obstacles to trade in Europe.

The Eurocodes are thus a series of EN standards (EN 1990 to EN 1999) that have been adopted as national standards by most EU Member States (MS). However, to take into account for differences in geographical or climatic conditions, ways of life or even different levels of protection at the national level, each MS has the right to specify, in a National Annex, the corresponding values, classes or alternative methods.

The basic document in the series of standards is EN 1990 [7]. This standard provides the procedure for the safety assessment of structures that is based on the partial safety method (level I approach).

According to this method, uncertainties are accounted separately on the action and on the resistance sides, and they are reflected by partial factors. Hence, for every relevant design situation, safety factors are used on the loading side and on the resistance side to account for the respective uncertainties. The design is considered adequate when the appropriate limit state is verified, i.e.:

$$R_d \geq E_d \tag{12}$$

where, R_d and E_d are the design values of the resistance and of the actions, respectively, given by,

$$E_d = E\{F_{d1}, F_{d2}, \dots a_{d1,} a_{d2,} \dots \theta_{d1}, \theta_{d2}, \dots\} \tag{13}$$

$$R_d = R\{X_{d1}, X_{d2}, \dots a_{d1,} a_{d2,} \dots \theta_{d1}, \theta_{d2}, \dots\} \tag{14}$$

where, *F* represents actions; *X* material properties, *a* geometric properties and θ model uncertainties.

Design values are calibrated based on FORM and partial factors for resistance and for actions are derived based on:

$$P(E > E_d) = \Phi(+\alpha_E \beta) \tag{15}$$

$$P(R \leq R_d) = \Phi(-\alpha_R \beta) \tag{16}$$

where, β is the target reliability index, α_E and α_R are the coefficients representing the scatter due to loading and resistance, respectively.

According to Gulvanessian et al. [12] 'the target reliability index or the target failure probability is the minimum requirement for human safety from the individual or societal point of view when the expected number of fatalities is taken into account'. For instance, based on an accepted fatal accident rate of 10^{-6} per year, this leads to a reliability index β of 4.7.

The level of safety in EN1990 is chosen according to Consequence Classes (CC), which establish the reliability differentiation of the code by considering the consequences if failure or malfunction of the structure. The CC correspond to Reliability Classes (RC), which define the target reliability level through the reliability index (β).

Residential and office buildings are classified as CC2, according to EN1990, which correspond to medium consequence for loss of human life, economic, social or environmental consequences considerable. Thus, for CC2 and consequently RC2, the recommended minimum values of β for ultimate and serviceability limit states are indicated in Table 1 for design periods of 1 year and 50 years.

Table 1. Target reliability index (β) for Class RC2 structural members

Limit state	Target reliability index (β)	
	1 year	50 years
Ultimate	4.7	3.8
Serviceability	2.9	1.5

The limit state approach briefly described in the above paragraphs will be adopted for the sustainable design of buildings, as described in Section 4 of this report.

Hence, references to this section will often be made, in particular, when establishing the analogy between structural design and sustainable design.

3 Uncertainties in life cycle assessment of buildings

In the previous section, the uncertainties inherent to the structural design of buildings were introduced and the methods to address such uncertainties were briefly described.

Likewise, uncertainties are unavoidable in a life cycle approach and neglecting them in the outcome of the analysis might lead to incorrect or biased conclusions [1][14][15]. 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.

Moreover, when LCA is used as an aiding tool for decision making, the quality of the decision-based information should be clear [16] to ensure that sound decisions are made.

In the following paragraphs, a description of the main uncertainties and variabilities in LCA is provided, followed by the framework adopted to address them in the context of LCA of buildings.

3.1 Type of uncertainties

In general, the sources of uncertainty may be classified into two broad types: aleatory and epistemic. Aleatory uncertainty is the uncertainty associated with the randomness of the underlying phenomenon that is exhibited as variability in the observed information; whilst epistemic uncertainty is the uncertainty associated with imperfect models of the real world due to insufficient data or imperfect knowledge of reality [17]. Both types of uncertainty are usually presented in life cycle analysis.

Huijbregts [18] distinguishes between uncertainty and variability to address the epistemic and aleatory uncertainties, respectively. According to the author, uncertainty in LCA is divided into:

- parameter uncertainty – imprecise measurements, incomplete or outdated measurements, and general lack of data in the inventory analysis and in the models;
- model uncertainty – spatial and temporal characteristics are forgotten in the inventory analysis, simplified and linear (instead of non-linear) models;
- uncertainty due to choices – choice of the functional unit, allocation procedure, characterisation methods, weighting, etc.;
- spatial variability – variability across locations, such as physic-chemical and ecological properties of the environment, background concentrations of chemicals and human population density, is generally not taken into account;
- temporal variability – differences in emissions over time;
- variability between objects/sources – variability caused by different inputs and emissions of comparable processes in a product system, for instance, due to the use of different technologies in factories producing the same material.

Other classifications of uncertainties have been suggested in the literature. However, as emphasised by Heijungs and Huijbregts [16], more important than classifying uncertainties is to distinguish between sources and sorts of uncertainties and it is the sorts of uncertainty that determine the choice of the approach to deal with uncertainty.

Throughout the following paragraphs, the term "uncertainty" will be used to refer both to aleatory and epistemic uncertainties in life cycle analysis, unless otherwise indicated.

The evaluation of the types of uncertainty, and to what extent the outcome of a life cycle analysis is affected by them, is an issue that has been addressed over the last years by different authors.

Most studies focussed on specific types of uncertainty in individual stages of LCA. For instance, the evaluation and discussion of uncertainties in the inventory stage may be found in [19][20][21][22][23]. Other authors discussed the outcome of a LCA based on the use of different Life Cycle Impact Assessment (LCIA) methods [24][25][26][27].

Only a few studies attempt to assess the simultaneous effect of several types of uncertainties in the result of LCA. A methodology taking into account simultaneously parameter, scenario and model uncertainties was proposed by Huijbregts et al. [1], although the weighting and normalisation steps of LCA were not considered. The evaluation of uncertainties and variabilities in the inventory flows and LCIA, based on a case study, was also performed by Geisler et al. [28]. Hung and Ma [29] proposed a methodology to analyse the uncertainties involved in the LCI, LCIA, normalisation and weighting steps of LCA. In this study, uncertainties in the LCI stage were considered by the introduction of probabilistic distributions, whilst the uncertainty in the remaining stages was evaluated by the use of different available methodologies for LCIA and relative values of normalization and weighting. More recently, the uncertainty that methodological choices have on LCA, namely the selection of the allocation procedure and environmental categories, was assessed by Cherubini et al. [30].

The explicit introduction of uncertainties in LCA is carried out by the use of different statistical approaches [16]: (i) scenario analysis, where different data sets, models and/or choices are used; (ii) sampling methods, like Monte-Carlo Simulation or Latin-hypercube Simulation; (iii) analytical methods based on mathematical expressions; and (iv) non-traditional methods such as fuzzy sets, Bayesian methods, neural networks, etc. Examples and references of the application of each approach to LCA are provided in [16].

Different authors have different opinions regarding the appropriateness of the approach for processing uncertainties. Heijungs [31] argues that analytical methods are efficient and easily operationalized although requiring complex mathematical expressions. Steen [32], on the other side, says that the complexity involved in the mathematical models make the use of analytical methods almost impractical and suggests the use of stochastic modelling. The same opinion is expressed by Lloyd and Ries [14] saying that the use of complex numerical solutions for solving analytical methods may not provide reliable estimates for tails of output distributions leading to inaccurate approximations.

The increasing advancement of computer technology allows to deal with more complex analysis and to use more sophisticated models such as intervals, fuzzy sets and stochastic modelling. This explains the more recent trend in processing uncertainties.

Tan et al. [33] argue that the use of fuzzy sets are more appropriate than stochastic modelling because imprecision in LCI data is caused by ambiguity that cannot be described in probabilistic terms. Fuzzy sets are effective for quantifying imprecise language in uncertainty analysis, although they may overestimate results as correlation between variables is not considered [34].

On the other hand, uncertainty in normative choices and model formulations may, in some cases, be modelled more appropriately using scenarios. Furthermore, if probabilities can be assigned to each scenario, nonparametric bootstrapping can be used to sample from the set of scenarios [14].

A survey of quantitative approaches for analysing and propagating uncertainty in LCA showed that the use stochastic modelling is dominant (about 67%)[14]. Among such methods, Monte Carlo simulation is the most popular sampling approach.

A few disadvantages of such approaches are the amount of data needed for the characterization of uncertainty and the time needed for computation [15][33].

3.2 Uncertainties in the LCA of buildings

To enable the definition of benchmarks for the environmental performance of buildings, a LCA model was developed and is fully described in [35].

In the adopted model, which will be briefly described in the next section of this report, there are two different sources of uncertainties: one related to the LCA methodology and another one related to the modelling of the building.

The types of uncertainty related to the first source of uncertainty were already introduced in the previous sub-section.

The second source of uncertainty is directly related to the modelling of the building and consequently, to all input parameters and choices that are required to model the building over the different stages. Taking into account the types of uncertainties listed in the previous sub-section, these uncertainties fall mainly into the categories of parameter uncertainty and uncertainty due to choices.

The parameters that are required to consider in the modelling of buildings are, among others: the quantities of the different materials in the BoM, the distance between the source of each material to the construction site and respective type of transportation; the service life of the different materials and respective maintenance/replacement needs; the rates of recycling, reuse or recover, upgrading and downgrading factors, etc.

In relation to the choices taken in the LCA model, these are mainly related to the definition of end-of-life treatments and respective allocations of benefits and credits.

Each parameter in the model of the building has inherent uncertainty and each choice leads to a variability of the outcome of the analysis.

Hence, in a previous report [36], a simple sensitivity analysis was carried out in order to evaluate the sensitivity of the output of the model to an arbitrary change of single parameter values. A sensitivity ratio was then calculated for each parameter to identify the most important input values.

In addition, in order to evaluate the influence of different choices on the outcome of the analysis, different end-of-life scenarios were considered taking into account distinct end-of-life treatments for the materials and respective allocation procedures.

However, in the following, the analysis will focus on parameter uncertainty. End-of-life scenarios were selected in order to promote the recycling and reuse of materials, in agreement with current EU policies [35].

The above sensitivity analysis was important to make a preliminary identification of the (potentially) most important parameters and scenarios. However, this type of approach provides a very limited inspection of the model inputs and no information about the interaction between different inputs. Moreover, the above analysis does not account for uncertainty.

Therefore, in the following paragraphs a framework is described, with a twofold aim: to account for the propagation of input uncertainties in the outcome of the analysis, and to calculate the contribution of each parameter uncertainty in the outcome of the uncertainty analysis.

3.3 Framework to deal with uncertainties in the building model

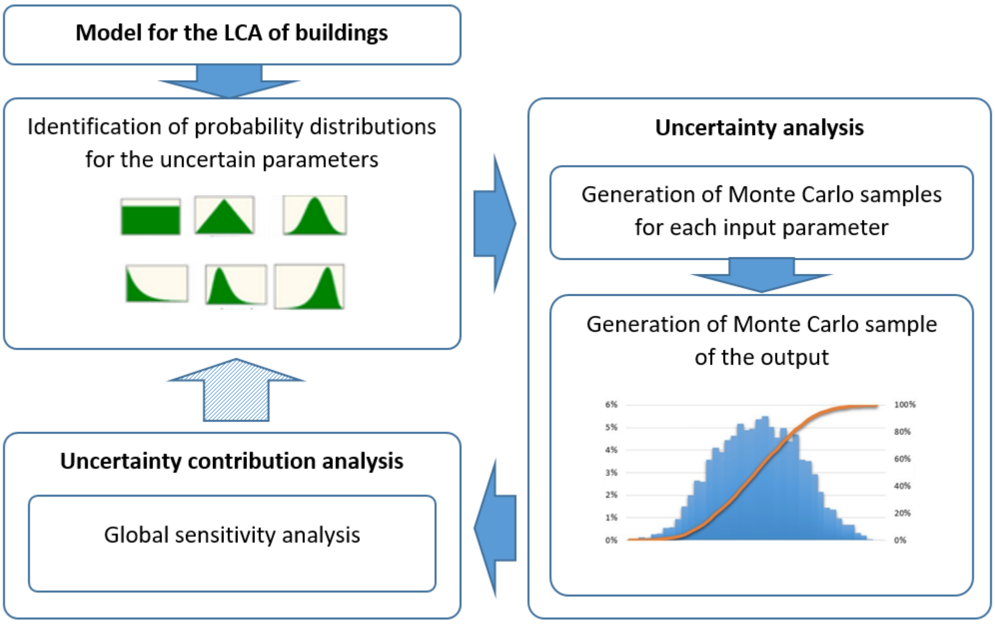
As previous mentioned, it is not possible to avoid uncertainties in LCA and it is important to assess the extent to which the outcome of the LCA reflects real-life environmental impacts. The implementation of uncertainties in LCA is needed in order to make the results of such analysis more precise and reliable [18].

A framework to deal with the uncertainties in the LCA of buildings is herein proposed, aiming to address most types of uncertainties described in the previous paragraphs, over the different stages in the life cycle of buildings.

In the proposed approach, the uncertainty in the parameters in propagated over the life cycle of the building and then the contribution of each parameter to the uncertainty of the result is calculated.

Hence, as illustrated in Figure 5, this framework has three main steps. The first step consists of the identification of all parameters in the model that may influence the outcome of the analysis. In addition, probability distribution functions are identified for each uncertain model input. Then, in the second step, the uncertainty analysis is performed by the use of a sampling propagation method. In this case, the Monte Carlo simulation (MCS) is adopted as the sampling method. Finally, in the third step, the uncertainty contribution is carried out, in which the most influential inputs in the uncertain outcome of the analysis are identified. This enables to focus the research needs on those parameters and thus, obtain a more accurate result.

Figure 5. General framework to address uncertainties



In this last step, a Global Sensitivity Analysis (GSA) is adopted as proposed by Cucurachi et al. [37]. In this GSA, sensitivity measures are considered and estimated based on the results of the MCS. According to the authors, the confidence in the estimates should be checked before conclusions may be drawn. When such confidence is not achieved, then the analysis should be repeated.

These main steps are further described in the following paragraphs. Then, in sub-section 3.4, the procedure is applied to the LCA of buildings.

3.3.1 Characterization of uncertainty in parameters

Before uncertainty propagation takes place, it is required to characterize the uncertainty in the parameters. Assuming that the uncertainties in the parameters of the model may be represented by probability distributions, then a probability distribution is selected for each parameter.

This selection usually relies on measured data, literature data, expert judgement or even personal judgement. In a first approach, conservative ranges of values may be assigned to the different parameters. Then, after the identification of the most influential parameters in the sensitivity analysis, a greater effort is provided in finding more detailed uncertainty data for the most relevant parameters and then the analysis is redefined.

3.3.2 Uncertainty analysis and propagation

Uncertainty propagation aims to propagate input uncertainties to obtain the model output distribution. The sampling method adopted for uncertainty propagation is MCS, which was already introduced in sub-section 2.2.1.

MCS involves repeating a simulation process, using a set of values for the input parameters based on the corresponding probability distributions. By repeating the process a large number of times, a sampling of solutions is obtained, which are then treated statistically [17].

Moreover, in MCS, dependencies between parameters may be addressed by rank correlation methods.

3.3.3 Global sensitivity analysis

The main goal of a standard SA is to identify the most influencing input parameters in the response of a model.

Generally, SA are divided into local sensitivity analysis and global sensitivity analysis. In a local SA, the response of the output around one point of interest is evaluated in the model space. In this case, typically, each input parameter is varied one at a time, while all the remaining parameters are kept constant.

The effect of the individual parameter perturbation on the model output is calculated using sensitivity indices. Hence, a sensitivity index (S_i) may be calculated through the use of a set of partial derivatives of the output (y), with respect to each input (x_i):

$$S_i = \frac{\delta g(x)}{\delta x} \tag{17}$$

This type of approach was applied in the uncertainty analysis carried out in a previous report [36]. A local SA is useful when the aim of the analysis is to assess how small variations in the input parameter affect the model output around one or more point of interest.

In spite of providing a preliminary sensitivity of the model, a local SA fails to provide important information of the model, such as the existence of potential interactions among the inputs of the model. Moreover, they do not take into account the uncertainties in the model.

Global SA, on the other hand, enable to identify which model inputs are the most influential in determining the uncertainty of the output of the model and to obtain additional information about the interactions between parameters to the model output variance.

Different methods are available for SA and a discussion of the different methods is beyond the scope of this report. A survey of sampling-based methods for uncertainty and sensitivity analysis is found in [38].

The adopted approach for SA is based on Sobol's method, which is based on variance decomposition technique and provides quantitative measurements of the contribution of the input to the output variance.

In this case, the first and total sensitivity measures are calculated [39], which represent the first order contribution and the overall effect of an input parameter to the output variance, respectively.

Hence, the first order indices are defined by expression (18) and they account for the expected reduction in variance of the model output when $X_i = x_i$,

$$S_i^{First} = \frac{V_i}{V[y]} = \frac{(\mathrm{V}[\mathrm{E}(Y|X_I)])}{V[y]} \tag{18}$$

When the sum of the first-order sensitivity indices is one, the model output is additive.

On the other side, total order SA, defined by expression (19), represent the portion of the variance of the model output contributed by X_i individually and through all its interactions with the remaining model inputs,

$$S_i^{Total} = \frac{(\mathrm{V}[\mathrm{V}(Y|X_{-i})])}{V[y]} \tag{19}$$

The higher the value of the indices, the higher is the influence of the respective model parameter.

3.4 LCA of buildings taking into account uncertainties

This sub-section aims to illustrate the application of the framework to deal with uncertainties in the LCA of buildings described above.

Hence, firstly the procedure is implemented in the LCA of a single building. Then, the same procedure is applied in the comparison of the life cycle performance of two buildings, taking as output of the analysis the ratio between the two environmental performances.

It is noted that this second application falls exactly into the aim of the proposed approach for sustainable design, in which the performance of a building is compared with a reference value.

3.4.1 Life cycle analysis of single buildings under uncertainty

In the following, the life cycle analysis of a building is carried out taking into account the uncertainties in different parameters. The analysis of the building is focussed on the structural system of the building; which, in this case is made by a reinforced concrete structure. Full details about this building (with reference RB1) are given in Annex B.

Moreover, in the LCA of the building only the environmental category of GWP is considered in this sub-section.

The uncertainty considered in the parameters of the model is indicated in Table 2. These parameters are related to input parameters (e.g. the quantities of materials retrieved from the BoM), parameters related to the characteristics of the building (the GFA) and to the reference period of analysis, and parameters related to the different scenarios considered in the analysis (e.g. distances considered in Modules A4 and C2, recycling rates of different materials, etc.).

In all cases, a uniform distribution is considered and the maximum and minimum values are indicated in Table 2. In case where values are given by a ±%, this represents the variation in relation to the deterministic value considered for each parameter; in all other cases, the maximum and minimum values are indicated in the table.

Table 2. Type of uncertainties in life cycle analysis of buildings

Variable	Description	Probability distribution function
Q_i	Mass of material *i*, provided by the BoM	Uniform (min = -10%, max = +10%)
d_i (A4)	Distance for material *i* in Module A4 (in km)	Uniform (min = 20, max = 100)
Elec (A5)	Use of electricity in Module A4	Uniform (min = -20%, max = +20%)
D_{fuel} (C1)	Consumption of diesel in Module C1	Uniform (min = -20%, max = +20%)
d_i (C2)	Distance for material *i* in Module C2 (in km)	Uniform (min = 20, max = 100)
d_i (D)	Distance for material *i* in Module D (in km)	Uniform (min = 20, max = 100)
RR_{conc}	Recycling Rate for concrete products (in %)	Uniform (min = 50%, max = 90%)
RR_{rebars}	Recycling Rate for steel reinforcement (in %)	Uniform (min = 50%, max = 90%)
F	Down-cycling factor for concrete prod. (in %)	Uniform (min = 35%, max = 70%)
GFA	Gross floor area of the building	Uniform (min = -10%, max = +10%)
Time	Reference period of time	Uniform (min = -10%, max = +10%)

In addition, uncertainties where considered in the input flows (air emissions) of the different processes included in the analysis and respective characterization factors.

To account for uncertainty in input flows and characterization factors, usually lognormal distributions are considered, as a skewed distribution is frequently observed in real life parameters and processes [40]. Moreover, this type of distribution avoids negative values and captures a large range of values [13][41][42].

For the air emissions of greenhouse gases (CO_2, N_2O and CH_4) in the different processes, the uncertainty data was taken from the Ecoinvent database [42]. It is noted that, in this database, the lognormal distribution is the most common distribution used to model uncertainties. In addition, two types of uncertainties are considered. The first type of uncertainty reflects the variation and stochastic error of data (e.g. error in measurements, temporal variation, etc.) and is given by the basic uncertainty. Then, additional uncertainty provided from quality data indicators is added to the lognormal distribution. This additional uncertainty is based on the pedigree matrix approach [43], which takes into account five different indicators: reliability, completeness, temporal correlation, geographical correlation and further technological correlation.

To depict uncertainty in characterization factors, uncertainty data may be retrieved from [13], which reflect parameter uncertainty and variability in the models. However, in this case, a simplified approach was considered taking into account the variation of the values provided by IPCC, due to new data and specific model improvements over the years. The GWP values indicated in Table 3 for three of the most important greenhouse gases are relative to the accumulated impact over 100 years.

Table 3. Evolution of GWP values relative to CO_2 for 100-year time horizon, according to IPCC reports [44]

Greenhouse gases	SAR (1995)	TER (2001)	AR4 (2007)	AR5 (2013)
Carbon dioxide (CO_2)	1	1	1	1
Methane (CH_4)	21	23	25	28
Nitrous oxide (N_2O)	310	296	298	265

The values considered in the analysis were the ones from the 4th and 5th reports. A uniform distribution was considered for CH_4 and N_2O as indicated in Table 4. A negative correlation was considered between the two values. It is observed that if the values from the 3rd and 4th reports were considered, the correlation between the two values would have a positive sign. However, the uncertainty depicted in characterization factors has not a major influence in the outcome of the analysis, as later discussed.

Table 4. Type of uncertainties in characterization factors

Variable	Description	Probability distribution function
CF_CH_4	Characterization factor for methane (CH_4)	Uniform (min = 25, max = 28)
CF_N_2O	Characterization factor for nitrous oxide (N_2O)	Uniform (min = 298, max = 265)

The uncertainty analysis was performed by Monte Carlo Simulation, Latin Hypercube sampling, considering 1000 iterations, by the LCA software GaBi [45].

The result of the MC simulation leads to a mean value of the environmental performance of the buildings of 7.56 kg CO_2 eq./m^2.yr and a COV of 10.3%.

Based in the results of this simulation, the correlation between the variables and the outcome of the analysis is firstly observed by plotting the scatter of data. The scatter of data for the most relevant variables is illustrated in Figure 6 to Figure 9, showing a linear relationship for all cases. In addition, the respective correlation coefficients showed a negligible relationship for most variables, except for the mass of concrete, GFA and Time.

Figure 6. Scatter of values for the mass of ready mix concrete and concrete blocks

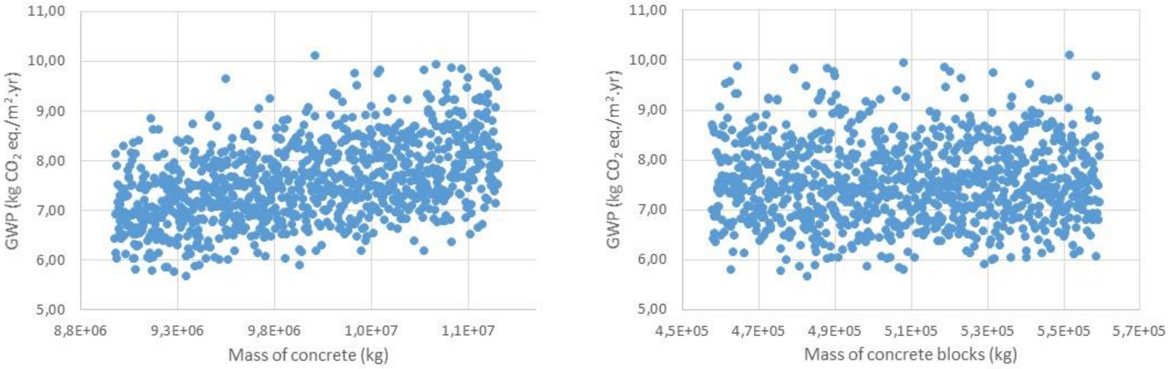


Figure 7. Scatter of values for inorganic emissions (CO_2) in the production of concrete and steel reinforcement

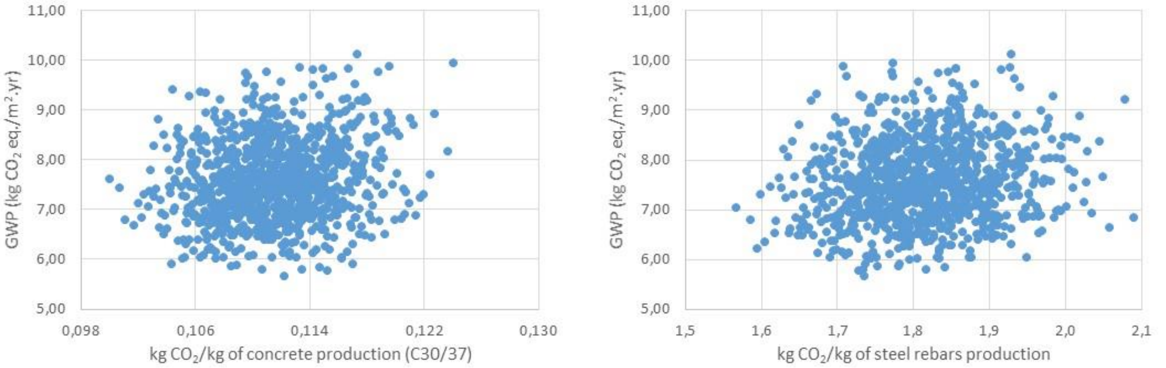


Figure 8. Scatter of values for recycling rates (RR) of concrete and steel reinforcement in the end-of-life stage

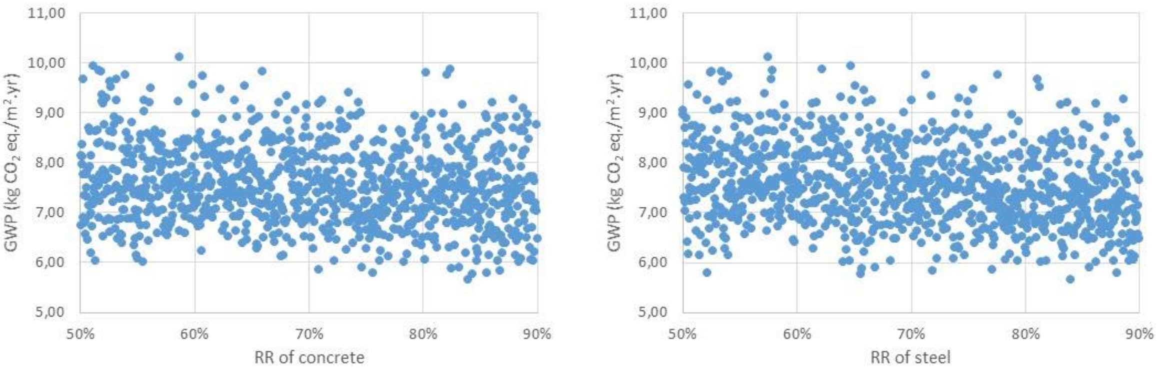
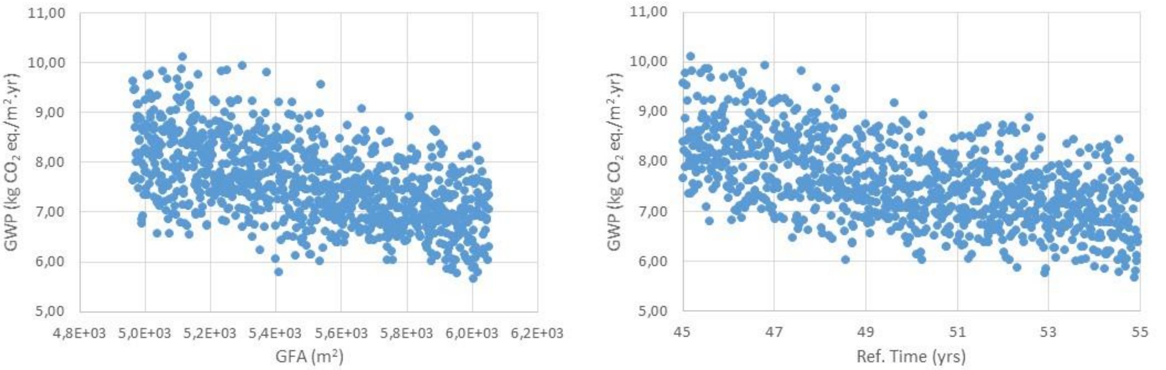


Figure 9. Scatter of values for the GFA of the building and the reference period of time



Then, the sources of uncertainty in the outcome of the analysis are assessed by their contribution to variance. Hence, based in the results of the simulation, first order (S_i) and total order (S_{Ti}) sensitivity indices were calculated. The most important sources of uncertainty, identified by their contribution to the variance (in %), are displayed in Table 5.

Table 5. First Order (S_i) and Total Order (S_{Ti}) Sensitivity Indices

Variable	Description	S_i	S_{Ti}
Q_{conc}/Q_{rebars}	Mass of concrete/rebars, provided by the BoM	21%	21%
RR_{conc}	Recycling Rate for concrete products	2%	2%
RR_{rebars}	Recycling Rate for steel reinforcement	9%	9%
F	Down-cycling factor for concrete	1%	1%
GFA	Gross floor area of the building	30%	30%
Time	Reference period of time	30%	30%
CO_{2_conc}	Emissions of CO_2 in the production of concrete	3%	3%
CO_{2_rebars}	Emissions of CO_2 in the production of steel reinf. (rebars)	2%	2%

As observed from Table 5, the sum of the sensitivity indices is about 100%. Therefore, the variance of the output is completely explained by the set of variables indicated in this table.

The GFA of the building and the period of time considered in the analysis are responsible for about 60% of the variance. The mass of concrete, and consequently the mass of reinforcement (assuming a correlation factor of 1), is responsible for about 21%. The recycling rate of the reinforcement has a smaller but still relevant contribution of 9%. The remaining variables have an individual contribution lower than 5%, which may be considered as not significant [46].

As already referred, the total-order sensitivity indices are used to assess the global contribution of a parameter and the interaction of the parameter with the other ones. In this case, the total-order sensitivity indices are equal to the first-order sensitivity indices. Therefore, as already expected, there is no second-order interaction between the parameters.

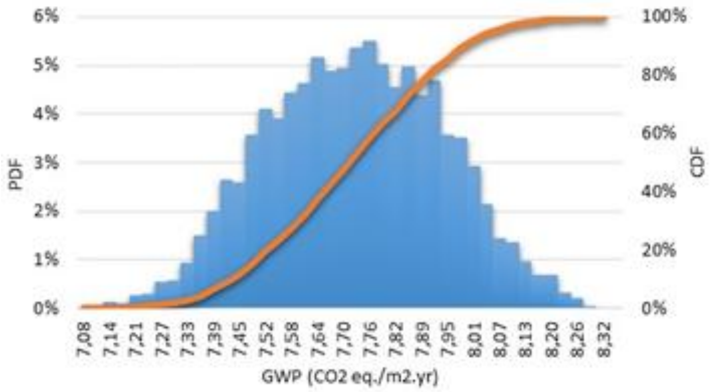
Furthermore, the most important variables are the parameters required to model the building. The uncertainty in CF is negligible and the uncertainty contribution of emissions has only a minor importance, in particular CO_2 emissions.

Then the life cycle analysis of the building was redefined taking into account only the most important parameters listed in Table 5, namely the mass of concrete and rebars and respective recycling rates. In this analysis, the GFA of the building and the period of time were fixed to allow comparisons with other non-normalized values. However, it is acknowledged these two parameters have a major importance in the results of the analysis and in a future review of this work, these values and respective uncertainty should be taken into account.

Likewise, the uncertainty analysis was performed by Monte Carlo Simulation and Latin Hypercube sampling. In this case, 5000 iterations were considered. The result of the MC simulation lead to a mean value of the environmental performance of the buildings of 7.73 kg CO_2 eq./m^2.yr and a standard deviation of 0.21 (CoV = 2.7%). The results are illustrated in Figure 10.

As observed from Figure 10, the shape of the distribution is close to a normal distribution. The 90% interval of confidence for the LCA of this building is 7.37-8.06 kg CO_2 eq./m^2.yr.

Figure 10. Final probability distribution and CDF of the building RB1



The procedure illustrated above will be used for the life cycle analysis of all buildings in Section 4 of this report.

3.4.2 Comparative life cycle analysis of buildings under uncertainty

The following analysis aims to assess the uncertainty contribution of the different parameters, when two buildings are compared. This example illustrates the case when the environmental performance of a building is compared with the mean value of the environmental performance of a set of buildings, which is the goal of the proposed approach for sustainable design.

The life cycle performance of the building considered above is herein compared with the life cycle analysis of another building. Details about this other building are also given in Annex B (building with reference RB3).

The comparison between the environmental performances of two buildings is herein considered by the ratio (dimensionless) between the two analyses:

$$R_{1-2} = \frac{LCA\_build_1}{LCA\_build_2} \tag{20}$$

where, LCA_build_1 and LCA_build_2 are the life cycle environmental performances of buildings 1 and 2, respectively.

It is noted that by taking into account this ratio, the uncertainty introduced in the analyses of both buildings is eliminated to a certain extent. This is particularly the case of the parameters that are common in both analyses, such is the case of the characterization factors.

The uncertainty analysis was performed by Monte Carlo Simulation and Latin Hypercube sampling, considering 5000 iterations. Like in the previous case, the LCA of the buildings is focussed on the environmental category of GWP.

The analyses of both buildings were carried out simultaneously to take into account the correlations between the parameters and processes that appear in the life cycle of both buildings. In this case, the scatter of data of the most important parameters are illustrated in Figure 11 to Figure 14. A linear relationship is observed in all cases. The respective correlation coefficients showed a weak or negligible relationship for most variables, except for the variables indicated in Figure 11 to Figure 14, which have a moderate relationship.

The slopes are positive or negative depending on the side they appear in the ratio expressed by (20).

Figure 11. Scatter of values for the mass of ready mix concrete in both buildings

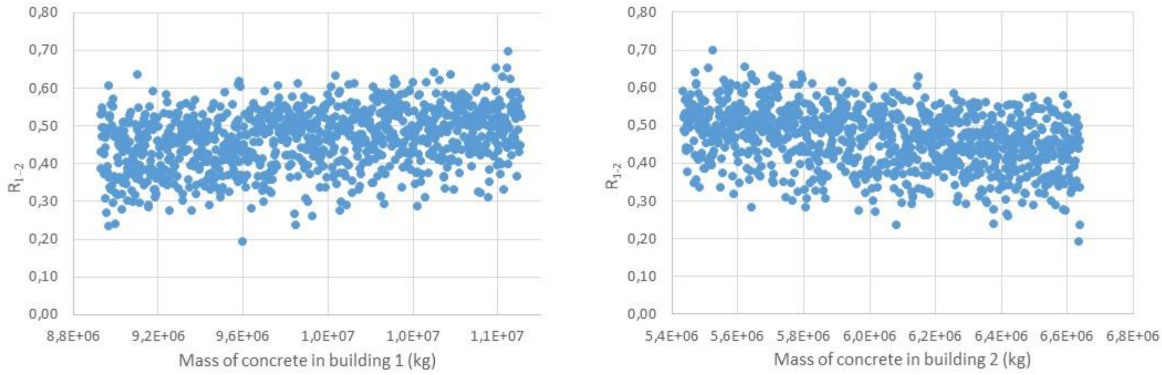


Figure 12. Scatter of values for the mass of steel reinforcement in both buildings

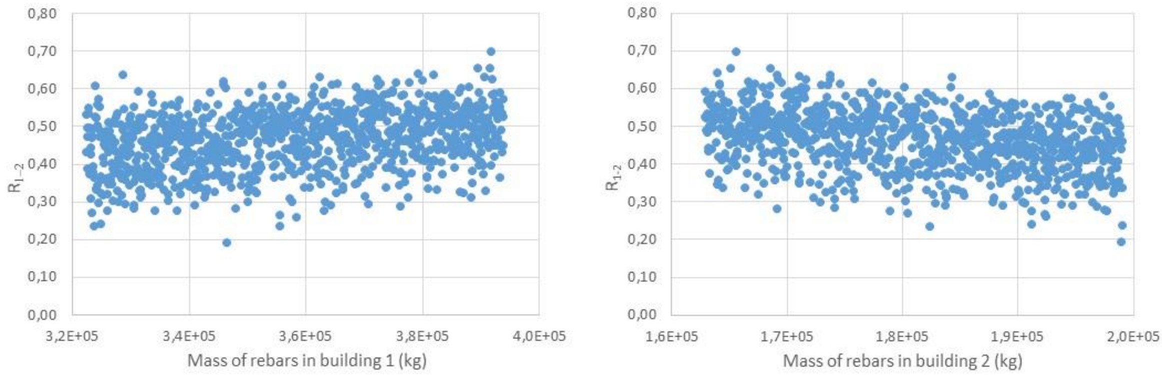


Figure 13. Scatter of values for the GFA of both buildings

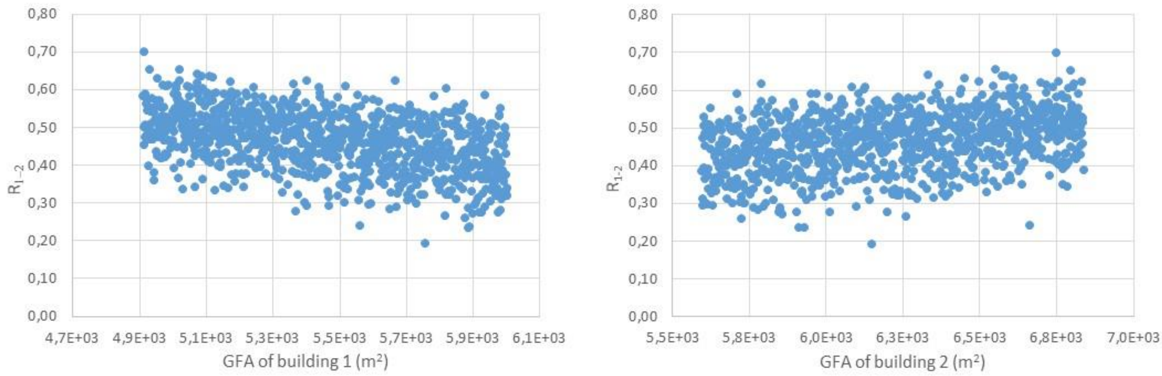
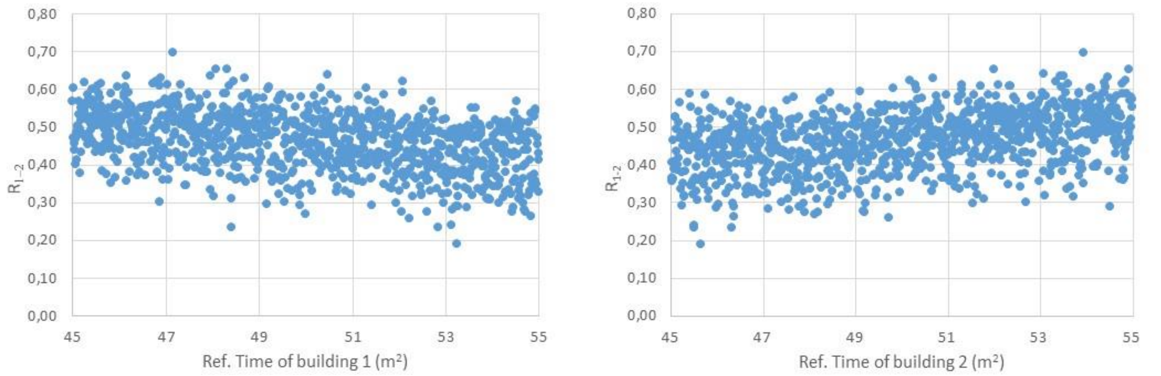


Figure 14. Scatter of values for the reference period of time considered for both buildings



The contribution to variance (in %) of the different parameters in the analysis is indicated in Table 6.

Table 6. First Order (S_i) and Total Order (S_{Ti}) Sensitivity Indices

Variable	Description	S_i	S_{Ti}
Q_{conc_1}/Q_{rebars_1}	Mass of concrete/rebars, provided by the BoM of building 1	11%	11%
RR_{conc_1}	Recycling Rate for concrete products in building 1	1%	1%
RR_{rebars_1}	Recycling Rate for steel reinforcement in building 1	5%	5%
$GFA_{\_1}$	Gross floor area of building 1	16%	16%
$Time_{\_1}$	Reference period of time of building 1	16%	16%
Q_{conc_2}/Q_{rebars_2}	Mass of concrete/rebars, provided by the BoM of building 2	10%	10%
RR_{conc_2}	Recycling Rate for concrete products in building 2	1%	1%
RR_{rebars_2}	Recycling Rate for steel reinforcement in building 2	4%	4%
$GFA_{\_2}$	Gross floor area of building 2	16%	16%
$Time_{\_2}$	Reference period of time of building 2	16%	16%

Likewise, the most important parameters are the GFA and the period of time considered for the analysis, followed by the mass of the most important materials. The recycling rates of the materials have a much lower impact on the result of the analysis. Furthermore, the uncertainty in the parameters related to the LCA, in particular characterization factors, is negligible, as already expected.

As observed in the two examples above, the variables used for the normalization of the functional unit have a primordial importance in the results of the analysis.

The quantification of the GFA is mainly dependent on the accuracy of the measurement and on the understanding of the concept. In this work, the GFA considered for benchmarking is measured according to the external dimensions of a building and includes all areas inside the building, including supporting areas. This definition is based in the *Code of Measuring Practice* (RICS) [47], which states that 'gross external area is the area of a building measured externally at each floor level'. Guidelines about what should be included and excluded in the GFA of the building are adopted from the above document. However, some deviations were considered in the GFA adopted in this work since in this case, the GFA is related to the structural system of the building. Hence, additional guidelines for the quantification of the GFA are given in Annex A of this report.

In relation to the period of time, this reference period is given by the estimated working life of the building, according to the code or regulation used in the design of the structural system of the building [35]. It is important to include a reference period in the functional equivalent of the building to account for the potential extension of this reference period due to special building design strategies like design for adaptability (see [35] for further details). When the estimated working life of the building is not provided in the project documentation, a period of time of 50 years may be considered, which is the design working life recommended by EN1990 [7] for residential and office buildings. It is noted that according to this code working life is the 'assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance but without major repair being necessary'. Additional guidance on the estimation of the design life of building components is given on the series of standards ISO 15686, parts 1 to 8.

In a future review of this work, the uncertainty in these two parameters will be taken into account. However, as previously mentioned, in the calculations provided in the following section, the GFA and reference period of time were fixed to allow comparisons with other non-normalized values available in the literature.

4 Sustainable design of buildings

4.1 Introduction

This section introduces a performance-based approach for the sustainable design of buildings, allowing to assess resource efficiency throughout the complete life span.

The proposed 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 [35]. However, the scope of the approach is open and when appropriate data become available, it may easily be extended to account for other building components.

Hereafter, for simplification, when reference is made to building(s), it should be interpreted as the structural system of building(s).

Moreover, it is acknowledged that by narrowing the scope of the approach to environmental aspects, the term 'sustainable design' is not accurate, since the concept of sustainability has a much broader and holistic scope. Nevertheless, in the future, the methodology introduced in this report may be easily extended to other criteria.

In the context of building design, a structure in a '*performance-based design, shall be designed in such a way that it will with appropriate degrees of reliability and in an economical way attain the required performance*' [49].

The aim of this section is thus to generalize this concept in order to encompass environmental concerns. Therefore, the above definition becomes '**in a 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**'.

As described is Section 2, according to the Eurocodes, the reliability of the design should be verified against all relevant limit states (ultimate limit states and serviceability limit states), whereas the limit state function separates satisfactory and unsatisfactory states. Hence, for each limit state, the value of the performance of the structure is compared with a reference value and the structure has a satisfactory performance when expression (2) is verified.

In the proposed approach for sustainable design of buildings, a similar comparison is pursued. In this case, a new limit state is 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.

Hence, the main goal of the benchmarks is to develop a consistent and transparent yardstick to assess the environmental performance of buildings, striving towards an effective reduction of the use of resources and relative environmental impacts in the building sector.

Thus, one of the key milestones in the development of the proposed approach is the definition of benchmarks for the life cycle environmental performance of buildings. The benchmarks aim to be representative of buildings in Europe and thus, they should take into account the building stock in EU. The development of benchmarks is addressed in the following sub-section.

Then, the new limit state of sustainability is introduced in sub-section 4.3. Finally, the main achievements but also the major limitations of the proposed approach, are discussed in sub-section 4.4

4.2 Benchmarking the environmental performance of buildings

The project *EFIResources* focusses on resource efficiency in the building sector. In this project, resource efficiency is understood as a reduction of the use of resources in buildings and relative environmental impacts, over the complete life cycle of the building [35]. Therefore, in order to measure such reduction and thus assess the efficiency of buildings, reference values or benchmarks are needed. Hence, a benchmark is here understood as a point of reference to enable comparisons; while benchmarking is the process that assesses and compares the performance of a building against the benchmarks.

The benchmarking of the life cycle performance of buildings should rely on a consistent methodology for life cycle assessment, allowing for comparability.

The methodology adopted for the development of benchmarks and the LCA model developed for the calculation of benchmarks are briefly described in the following paragraphs. These two milestones in the development of the project *EFIResources* were addressed in previous reports, [36] and [35] respectively.

A set of benchmarks is hereafter provided for residential and office buildings. This set of values is based on real data for buildings, collected from different sources. These values will then be used to illustrate the approach for sustainable design.

4.2.1 Methodology for the development of benchmarks

One of the key steps in the development of benchmarks is the collection of accurate, consistently measured and verifiable data [50]. However, as previously referred, in relation to buildings, data availability and collection are usually limiting the scope and accuracy of the life cycle assessment of buildings.

Hence, a graduated approach was adopted for the development of the benchmarks [36], starting on a simple basis and progressively refined and increasing in complexity over time, as data collection on buildings and relative processes becomes more complete and precise. This continuously improved process comprehends the following steps:

i) Definition of objectives and scope

ii) Data collection

iii) Quantification of initial benchmarks

iv) Identification of further improvement

v) Review of the set of benchmarks

The main steps are briefly summarized in the following paragraphs. Further details are given in [36].

4.2.1.1 Data collection

The definition of benchmarks entails the collection of two different types of data: (i) the collection of building data, which includes, at least, a bill of materials (BoM) and list of processes considered in the scope of the analysis, throughout the life cycle of the building; and (ii) the collection of environmental data for the quantification of potential environmental impacts.

The benchmarks provided in this report are based on data collected from design offices building promoters and research centres. All collected data refers to recent buildings as the oldest BoM corresponds to year 2006.

However, it is observed that a preliminary set of benchmarks for residential buildings is provided in [36], based on data representative of the existing building stock in the EU-25. This data, retrieved from the *IMPRO-Building* project [51], is mostly referring to buildings from the second half of the 20th century (although a few cases are from the beginning of the century).

A comparison between the two sets of benchmarks is provided in sub-section 4.2.4 of this report.

In relation to the second type of information, data for the environmental assessment of buildings may be collected from generic databases for LCA and/or from Environmental Product Declarations (EDPs). Both sources of data and respective quality requirements are described in [35].

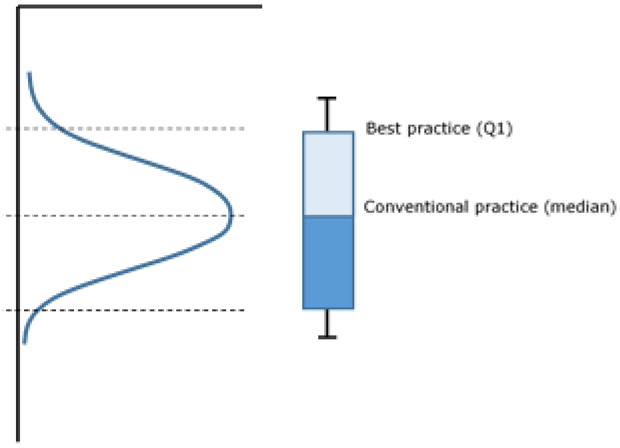
The databases used in this project are the 'Professional database' and the 'Extension database XIV: Construction materials', provided by the LCA software GaBi [45]. The version of the databases is 8.6 (service pack 34).

4.2.1.2 Quantification of benchmarks

The definition of the set of benchmarks is based on the statistical analysis of the sample of buildings referred to in the previous paragraphs. Hence, the life cycle environmental performance of each building is assessed by the LCA model described in sub-section 4.2.2, and a statistical analysis is made upon the outcome of all analyses, for each building typology (residential and office buildings).

Moreover, 'conventional' practice (also known as 'business as usual') is assumed to be given by the median value of the environmental performance of the buildings (represented by any of the indicators in Table 8 and Table 9); while, 'best practice' is assumed to be given by the value of the environmental performance that is achieved by only 25% of the buildings, i.e., the upper limit of the first quartile, as illustrated in Figure 15.

Figure 15. 'Conventional' and 'best' values [36]



The set of benchmarks is aimed to be representative of the building stock in the EU. However, the design of buildings depends on local conditions, technical and functional requirements from national safety regulations, client's specific requirements, etc. Naturally, the environmental performance of buildings and consequently the definition of benchmarks, will also be influenced by the same factors.

Hence, the following differentiation factors are considered in the definition of the benchmarks [36]: (i) seismic requirements; (ii) climatic requirements; (iii) vulnerability to climatic changes. In an analogy with the Eurocodes, these requirements may be considered in the benchmarks by specific settings or factors, at each national level, provided in a National Annex.

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 is reduced and does not result from a genuine random selection of the building stock in the EU. Therefore, the results provided in the following sub-sections, cannot be considered to be representative of the actual building stock.

Nevertheless, these set of values will be used to illustrate the approach for sustainable design, proposed hereafter.

4.2.2 LCA model for the calculation of benchmarks

The other key milestone in the project *EFIResources* 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 [52] and EN 15978 [53].

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 [35]:

$$Building\ performance\ for\ environmental\ category\ i = \frac{Environmental\ result\ i}{GFA \times Ref.period\ of\ time} \qquad (21)$$

The reference period of time is given by the estimated working life of the building, according to the code or regulation used in the design of the structural system of the building. In case the estimated working life of the building is not provided in the project documentation, a period of time of 50 years may be considered, which is the design working life recommended by EN1990 [7] for residential and office buildings.

Guidelines for the quantification of the GFA of buildings are provided in Annex A of this report.

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), as illustrated in Table 7. Modules B6 and B7, which are related to the operation of the building, are not considered in the analysis.

On the other hand, Module D, which allocates net benefits due to recycling and/or recovery processes, is taken into account in the analysis. This is a deviation from CEN TC 350 standards, which consider Module D an optional stage in the LCA of buildings.

Table 7. Scope of the LCA

Product stage			Process stage		Use stage							End-of-life stage				
A1	A2	A3	A4	A4	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction	Transport	Waste processing	Disposal	Reuse-recycling-recover
x	x	x	x	x	x	x	x	x	x	n.a.	n.a.	x	x	x	x	x

Taking into account the functional equivalent and the scope of the analysis, the information contained in each module of Table 7 is the following:

- Modules A1 to A3 – Include the production of all buildings materials that are used in the foundations and structure of the building, until the gate of the factory. Data for these modules is usually provided from the Bill of Materials (BoM) of the building;

- Module A4 - Transportation of the materials needed for the foundations and structure of the building, from the production place to the construction site. This information is based on best guesses or scenarios taking into account the location of the building and the type of transportation;
- Module A5 – Use of equipment and machinery for the construction of the foundations and erection of the structure; in case this information is not available, scenarios may be considered. In the model, the preparation of the terrain for the construction of the building, the installation of auxiliary infrastructures and the construction of accesses to the construction site are not taken into account;
- Modules B1-B5 – These modules include all relevant data in relation to the maintenance, repair and refurbishment of the structural system of the building. This should include the use of materials and equipment, and the management of the waste created. In case secondary materials are created, credits should be allocated in Module D. Data for these modules should be based on scenarios taking into account the estimated working life of the structural components of the building;
- Module C1 – C4 – These modules include all relevant data from the decommission of the structural system of the building to the stage in which the end-of-waste state is reached by all the structural materials. This includes the use of equipment and machinery for the deconstruction of the building structure, sorting of materials and transport of the resulting materials to their final destination. This data should be based on scenarios;
- Module D – This module allocates net benefits due to the reuse, recycling and recover of materials. Data for this module should be based on scenarios taking into account the average available technology, current practices and current rates of recycling, reuse and recover of materials.

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 [35]. 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 considered for the environmental performance of buildings are listed in Table 8.

Table 8. Indicators describing environmental impacts [52]

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_2H_4 eq.
Abiotic Resource Depletion Potential of fossil fuels	ADP_f	MJ, n.c.v. (*)

(*) net calorific value

Additionally, the indicators based on inventory flows considered in the analysis are listed in Table 9.

Table 9. Indicators describing input and output flows [52]

Indicator	Abbreviation	Unit
Total use of non-renewable primary energy resources	PENRT	MJ, n.c.v.
Total use of renewable primary energy resources	PERT	MJ, n.c.v.
Use of net fresh water	FW	m^3
Hazardous waste disposed	HWD	kg
Non-hazardous waste disposed	NHWD	kg
Radioactive waste disposed	RWD	kg

It is observed that the above LCA model is open and additional indicators can be added when relevant.

The model was implemented into the expert software for LCA GaBi (version 8.1.0.29) [45].

Further details about this model and about all the assumptions and scenarios that are required to perform the life cycle analysis, are provided in [35].

4.2.3 Types of buildings

Reference values for the environmental performance of buildings are provided at different levels as indicated in Table 10. This report focusses on two building typologies (Tier 2): residential and office buildings.

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 10.

An additional category of tall buildings is considered, as a particular case of high-rise office buildings. According to the Council on Tall Buildings and Urban Habitat (CTBUH) [54], tall buildings are buildings that can be differentiate from others in terms of height, slenderness (small base in comparison to its height) and/or use of specific building technologies for this type of buildings, such as the use of vertical transport technologies, etc.

Moreover, it is observed that tall buildings have usually a mixed-use, with floors for offices and commercial spaces, for residential use and others. However, they are herein included in the typology of office buildings, as the analysis provided in this report is related to this building typology. In the future, this classification may be reviewed.

Table 10. Types of buildings and classification levels

<table>
<tr><td>Tier 1</td><td>Tier 2</td><td colspan="2">Tier 3</td><td rowspan="9">Tier 4</td><td rowspan="2">Reinforced concrete structure</td></tr>
<tr><td rowspan="8">Buildings</td><td rowspan="4">Residential buildings</td><td>SF</td><td>Single-family houses (SF)</td></tr>
<tr><td>MF</td><td>Multi-family houses (≤ 5 stories)</td><td>Steel structure</td></tr>
<tr><td>MR</td><td>Medium rise buildings (5 – 15 stories)</td><td>Composite structure</td></tr>
<tr><td>HR</td><td>High rise buildings (> 15 stories)</td><td>Wood structure</td></tr>
<tr><td rowspan="4">Office buildings</td><td>LR</td><td>Low rise buildings (≤ 5 stories)</td><td>Masonry structure</td></tr>
<tr><td>MR</td><td>Medium rise buildings (5 – 15 stories)</td><td>Hybrid structure</td></tr>
<tr><td>HR</td><td>High rise buildings (> 15 stories)</td><td rowspan="2">Others</td></tr>
<tr><td>TB</td><td>Tall buildings (> 60 stories)</td></tr>
</table>

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.

4.2.4 Calculation of benchmarks for buildings

The calculation of benchmarks for residential and office buildings is provided in the following paragraphs based on the statistical analysis of the buildings collected in the scope of the project *EFIResources*.

As already mentioned, the number of buildings collected is reduced and does not enable a proper statistical analysis. In spite of this limitation, the following procedure aims to illustrate the methodology adopted for the calculation of benchmarks, described in the previous text. Moreover, the following set of values will be used to demonstrate the approach for sustainable design, proposed in this report.

4.2.4.1 Benchmarks for residential buildings

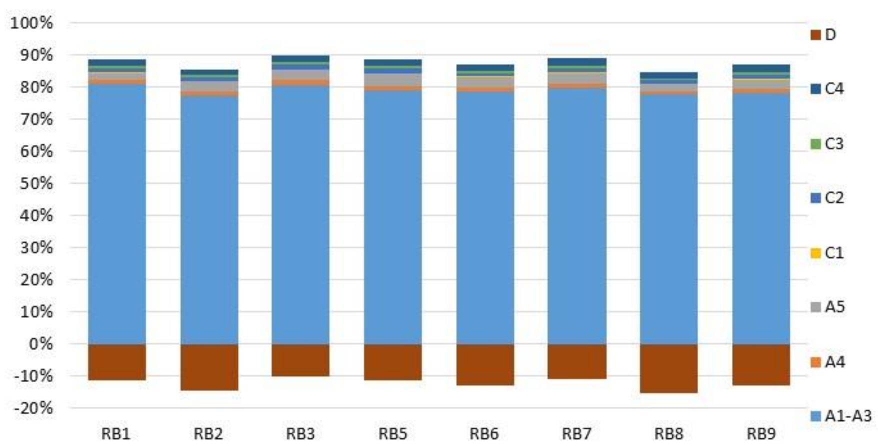
The calculation of benchmarks for residential buildings is based on data collected for eight medium-rise buildings and a single family house.

All data collected refers 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 Annex B. This set of buildings may be classified in Tier 4 as reinforced concrete buildings.

The LCA of each building was carried out based on the model described in sub-section 4.2.2 and with the software GaBi (version 8.1.0.29) [45]. All details about this model and about all the assumptions and scenarios that are required to perform the analysis, are provided in [35].

The results for the impact category of GWP are illustrated in Figure 16, showing the contribution of each module (see Table 7) to the aggregated result of the analysis.

Figure 16. Contribution to GWP of the different modules



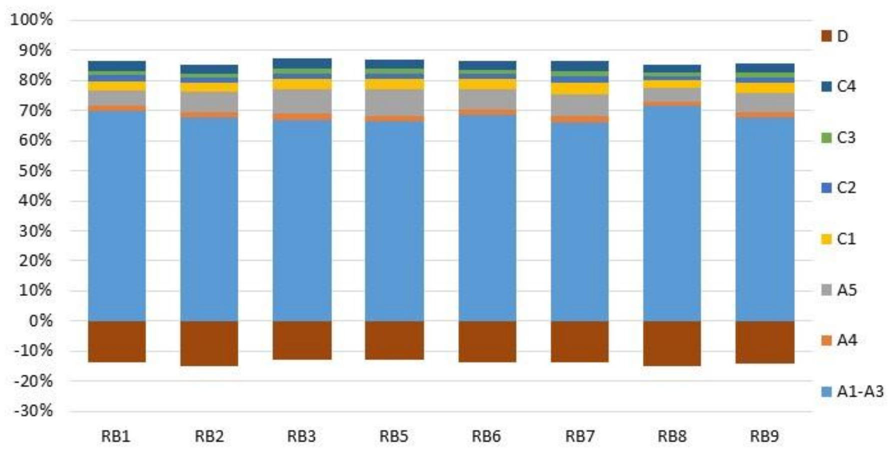
As observed from the above picture, the contribution of Modules A1-A3 is dominant for all buildings, with a share of about 80%. Module D has also a significant contribution, with a share of about 10%, in some cases, slightly higher. The contribution of the remaining modules, all together, account for the other share of 10%.

In relation to the impact category of Primary Energy (PE), the contribution of each module is illustrated in Figure 17. It is noted that this environmental category refers to the total use of primary energy resources, given by the sum of the non-renewable (PENRT) and renewable (PERT) components.

In this case, the contribution of Modules A1-A3 is still dominant for all buildings, but with a share of about 70%. On the other hand, the contribution of Module D remains about 10% for all buildings.

The contribution of the remaining modules is similar to the above environmental category, except for Module A5. In this case, the contribution of module A5 is underlined among the remaining modules, getting close to a share of 10% for some buildings.

Figure 17. Contribution to PE of the different modules



A statistical analysis was performed, based on the outcome of the LCA of the buildings, and the results are summarized in the following paragraphs. These results are relative to Tier 2 in Table 10.

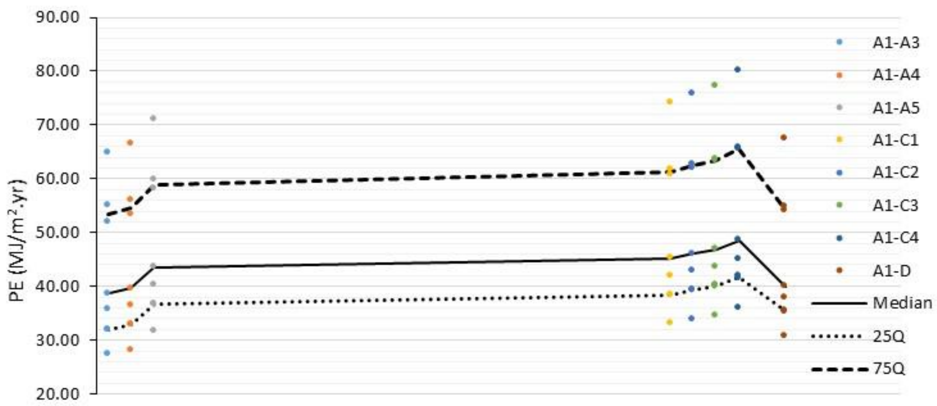
The range of the cumulative values over the life cycle of the buildings is indicated in Figure 18, for the impact category of GWP. The horizontal axis represents the lifetime of the buildings. A reference period of 50 years was considered for all cases.

In addition, Figure 18 indicates the median and the main quartiles of the cumulative range of values, over the reference period of time considered in the analysis.

Figure 18. Range of values for GWP in each module

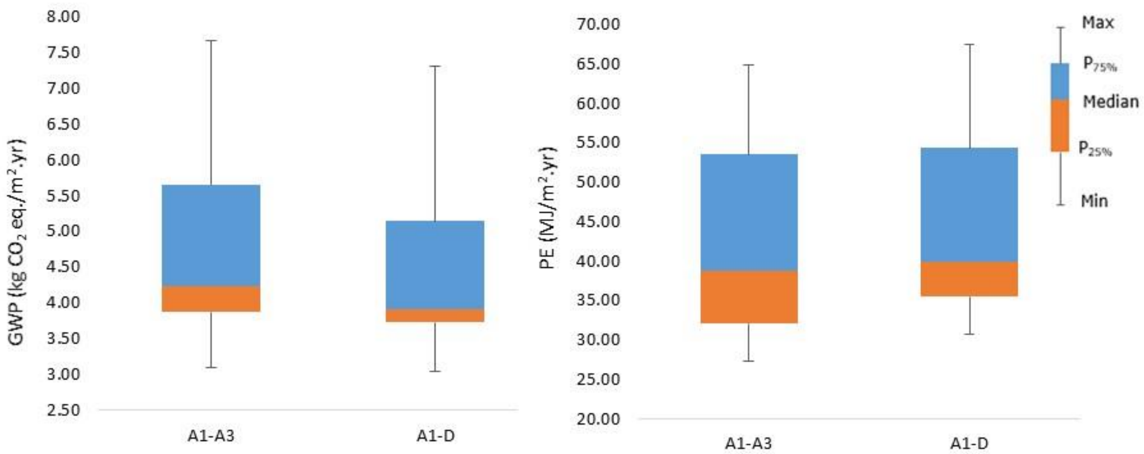
For the impact category of PE, a similar range of values was obtained and the results are represented in Figure 19

Figure 19. Range of values for PE in each module



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 20 for the impact categories of GWP and PE.

Figure 20. Range of values for GWP and PE in A1-A3 and A1-D



The results for the remaining environmental categories are provided in Table 11, per group of modules.

As previously stated, the implementation of uncertainties in LCA is needed to make the results of the analysis more credible.

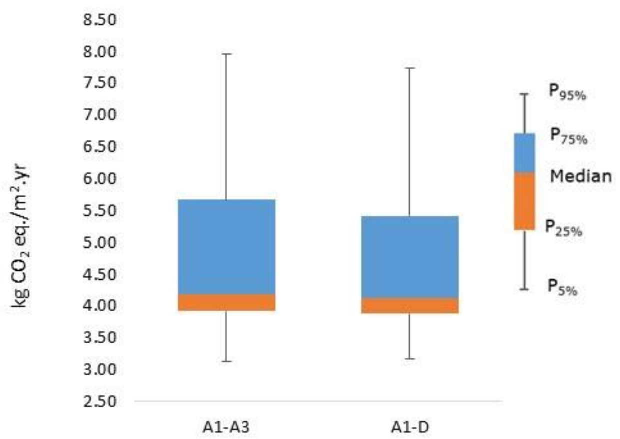
The propagation of the uncertainties in the LCA of each building was carried out based on the procedure described in sub-section 3.3 and illustrated in sub-section 3.4 of this report. The results of the probabilistic analysis of each building are given in Annex B, for the impact categories of GWP, AP, EP and POCP.

The resulting distribution of values, given by the 90% interval of confidence, for the set of buildings considered in the analysis is illustrated in Figure 21, for the impact category of GWP.

Table 11. Statistical results for residential buildings

		A1-A3	A4-A5	C1-C4	D	A1-D
ADP_f ($MJ/m^2.yr$)	Mean	37.53	2.64	5.38	-8.63	36.93
	Median	33.64	2.56	4.88	-8.39	32.47
	$P_{25\%}$	27.21	2.42	4.45	-11.71	28.61
	$P_{75\%}$	47.38	3.04	6.31	-5.86	45.58
AP (kg $SO_2/m^2.yr$)	Mean	1.37E-02	6.69E-04	1.35E-03	-1.35E-03	1.43E-02
	Median	1.29E-02	6.49E-04	1.22E-03	-1.37E-03	1.33E-02
	$P_{25\%}$	1.00E-02	6.12E-04	1.10E-03	-1.88E-03	1.10E-02
	$P_{75\%}$	1.75E-02	7.68E-04	1.58E-03	-8.32E-04	1.80E-02
EP (kg $PO_4^{3-}/m^2.yr$)	Mean	1.32E-03	1.02E-04	2.26E-04	-1.09E-04	1.54E-03
	Median	1.21E-03	9.61E-05	2.05E-04	-1.09E-04	1.38E-03
	$P_{25\%}$	1.05E-03	8.76E-05	1.85E-04	-1.50E-04	1.25E-03
	$P_{75\%}$	1.57E-03	1.17E-04	2.65E-04	-6.94E-05	1.80E-03
GWP_{exc} (kg CO_2 eq./m^2.yr)	Mean	4.92	0.23	0.26	-0.79	4.62
	Median	4.35	0.22	0.24	-0.78	4.02
	$P_{25\%}$	3.93	0.21	0.22	-1.08	3.80
	$P_{75\%}$	5.75	0.26	0.31	-0.51	5.26
POCP (kg $C_2H_4/m^2.yr$)	Mean	1.06E-03	-6.39E-05	5.68E-05	-3.22E-04	7.34E-04
	Median	1.01E-03	-5.68E-05	5.15E-05	-3.24E-04	6.91E-04
	$P_{25\%}$	7.17E-04	-8.04E-05	4.68E-05	-4.45E-04	5.14E-04
	$P_{75\%}$	1.46E-03	-4.30E-05	6.63E-05	-1.99E-04	9.68E-04

Figure 21. Distribution of values for GWP in A1-A3 and A1-D



Although the distributions resulting from the uncertainty analysis of each building have a shape close to a normal distribution (see Annex B), the resulting distribution from the set of buildings is not normal distributed. This was already expected as the number of buildings considered in the analysis is reduced.

However, in virtue of the central limit theorem [17], *the sampling distribution of the sample means approaches a normal distribution as the sample size gets larger, irrespective of the shape of the population distribution*.

Therefore, with a higher number of buildings, it is expected that the resulting distribution will become normal distributed.

4.2.4.2 Benchmarks for office buildings

In the case of office buildings, two different types of analyses are performed. The first is based on data collected for low and medium rise buildings, in the scope of the project *EFIResources*, and the process is similar to the one described for residential buildings. The second type of analysis is performed based on literature data for tall buildings.

In the former analysis, benchmarks are calculated based on the statistical procedure previously described and used for the calculation of benchmarks for residential buildings. In the second case, the calculation is based on a reference building, aiming to be representative of tall buildings.

4.2.4.2.1 Low to medium-rise buildings

The BoM of the main materials and detailed LCA calculation for each building are given in Annex C. Since the bill of materials for some buildings did not include the foundations, the LCA and the following statistical analysis were made for the structural system of each building, excluding the foundations.

In this case, ten buildings were collected, in which two buildings are classified as medium-rise buildings and the remaining buildings fall into the category of low-rise buildings, according to Table 10.

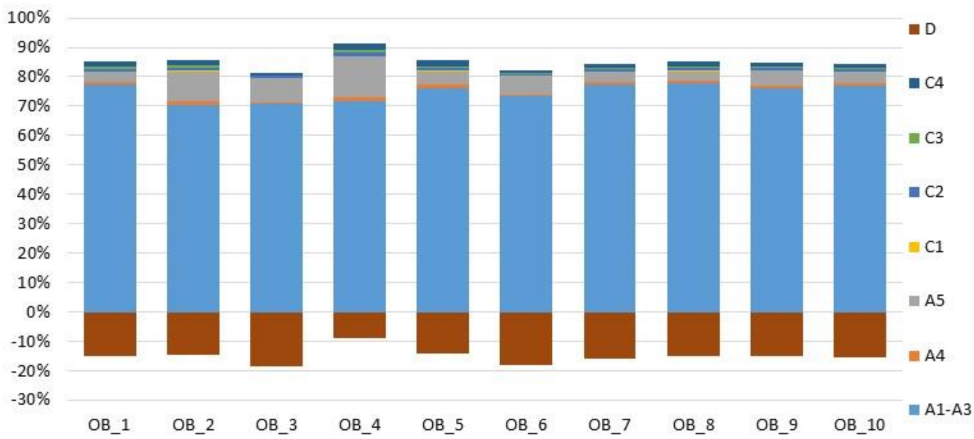
In relation to Tier 4, four buildings are classified as reinforced concrete buildings and the other six are classified as composite (concrete and steel) buildings.

The LCA of each building was carried out based on the model described in sub-section 4.2.2 and with the software GaBi (version 8.1.0.29) [45]. All details about this model and about all the assumptions and scenarios that are required to perform the analysis, are provided in [35].

Likewise, in this sub-section, relevance is provided to the environmental categories of Global Warming Potential (GWP) and Primary Energy (PE). It is noted that the environmental category of PE refers to the total use of primary energy resources, given by the sum of the non-renewable (PENRT) and renewable (PERT) components

The results for the impact category of GWP are illustrated in Figure 22, showing the contribution of each module to the aggregated result of the analysis.

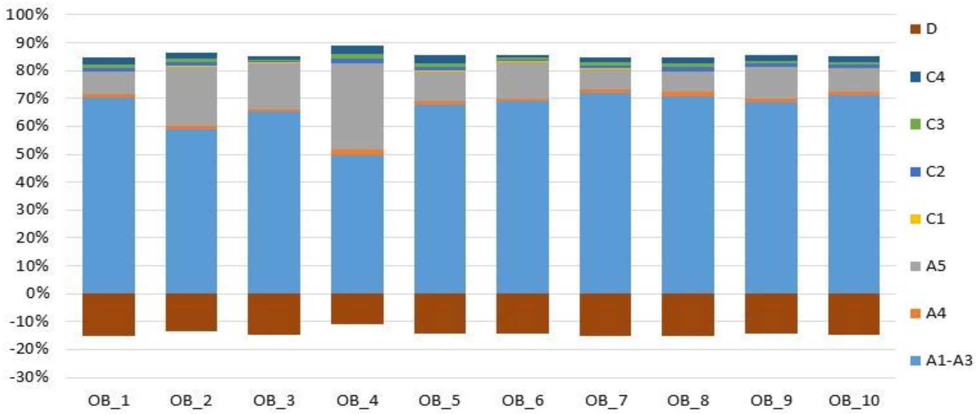
Figure 22. Contribution to GWP of the different modules



The highest contribution is clearly of Modules A1-A3, with a share higher than 70%. Module D has also a significant contribution, higher than 10%, and in some cases, close to 20%. In addition, Module A5 has a relevant contribution, in particular for some buildings. This difference, in relation to residential buildings, is due to different scenarios assumed for the construction stage of both types of buildings, as described in [35].

In relation to the impact category of Primary Energy (PE), the contribution of each module is illustrated in Figure 23. In this case, the contribution of Modules A1-A3 is about 60% to 70% for most of the buildings. On the other hand, Module D has about the same importance as Module A5. In few cases, the contribution of the later is even higher.

Figure 23. Contribution to PE of the different modules



A statistical analysis was performed, based on the outcome of the LCA of the buildings, and the results are summarized in the following paragraphs. These results are relative to Tier 2 in Table 10.

The range of the cumulative values over the life cycle of the buildings is indicated in Figure 24 and Figure 25, for the impact categories of GWP and PE, respectively. It is noted that the horizontal axis represents the lifetime of the buildings, considered to be 50 years for all cases. These graphs indicate the median and the main quartiles of the cumulative range of values over the reference period of time considered in the analysis.

Figure 24. Range of values for GWP in each module

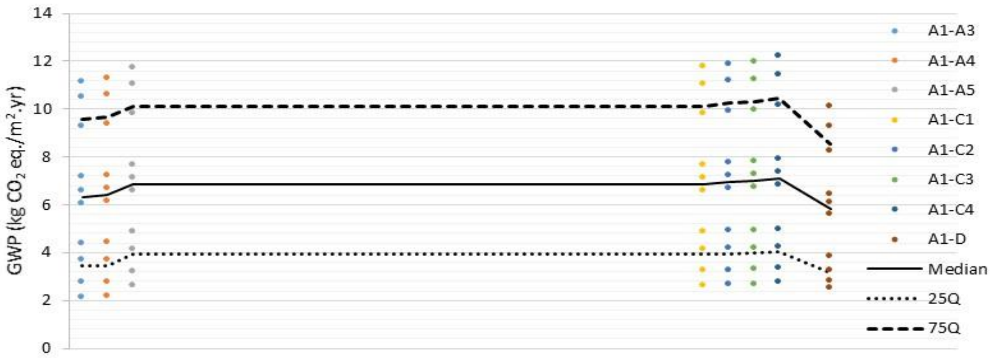
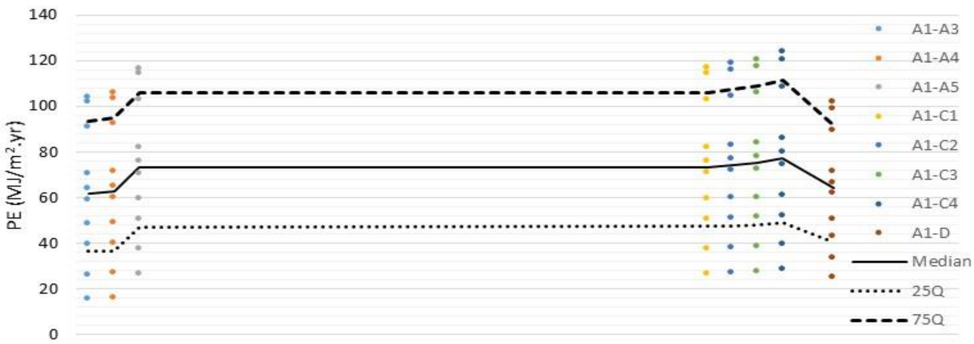
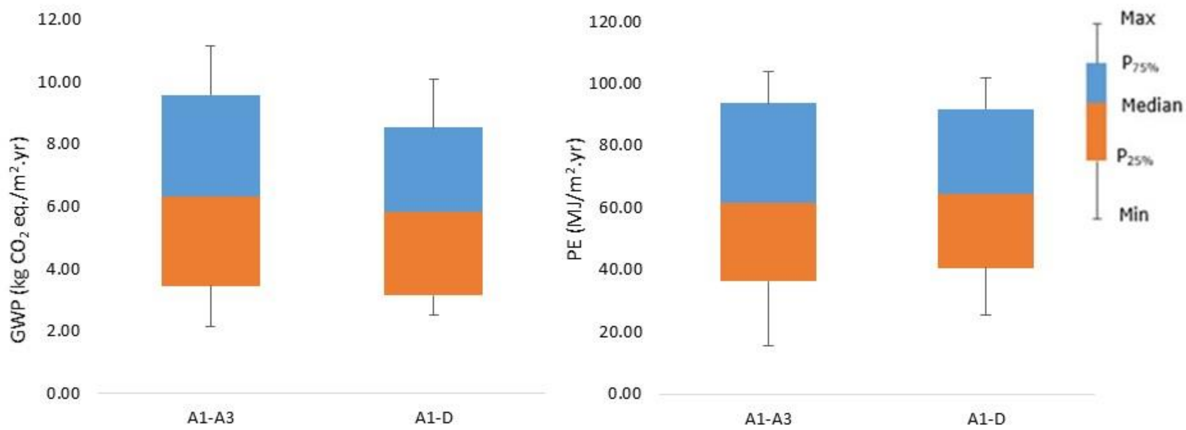


Figure 25. Range of values for PE in each module



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 26 for the impact categories of GWP and PE.

Figure 26. Range of values for GWP and PE in A1-A3 and A1-D



The results for the remaining environmental categories are provided in Table 12, per group of modules.

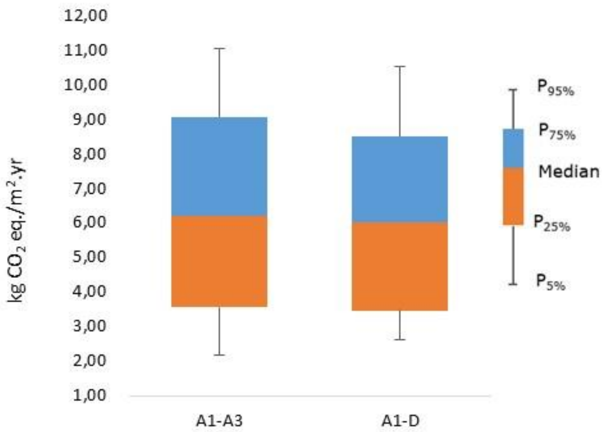
Table 12. Statistical results for office buildings

		A1-A3	A4-A5	C1-C4	D	A1-D
ADP_{fossil} (MJ/m^2.yr)	Mean	55.80	5.75	3.33	-13.35	51.53
	Median	55.10	5.78	3.38	-13.02	51.40
	$P_{25\%}$	32.22	5.26	1.70	-19.92	30.03
	$P_{75\%}$	84.52	6.23	4.96	-8.70	75.79
AP (kg SO_2/m^2.yr)	Mean	2.01E-02	1.38E-03	1.20E-03	-2.43E-03	2.03E-02
	Median	2.05E-02	1.35E-03	1.22E-03	-2.35E-03	2.09E-02
	$P_{25\%}$	9.41E-03	1.31E-03	6.14E-04	-3.62E-03	9.91E-03
	$P_{75\%}$	3.13E-02	1.45E-03	1.79E-03	-1.67E-03	3.09E-02
EP (kg PO_4^{3-}/m^2.yr)	Mean	1.72E-03	1.57E-04	2.01E-04	-1.86E-04	1.89E-03
	Median	1.74E-03	1.52E-04	2.03E-04	-1.80E-04	1.94E-03
	$P_{25\%}$	8.48E-04	1.43E-04	1.03E-04	-2.77E-04	9.53E-04
	$P_{75\%}$	2.60E-03	1.73E-04	3.00E-04	-1.26E-04	2.79E-03
GWP_{exc} (kg CO_2 eq./m^2.yr)	Mean	6.45	0.52	0.23	-1.31	5.90
	Median	6.44	0.52	0.24	-1.27	5.95
	$P_{25\%}$	3.52	0.48	0.12	-1.95	3.22
	$P_{75\%}$	9.68	0.56	0.35	-0.88	8.63
POCP (kg C_2H_4/m^2.yr)	Mean	1.80E-03	2.16E-05	4.21E-05	-5.75E-04	1.29E-03
	Median	1.75E-03	2.71E-05	4.31E-05	-5.54E-04	1.25E-03
	$P_{25\%}$	1.12E-03	1.66E-06	2.15E-05	-8.55E-04	7.94E-04
	$P_{75\%}$	2.70E-03	3.71E-05	6.27E-05	-3.92E-04	1.91E-03
PE (MJ/m^2.yr)	Mean	6.20E+01	1.16E+01	3.77E+00	-1.31E+01	6.43E+01
	Median	6.16E+01	1.16E+01	3.86E+00	-1.29E+01	6.43E+01
	$P_{25\%}$	3.64E+01	1.10E+01	1.93E+00	-1.96E+01	4.06E+01
	$P_{75\%}$	9.36E+01	1.21E+01	5.60E+00	-8.27E+00	9.18E+01

Likewise, the propagation of the uncertainties in the LCA of each building was made according to the procedure described in sub-section 3.3 and illustrated in sub-section 3.4 of this report. The results obtained for each building are indicated in Annex C.

The resulting distribution of values for the set of buildings, given by the 90% interval of confidence, is illustrated in Figure 27, for the impact category of GWP.

Figure 27. Distribution of values for GWP in A1-A3 and A1-D



Given the reduced number of buildings considered in the analysis, the resulting distribution from the set of building is not normal distributed.

However, as previously explained, it is expected that the resulting distribution will become normal distributed with a higher number of buildings.

4.2.4.2.2 Tall buildings

Tall buildings were first built in the U.S. but are currently spread everywhere around the world. They are considered as a symbol of modernity and prosperity and the quest for the highest building is continually pursued by many wealthy countries around the world.

Due to their height, the design of the structural system of tall buildings is very demanding in terms of the resistance to horizontal loads. Consequently, the structural system of tall buildings is different from lower buildings and they require a greater amount of structural materials.

Tall buildings are a particular type of buildings in the context of LCA. The main reason for this is the reference period of time considered for the analysis, which goes far beyond the traditional period of 50-70 years. It is not reasonable to build such type of buildings, with the consequent use of such huge amount of materials, for a relative 'short' period of time. In fact, there is not much data about the demolition of such buildings, except due to unforeseen events, such as the terrorist attacks in the U.S. [54].

The analysis presented in the following paragraphs is based on data provided by a previous research work performed by Trabucco et al. [54]. In the referred study, a life cycle analysis was performed for a building with 60 floors (about 246 m of height and a gross floor area per floor of 2400 m^2) and a building with 120 floors (about 490 m of height and a gross floor area per floor of 3750 m^2). The study is based on a fictitious building prototype, aiming to be representative of tall building practice in the U.S.

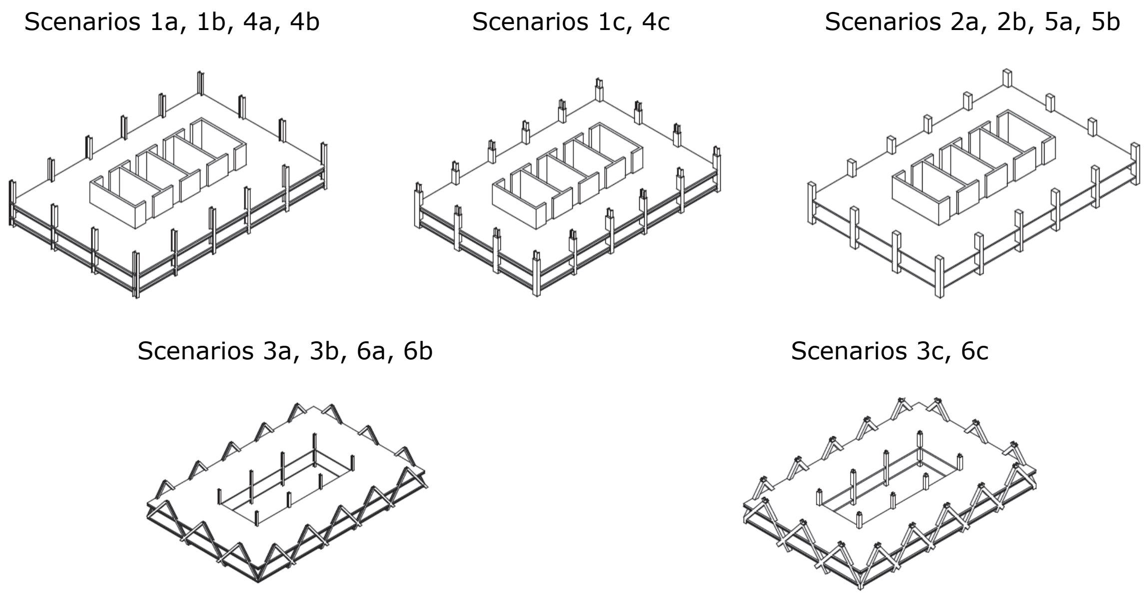
Moreover, in order to enable a comparison of the relative importance of different materials and construction systems, the study took into account the most common structural systems for such buildings. Hence, different scenarios were defined for the two buildings, taking into account: (i) the primary system for resisting lateral loads (internal central core or external diagrid system), (ii) different types of slabs and (iii) different grades for steel and concrete. In the total 16 scenarios were defined for both types of buildings, as indicated in Table 13 and illustrated in Figure 28.

Table 13. Characteristics of the structural system of the buildings (adapted from [54])

Scenario		Structural systems	
60 floors	120 floors	Vertical elements	Horizontal elements
1a	4a	Concrete core with standard steel frame	Concrete-steel composite slab
1b	4b	Concrete core with high strength steel frame	Concrete-steel composite slab
1c	4c	Concrete core with composite columns	Concrete-steel composite slab
2a	5a	Concrete columns	Concrete wide and shallow beams
2b	5b	Concrete columns	Concrete narrow and deep beams
3a	6a	Steel diagrid	Concrete-steel composite slab
3b	6b	High strength steel diagrid	Concrete-steel composite slab
3c	6c	Composite diagrid	Concrete-steel composite slab

The inventory of materials for each scenario is relative to the structural system of the building above ground. The foundations were excluded in the aforementioned research work and therefore they are not considered in the present LCA.

Figure 28. Structural systems of the buildings [54]



The LCA of tall buildings provided in the following paragraphs is mainly based on building data from the above reference. A few exceptions were considered, as explained in the following paragraphs:

- For the stage of material production (modules A1-A3), the inventory of materials for each scenario considered in the analysis was obtained from the referred source. Each building scenario was designed by two different engineering firms. Therefore, the total number of BoM for each type of building is 16.
- For the construction stage (modules A4-A5), the transportation distances were considered assuming that the buildings were built in Europe; therefore, some

differences were considered in module A4, in relation to the distances considered in the source. However, in relation to on-site operations (module A5), all data was considered from [54], which included the use of equipment (cranes and pumping system for concrete) and respective energy consumption. In this case, data was obtained from firms specialised in the construction of tall buildings.

- The environmental impacts during the operation stage were considered to be minimal and therefore, Modules B1-B5 were not taken into account in the analysis.
- Data for the end-of-life stages (C1-C4) was also obtained from the aforementioned source; which, in this case, was estimated from large demolition contractors and included the diesel fuel required to operate machinery. Likewise, the transportation distances of debris was estimated based on the European context (module C2).
- In relation to Module D, the recycling scenarios considered for concrete and steel are the ones defined in the model summarized in sub-section 4.2.2. Thus, in particular data used for the scenario of concrete recycling, is slightly different from the scenario described in [54].

As it is hard to set an accurate lifetime for this type of buildings, no period of time was associated with the unit of the analysis. Hence, in this case, the results of the LCA for each environmental category, are provided for the following functional equivalent:

$$Building\ performance\ for\ environmental\ category\ i = \frac{Environmental\ result\ i}{GFA} \quad (22)$$

Apart from this slightly different functional equivalent, the LCA was performed based on the LCA model used for the previous building types, and summarized in sub-section 4.2.2. Likewise, the analysis was performed with GaBi and all environmental data was provided from the generic database of the software.

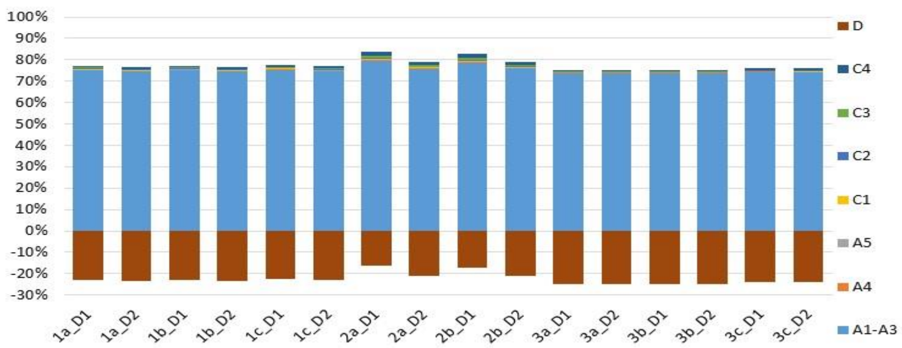
The life cycle results for both types of buildings are provided in the following paragraphs. The focus is given to two impact categories: Global Warming Potential (GWP) and Primary Energy (PE). The results for the remaining impact categories are given in Annex C.

As previously indicated, for each building scenario, two BoM from two different building designers are provided in [54]. Hence, for each building type, 16 BoM were taken into account. For each scenario, references D1 and D2 correspond to the two distinct designs.

i) Buildings with 60 floors

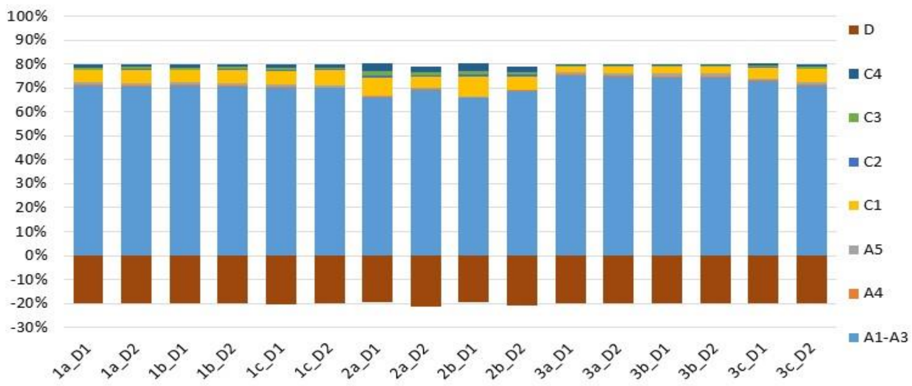
The results for the impact category of GWP are illustrated in Figure 29, showing the contribution of each module to the aggregated result of the analysis.

Figure 29. Contribution to GWP of the different modules



Likewise, the results for the impact category of PE are illustrated in Figure 30.

Figure 30. Contribution to PE of the different modules



For both impact categories, the contribution of Modules A1-A3 is dominant for all scenarios with values varying from 70% to 80%.

The contribution of Module D is also similar for both impact categories. In this case, the values for most scenarios are slightly higher than 20% for GWP and about 20% for PED.

The contribution of the remaining modules is negligible for GWP and has a contribution, in general, lower than 10% for PE.

The range of the cumulative values over the life cycle of the building, is indicated in Figure 31 and Figure 32, for the impact categories of GWP and PE. The horizontal axis in the following graphs aims to represent the lifetime of the buildings. However, in this case, no period of time was assigned to the analyses.

Figure 31. Range of values for GWP in each module

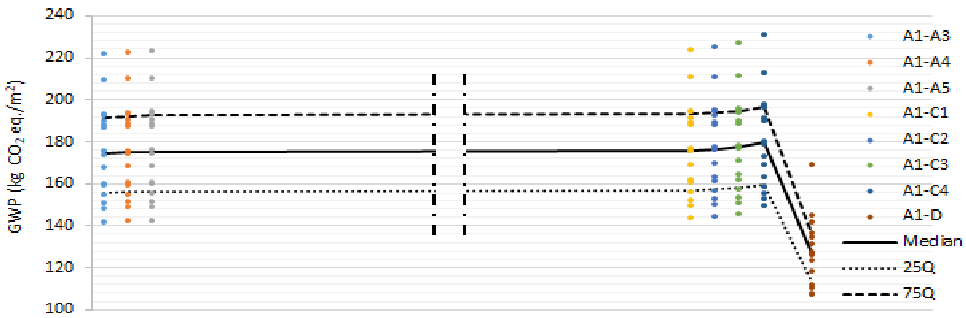
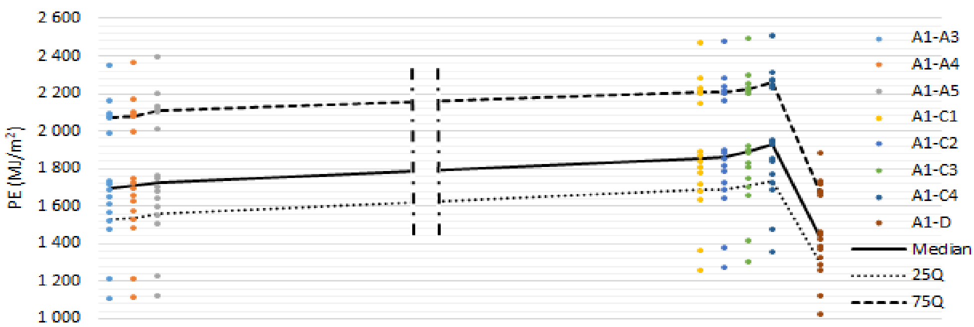


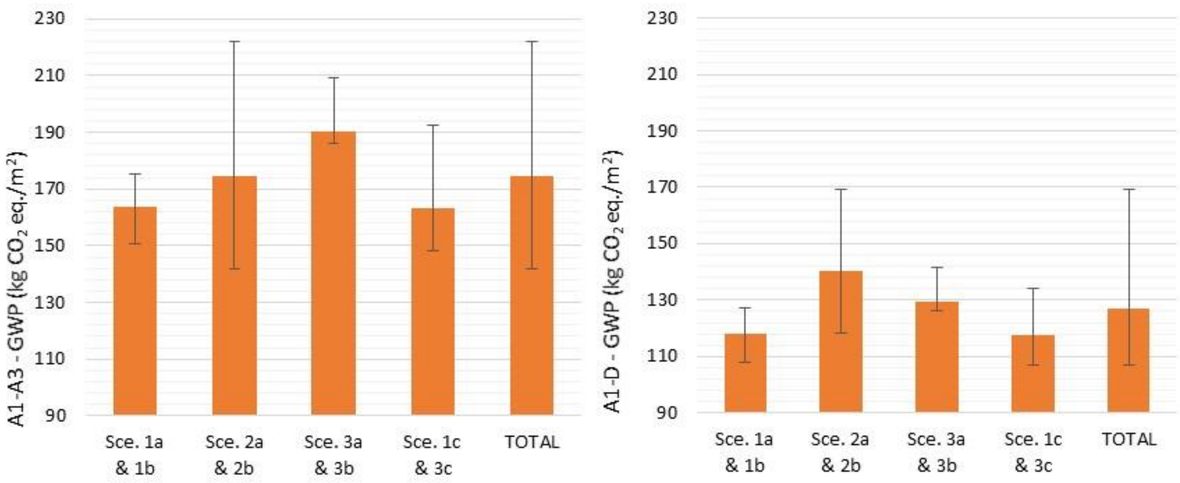
Figure 32. Range of values for PE in each module



As already observed from the contribution graphs, the most important stages are the initial stage of material production (A1-A3) and the recycling stage (Module D). Moreover, to assess the influence of different structural systems, the values for modules A1 to A3 and A1 to D are represented for each structural system (according to Table 13) in Figure 33 and Figure 34, for GWP and PE, respectively. The graphs show the median value for each scenario, together with minimum and maximum values.

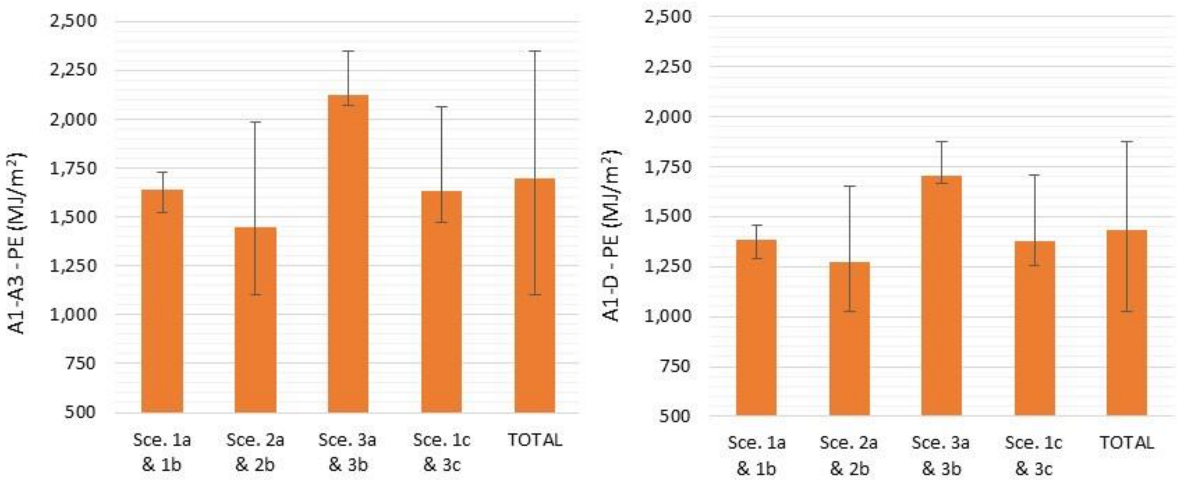
As observed from Figure 33, the selection of a structural systems has influence in the outcome of the analysis. For Modules A1-A3, the difference between structural systems is up to 16%.

Figure 33. Range of values for GWP in A1-A3 and A1-D



However, independently of the structural system, all cases benefit from the recycling of materials, in the end-of-life stage. This benefit is higher for scenarios 3a and 3b, which are relative to a steel structure.

Figure 34. Range of values for PE in A1-A3 and A1-D



For the environmental category of PE, similar conclusions may be drawn from Figure 34. However, in this case, all structural systems have about the same benefit in terms of recycling.

ii) Buildings with 120 floors

A similar analysis was performed for the building with 120 floors. In this case, the results of the contribution analysis for the impact categories of GWP and PE, are illustrated in Figure 35 and Figure 36, respectively.

Figure 35. Contribution to GWP of the different modules

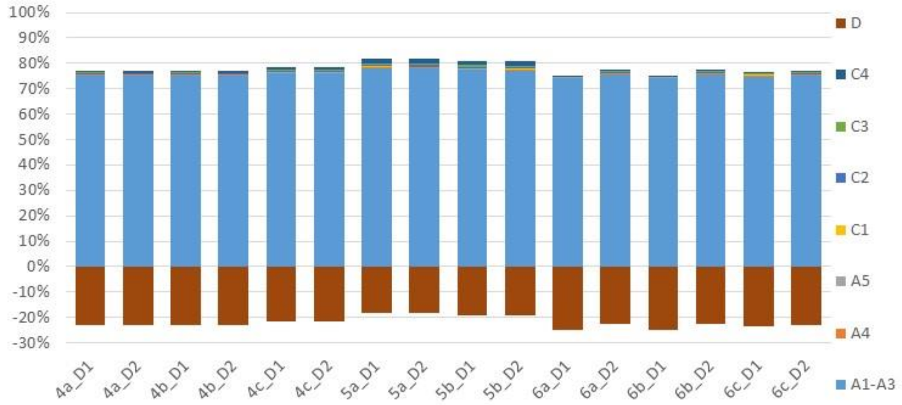
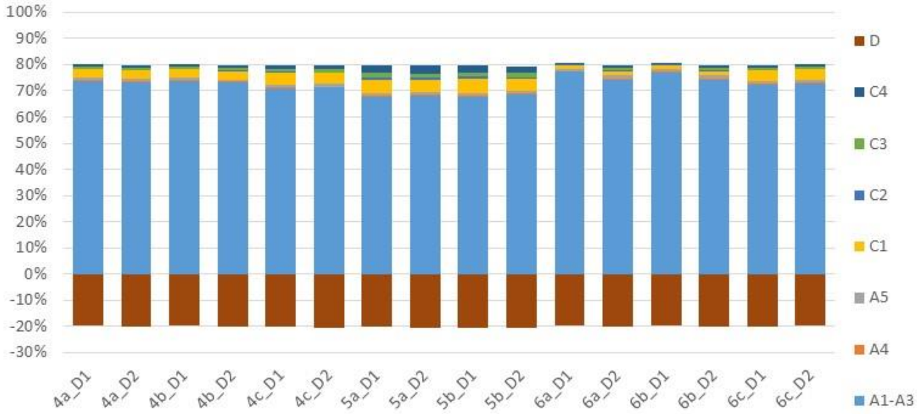


Figure 36. Contribution to PED of the different modules



The above results are similar to the results obtained for the previous building. In all cases, the stage of material production (Modules A1-A3) is the most relevant stage, followed by the recycling of materials in the end-of-life stage (Module D).

Additionally, the range of the cumulative values over the life cycle of the building, is indicated in Figure 37 and Figure 38, for the impact categories of GWP and PE, respectively.

Figure 37. Range of values for GWP in each module

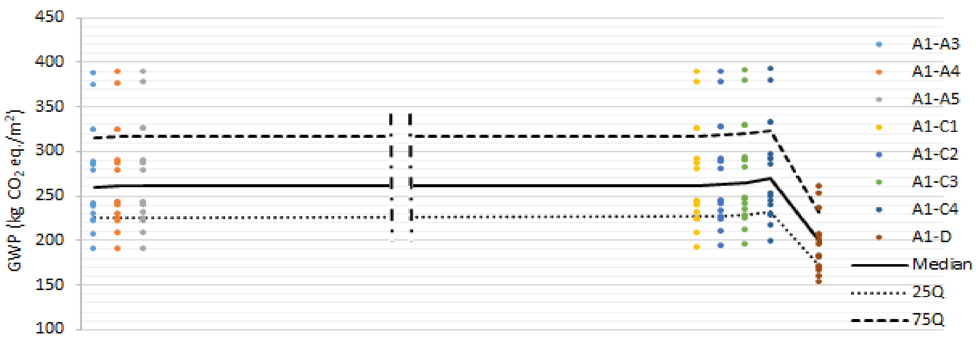
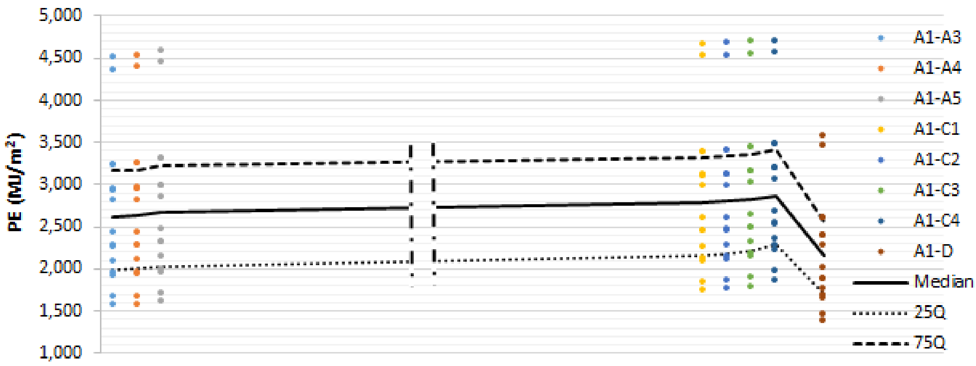


Figure 38. Range of values for PED in each module



Focussing on the structural system (see Table 13) of the building and on the main stages, the median, minimum and maximum values for each scenario are indicated in Figure 39 and Figure 40, for GWP and PE, respectively.

Figure 39. Range of values for GWP in A1-A3 and A1-D

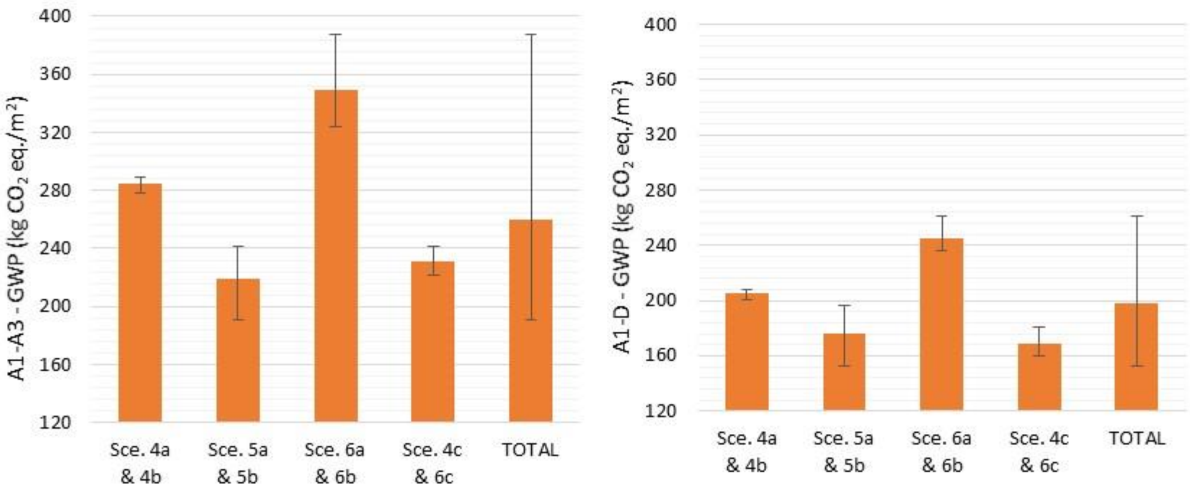
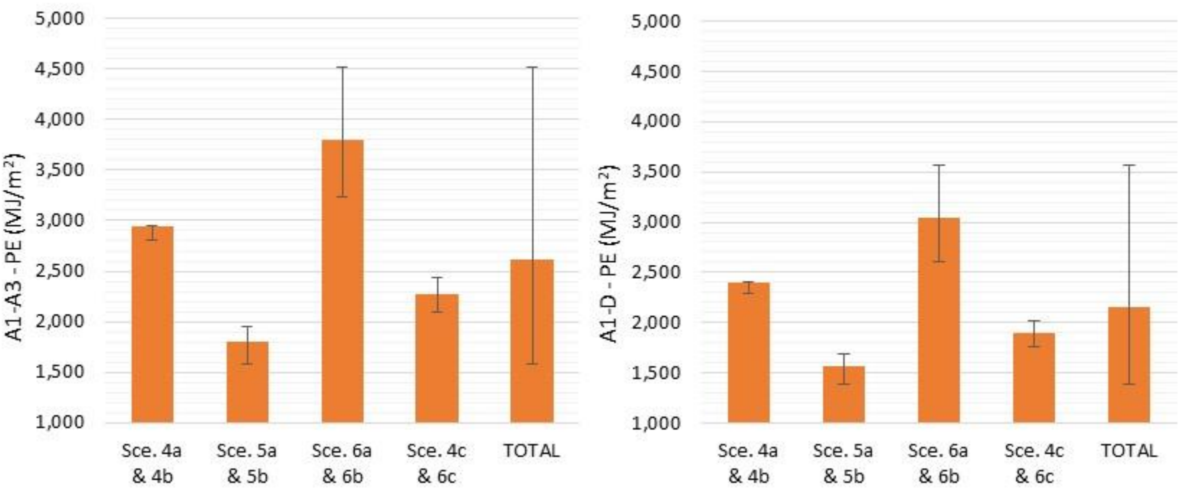


Figure 40. Range of values for PE in A1-A3 and A1-D



As observed from Figure 39 and Figure 40, the selection of the structural system has even a higher influence in the outcome of the analysis. In this case, the difference between structural systems is about 60% for GWP and more than 100% for PE.

As already expected, regardless of the structural system, all cases equally benefit from the recycling of materials, in the end-of-life stage.

iii) Remarks about this study

In general, the results of the analysis are consistent with the values provided in [54]. However, some discrepancies were found between both results. Apart from some differences in terms of building scenarios, as previously described, another major reason for such discrepancies is the use of different environmental data.

Table 14 indicates the values of GWP and embodied energy (EE) for the production of 1 kg of steel and 1 kg of concrete, considered in both analyses. The first two columns refer to the environmental data used in [54], while the two last columns refer to the environmental data used in the present study, which is based on the generic database of GaBi software. In both cases, data is relative only to Modules A1-A3.

Table 14. Differences in environmental data of materials

	Values considered in [54]		Values considered in this study	
	GWP (kg CO_2 eq./kg)	EE (MJ/kg)	GWP (kg CO_2 eq./kg)	EE (MJ/kg)
Steel rebar	1.24	16.42	1.92	23.40
Steel sections	1.14	14.80	1.52	19.10
Concrete C30/37	0.11-0.15	0.83-1.22	0.11	0.62
Concrete C35/45	0.15-0.17	1.21-1.28	0.13	0.70
Concrete C45/55	0.17-0.20	1.25-1.49	0.13	0.66
Concrete C50/60	0.16-0.24	1.23-1.60	0.14	0.69

The environmental data used in [54] refers to the U.S. context, while the generic database of GaBi is based on average European values. The variability of environmental data and consequently, the variability of the outcome of the LCA has already been addressed in [35].

4.2.4.3 Synopsis of benchmarks for residential and office buildings

The benchmarks for residential and office buildings are summarized in Table 15 for the environmental category of GWP. These results are relative to Tier 2 level in Table 10.

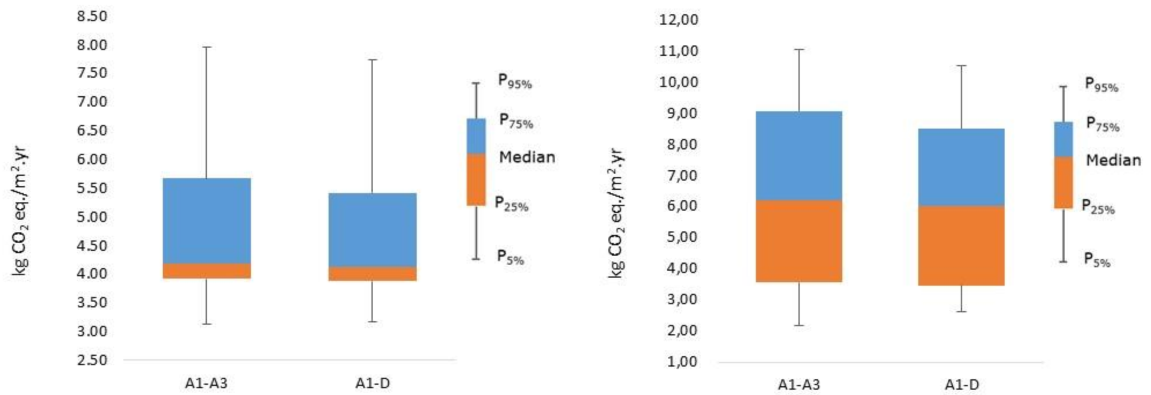
Table 15. Summary of values of GWP (kg CO_2 eq./m^2.yr) for Tier 2

		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

When uncertainties are taken into account in the life cycle analysis of each building, the resulting distribution of values, given by the 90% interval of confidence, for the set of buildings considered in the analysis is illustrated in Figure 41, for the impact category of GWP.

Figure 41. Distribution of values for GWP in A1-A3 and A1-D, for residential and office buildings

(a) residential buildings (b) office buildings



Taking into account the volume of the building (Tier 3), the minimum and maximum values are indicated in Table 16, 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 16. 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 comparison with other office buildings, the values for tall buildings are lower than expected, taking into account the higher demands of the respective structural system. Nevertheless, these values are based on a single study and therefore, no trend may be established from this analysis.

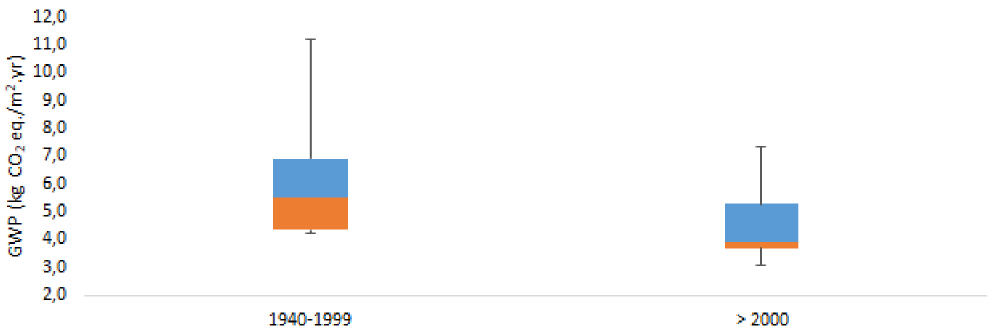
In relation to Tier 4, the minimum and maximum values for each structural system are given in Table 17.

Table 17. 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

Finally, the values obtained for residential buildings provided in this report, which are based on recent building designs (made after the year 2000), are compared in Figure 40 with the values referring to building data representative of the building stock in the second half of the XX century, provided in the previous report [36].

Figure 42. Comparison of values (in terms of GWP) referring to building data from different periods of time



As observed from Figure 40, there is a clear reduction of the values found from the two sets of buildings, in terms of median values and in terms of scatter of values. Regardless of the limitations of the study presented in this report, this optimistic trend may be representative of some improvements over the years on the way buildings are designed, with more efficient materials and structural systems.

As previously emphasized, the values provided in the above tables cannot be considered as representative of the current building stock, 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 may serve as reference for future works and they will be used to illustrate the approach for sustainable design, described in the following sub-section.

Finally, it is observed that the values provided in Table 15 to Table 17 are limited to the structural system of buildings but it is hoped that in the near future, similar values will be available for the full building, thus effectively increasing the efficiency of the building sector.

4.3 Limit state of sustainability

As described in Section 2, 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.

In this section, a performance-based approach for sustainable design is proposed, which enables to assess the efficient use of resources in buildings throughout the complete life cycle of the building, and complies with the design rules and reliability provisions of the Eurocodes.

In a 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 a lower environmental performance than a 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, 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 (23)

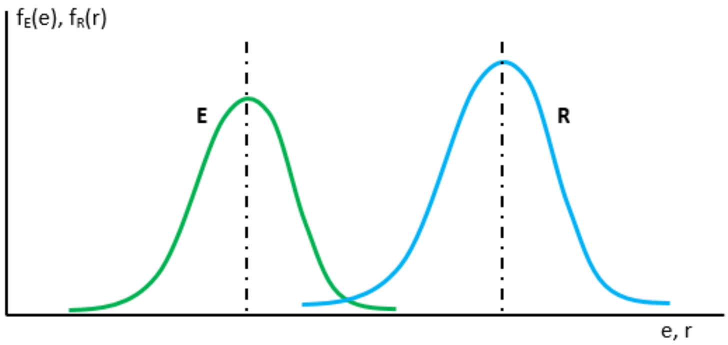
$$E \leq R \tag{23}$$

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

$$S = E - R \leq 0 \tag{24}$$

As discussed in the previous section of this report, both variables are 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. 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 43.

Figure 43. 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 better than the reference one, is given by,

$$P\{f(S) \leq 0\} \tag{25}$$

This new limit state is herein denominated sustainability limit state and is complementary to the ultimate and serviceability limit states introduced in Section 2.

The determination of the probability above may be solved by any of the methods described for the determination of the probability of failure, expressed by (5).

In this case, defining a reliability index β^* similar to the one expressed by (10) and assuming that both *E* and *R* are normal distributed, the probability of achieving a good environmental performance can be provided by the tables of the standard normal distribution:

$$P(E - R < 0) = \Phi(-\beta^*) \tag{26}$$

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

As already referred, the distributions resulting from the uncertainty analysis of individual buildings have a shape close to a normal distribution (see Annexes B and C) but the resulting distribution for the set of buildings (either residential and office buildings) is not normal distributed. Hence, the lack of statistical information for the buildings is currently a limitation in the application of the reliability index. Nevertheless, as previously explained, this limitation will be reduced by increasing the number of buildings in the sample and consequently, improving the statistical evaluation of the sampling distribution, which will then tend to be normal distributed.

The calculation of the probability given by (25) 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 (see Table 1).

In 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.

An alternative way of measuring the difference between the two values, may be the ratio of the percentiles of the distributions *E* and *R*. For instance, considering the 95% percentile of the distribution *E* ($e_{95\%}$) and the 50% percentile of distribution *R* (median value) ($r_{50\%}$), the quotient of both should be higher than 1,

$$\frac{r_{50\%}}{e_{95\%}} \geq 1.0 \tag{27}$$

This ensures that, at least 95% of all values of the distribution *E* are lower than 50% of all values of the distribution *R*.

However, when best practices are pursued, then instead of the median value of distribution *R*, the 25% percentile may be used instead, as given by,

$$\frac{r_{25\%}}{e_{95\%}} \geq 1.0 \tag{28}$$

Naturally, this would lead to a lower overlap of the distributions in Figure 43.

Finally, in order to avoid the need for probabilistic or semi-probabilistic methods, partial coefficients may be considered in both sides of the comparative function, to account for the respective uncertainties, based in the analogy with the partial coefficients discussed in sub-section 2.3. However, the calibration of partial coefficients requires statistical data of buildings, which has already been emphasized as a major limitation.

5 Conclusions

This report focussed on 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 the harmonization between structural design and sustainability design of buildings, and is based on the concept of 'limit state', which is a concept that is familiar to architects and engineers.

Therefore, the limit state of sustainability was introduced, 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 for the environmental performance of buildings, which are aimed to be updated over time, will provide 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.

Based on the statistical analysis of data collected for real residential and office buildings, benchmarks were defined for these two buildings typologies. The set of benchmarks obtained for residential buildings was compared with a previous set of values, showing an optimistic trend that could be representative of some improvement over the years on the way buildings are designed, with more efficient materials and structural systems.

However, 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. In fact, the sample used for the evaluation of such values is reduced and, *per se*, do not enable a proper statistical evaluation.

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.

References

[1] COM(2011) 571 final, Communication from the Commission to the European Parliament, the Council, The European Economic and Social Committee and the Committee of the regions, Roadmap to a Resource Efficient Europe, Brussels.

[2] Lorch, R., *Climate policies for buildings*, Building Research Information, Vol. 45, no. 5, pp. 475-477, 2017.

[3] Gervásio, H., Martins, R., Santos, P., Simões da Silva, L., *A macro-component approach for the assessment of building sustainability in early stages of design*, Building and Environment 73, 2014, pp. 256-270.

[4] COM(2014) 445 final, Communication from the Commission to the European Parliament, the Council, The European Economic and Social Committee and the Committee of the regions on Resource Efficiency opportunities in the building sector, Brussels.

[5] COM(2015) 614 final, Communication from the Commission to the European Parliament, the Council, The European Economic and Social Committee and the Committee of the regions, Closing the loop – An EU action plan for the Circular Economy, Brussels.

[6] Dodd, N., Donatello, M., Traverso, M., Donatello, S., *Level(s) – A common EU framework of core sustainability indicators for office and residential buildings, Parts 1 and 2: Introduction to Level(s) and how it works* (Draft Beta v1.0), JRC Technical Report, 2017, EC.

[7] EN 1990:2002 + A1:2005, Eurocode: Basis of Structural Design, CEN, Brussels.

[8] Schneider, J., Vrouwenvelder, T., *Introduction to safety and reliability of structures*, SED 5, 3rd reviewed and extended edition, IABSE, 2017, Zurich.

[9] Tankova, T., Simões da Silva, L., Marques, L., Rebelo, C., Taras, A., *Towards a standardized procedure for the safety assessment of stability design rules*, Journal of Constructional Steel Research, Vol. 103, 2014, pp. 290-302.

[10] Tankova, T., Marques, L., Simões da Silva, L., Rebelo, C., Taras, A., *Safety assessment of EC3 stability design rules for the lateral-torsional buckling of prismatic beams*, Advanced Steel Construction, 14(4), 2018.

[11] Tankova, T., Marques, L., Simões da Silva, L., Rebelo, C., *Safety assessment of EC3 stability design rules for the flexural buckling of columns*, Advanced Steel Construction, 12(3), 2016, pp. 328-358.

[12] Gulvanessian, H., Calgaro, J-H., Holicky, M., *Designers' Guide to EN 1990. Eurocode: Basis of Design*, Thomas Telford Publishing, London, 2002.

[13] Huijbregts, M., Gilijamse, W., Ragas, A., Reijnders, L., *Evaluating uncertainty in environmental life-cycle assessment. A case study comparing two insulation options for a Dutch one-family dwelling*, Environmental Science & Technology, Vol. 37, no. 11, 2003, pp. 2600-2608.

[14] Lloyd, S., Ries, R., *Characterizing propagating and analysing uncertainty in life-cycle assessment*. *A survey of quantitative approaches*, Journal of Industrial Ecology, Vol. 11, no. 1, 2007, pp. 161-179.

[15] Schaltegger, S. (ed), Life cycle assessment (LCA) - Quo Vadis?, Birkhauser, Verlag, 1996.

[16] Heijungs, R., Huijbregts, M., *A review of approaches to treat uncertainty in LCA. Complexity and integrated resources management*, Proceedings of the 2nd biennial meeting of the International Environmental Modelling and Software Society (iEMSs), C. Pahl-Wostl et al. (Eds), 2004, Manno, Switzerland.

[17] Ang, A., Tang, W., Probability concepts in Engineering. Emphasis on applications to civil and environmental engineering, 2nd Edition, John Wiley & Sons Inc., 2007.

[18] Huijbregts, M., Uncertainty and variability in environmental life-cycle assessment, PhD Thesis, 2001, University of Amsterdam, The Netherlands.

[19] Weidema, B., Wesnaes, M., *Data quality management for life cycle inventories – an example of using data quality indicators*, Journal of Clean Production 4 (3-4), 1996, pp 167-174.

[20] Huijbregts, M., Norris, G., Bretz, R., Ciroth, A., Maurice, B., von Bahr, B., Weidema, B., de Beaufort, A., *Framework for modeling data uncertainty in life cycle inventories*, International Journal of Life Cycle Assessment 6 (3), 2001, pp. 127-132.

[21] Frischknecht, R., Jungbluth, N., Althaus, H., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier. R., Nemecek, T., Rebitzer, G., Spielmann, M., *The ecoinvent database: overview and methodological framework*, International Journal of Life Cycle Assessment 10 (1), 2005, pp. 3-9.

[22] Sugiyama, H., Fukushima, Y., Hirao, M., Hellweg, S., Hungerbuhler, K., *Using standard statistics to consider uncertainty in industry-based life cycle inventory databases*, International Journal of Life Cycle Assessment 10 (6), 2005, pp. 399-405.

[23] von Bahr, B., Steen, B., *Reducing epistemological uncertainty in life cycle inventory*, Journal of Clean Production 12 (4), 2004, pp. 369-388.

[24] Baumann, H., Rydberg, T., *Life cycle assessment: a comparison of three methods for impact analysis and evaluation*, Journal of Clean Production 2 (1), 1994, pp. 13-20.

[25] Bovea, M., Gallardo, A., *The influence of impact assessment methods on materials selection for eco-design*, Mater. Des. 27 (3), 2006, pp. 209-215.

[26] Brent, A., Hietkamp, S., *Comparative evaluation of life cycle impact assessment methods with a South African case study*, International Journal of Life Cycle Assessment 8 (1), 2003, pp. 27-38.

[27] Dreyer, L., Niemann, A., Hauschild, M., *Comparison of three different LCIA methods: EDIP97. CML2001 and Eco-indicator 99 – does it matter which one you choose*?, International Journal of Life Cycle Assessment 8 (4), 2003, pp 191-200.

[28] Geisler, G., Hellweg, S., Hungerbuhler, K., *Uncertainty Analysis in Life Cycle Assessment (LCA): Case study on Plant-Protection Products and Implications for Decision Making*, International Journal of Life Cycle Assessment 10 (3), 2005, pp. 184-192.

[29] Hung, M., Ma, H., *Quantifying system uncertainty of life cycle assessment based on Monte Carlo simulation*, International Journal of Life Cycle Assessment, Vol. 14, 2009, pp. 19-27.

[30] Cherubini, E., Franco, D., Zanghelini, G., Soares, S., *Uncertainty in LCA case study due to allocation approaches and life cycle impact assessment methods*, International Journal of Life Cycle Assessment, published online in January 2018.

[31] Heijungs, R., *Identification of key issues for further investigation in improving the reliability of life-cycle assessments*, Journal of Cleaner Production 4(3-4), 1996, pp. 159-166.

[32] Steen, B., *On uncertainty and sensitivity of LCA-based priority setting*, Journal of Cleaner Production 5(4), 1997, pp. 255-262.

[33] Tan, R., Culaba, A., Purvis, M., *Application of possibility theory in the life-cycle inventory assessment of biofuels*, International Journal of Energy Research 26(8), 2002, pp. 737-745.

[34] Ferson, S., Cooper, J., Myers, D., Beyond point estimates – Risk assessment using interval fuzzy and probabilistic arithmetic. Society for risk analysis workshop booklet, Applied biomathematics, New York, 2001.

[35] Gervasio, H., Dimova, S., *Model for Life Cycle Assessment (LCA) of buildings*, EUR 29123 EN, Publications Office of the European Union, 2018, ISBN 978-92-79-79974-7; doi:10.2760/789069, JRC110082.

[36] Gervasio, H., Dimova, S., *Environmental benchmarks for buildings*, EUR 29145 EN, Publications Office of the European Union, 2018, ISBN 978-92-79-80969-9; doi:10.2760/90028, JRC110085.

[37] Cucurachi, S., Borgonovo, E., Heijungs, R., *A protocol for the global sensitivity analysis of impact assessment models in Life Cycle Assessment*, Risk Analysis , Vol. 36, No. 2, 2016, pp. 357-377.

[38] Helton, J., Johnson, J., Sallaberry, C., Storlie, C., *Survey of sampling-based methods for uncertainty and sensitivity analysis*, Reliability Engineering & System Safety, Vol. 91, Issues 10–11, 2006, pp. 1175-1209.

[39] Sobol, I., *Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates*, Mathematics and Computers in Simulation, Vol. 55, Issues 1–3, 2001, pp. 271-280.

[40] Koch, A., *The logarithm in biology. Mechanisms generating the log-normal distribution exactly*, Journal of Theoretical Biology 12(2), pp. 276-290, 1966.

[41] Geisler, G., Hellweg, S., Hungerbuhler, K., *Uncertainty Analysis in Life Cycle Assessment (LCA): Case study on Plant-protection products and implications for decision making*, International Journal of LCA 10(3), 2005, pp. 184-195.

[42] Weidema, B., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C., Wernet, G. *Overview and methodology. Data quality guideline for the ecoinvent database version 3*. Ecoinvent Report 1(v3). St. Gallen: The ecoinvent Centre, 2013.

[43] Weidema, B., Wesnaes, M., *Data quality management for life cycle inventories - an example of using data quality indicators,* Journal of Cleaner Production 4(3-4), 1996, pp. 167-174.

[44] Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., *2013: Anthropogenic and Natural Radiative Forcing*. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[45] Thinkstep AG. 2017. Leinfelden-Echterdingen GaBi software-System and Databse for Life Cycle Engineering 1992-2017 (version 8.1.0.29).

[46] Zhang, X-Y., Trame, M., Lesko, L., Schmidt, S., *Sobol sensitivity analysis: A tool to guide the development and evaluation of systems pharmacology models*, CPT Pharmacometrics Syst. Pharmacol 4, 2015, pp. 69-79.

[47] RICS, *Code of Measuring Practice: A Guide for Property Professionals*, RICS Guidance Note, 6th Edition, Royal Institution of Chartered Surveyors (RICS), UK, 2007. (available online: https://lambertsurv.co.uk/wp-content/files_mf/1392203502RICScodeofmeasuringpractice.pdf) (last accessed June 2018).

[48] ISO 15686-8:2008, Buildings and constructed assets -- Service-life planning -- Part 8: Reference service life and service-life estimation, International Organization for Standardization, Geneva.

[49] Heidkamp, H., Papaioannou, I., *Performance based design and Eurocode*, Vogt, Schuppener, Straub & Brau (eds), ISGSR 2011, 2011, pp. 519-526.

[50] *Sustainability Benchmarking Toolkit for Commercial Buildings, Principles for best practice*, The Building Centre, London, 2010.

[51] Nemry, F., Uihlein, A., Colodel, C., Wittstock, B., Braune, A., Wetzel, C., Hasan, I., Niemeier, S., Frech, Y., Kreißig, J., Gallon, N., *Environmental Improvement Potentials of Residential Buildings* (IMPRO-Building), EUR 23493 EN, Office for Official Publications of the European Communities, 2008, doi:10.2791/38942.

[52] EN 15804:2012 + A1:2013, Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products, CEN, Brussels.

[53] EN 15978:2011, Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method, CEN, Brussels

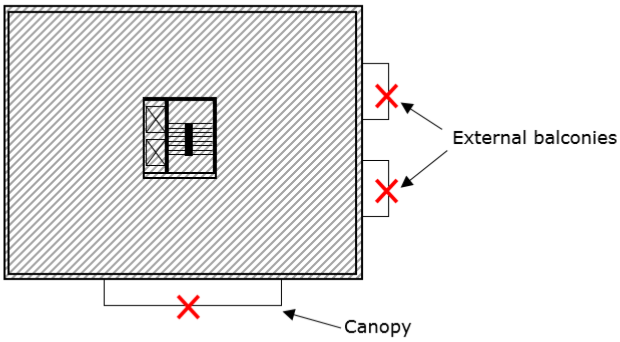
[54] Trabucco, D., Wood, A., Popa, N., Vassart, O., Davies, D., *Life Cycle Assessment of Tall Building Structural Systems*, Council on Tall Buildings and Urban Habitat, Chicago, 2015.

Annex A: Quantification of the GFA of buildings

The GFA is measured according to the external dimensions of a building and includes all areas inside the building including supporting areas. Further guidance for the measurement of the GFA is given in the *Code of Measuring Practice* (RICS) [47] and in the following illustrative schemes.

A) GFA per floor

The elements to be included and excluded in the measurement of the GFA (in m^2) of each floor level are the following:



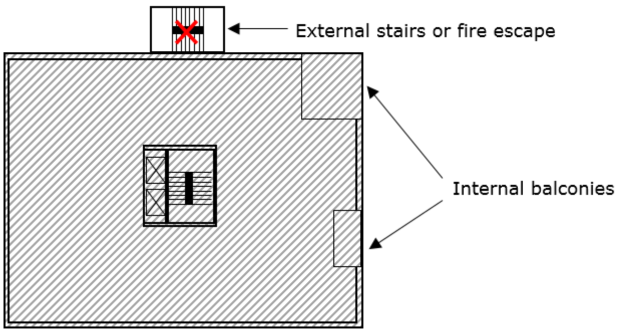
Including:

Area, in the horizontal plan, of all structural elements;

Structural, raked or stepped floors, projected into the horizontal plan;

Internal balconies;

Internal garages.



Excluding:

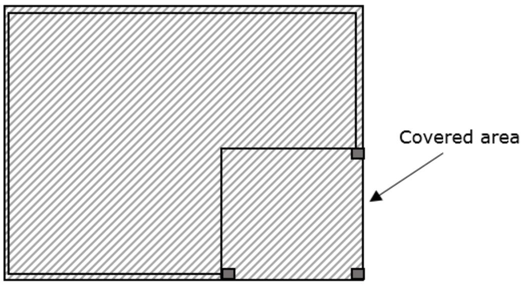
External open-sided balconies;

Fire escape stairs;

Canopies;

Uncovered parking areas;

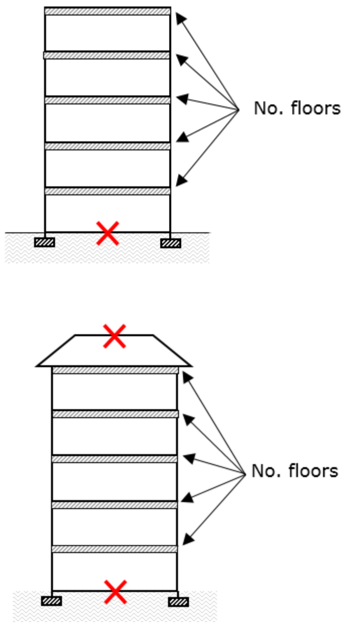
Greenhouses or temporary structures (e.g. garden stores, pergolas, etc.).



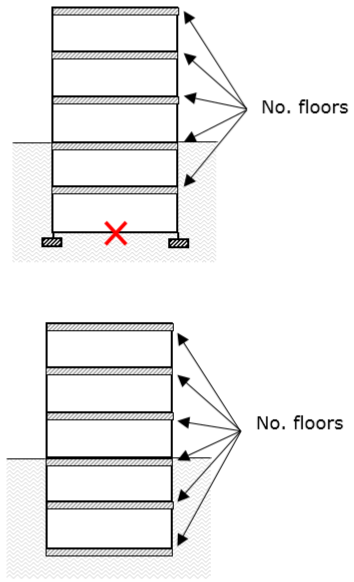
Note: The GFA is indicated by the dashed area in the pictures.

B) Total GFA of the building

The total GFA of the building is given by the sum of the GFA of each 'structural' floor. The number of floors to consider is illustrated in the pictures.



When the ground floor slab has no structural function, it is not considered as a floor.



When the ground floor slab has a structural function (foundation), it is considered as a floor.

Annex B: Residential buildings

Building 1 (RB1)

Building properties and main characteristics

Type of building	Medium rise residential building
Type of structure (Tier 4)	Reinforced concrete structure
Total Gross Floor Area	5458 m^2
Number of floors	9 (2 underground)
Number of occupants/working places	n.a.
Design working life	50 years (estimated)
Building ref. year	2015
Seismic area (PGA)	0.0357
Climatic area	Csb

Summarized BoM

Building main component	**Material**	**Quantity**
Sub-base	Concrete C30/37	486 m^3
	Steel reinforcement (S500)	28.5 ton
Super-structure	Concrete C30/37	996 m^3
	Steel reinforcement (S500)	111 ton
	Plywood	9007 m^2
Upper floors	Concrete C30/37	2831 m^3
	Steel reinforcement (S500)	219 ton
	Concrete blocks	21197 unid.
	Plywood	14381 m^2

A1) Deterministic analysis

i) LCA results per functional unit

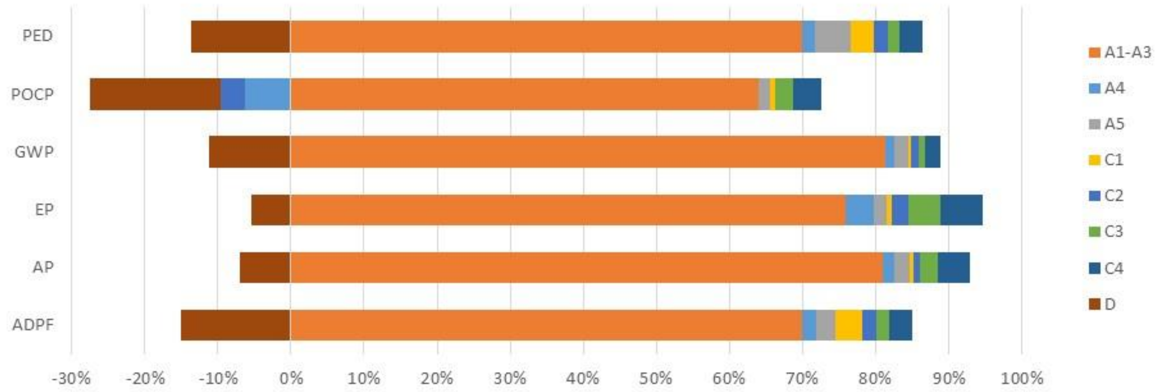
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	7.81E+00	1.14E-01	1.92E-01	2.96E-02	1.14E-01	7.55E-02	1.93E-01	-1.06E+00	7.46E+00
ADPF	5.56E+01	1.56E+00	2.04E+00	2.87E+00	1.56E+00	1.40E+00	2.51E+00	-1.19E+01	5.56E+01
AP	2.05E-02	4.17E-04	5.06E-04	1.32E-04	2.52E-04	5.91E-04	1.14E-03	-1.78E-03	2.18E-02
EP	2.06E-03	1.02E-04	4.79E-05	2.16E-05	5.88E-05	1.21E-04	1.54E-04	-1.46E-04	2.42E-03
GWP	7.68E+00	1.13E-01	1.91E-01	1.83E-02	1.13E-01	7.21E-02	1.94E-01	-1.06E+00	7.32E+00
ODP	-9.84E-09	3.78E-14	8.50E-12	6.97E-14	3.79E-14	3.60E-13	1.98E-13	3.84E-09	-5.99E-09
POCP	1.52E-03	-1.50E-04	3.49E-05	1.94E-05	-7.96E-05	5.82E-05	9.05E-05	-4.25E-04	1.07E-03

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	2.50E-06	8.21E-08	1.36E-09	1.51E-07	8.21E-08	4.27E-08	4.12E-08	-4.19E-07	2.48E-06
NHWD	1.55E+00	1.20E-04	2.21E-03	2.20E-04	1.20E-04	6.30E-04	1.21E+01	7.22E-02	1.37E+01
RWD	1.14E-03	2.13E-06	5.22E-04	3.93E-06	2.13E-06	2.12E-05	3.56E-05	-3.03E-04	1.42E-03
PENRT	5.86E+01	1.56E+00	3.36E+00	2.88E+00	1.56E+00	1.45E+00	2.60E+00	-1.24E+01	5.96E+01
PERT	6.34E+00	7.84E-02	1.14E+00	1.44E-01	7.85E-02	8.66E-02	3.04E-01	-1.88E-01	7.99E+00
FW	1.28E-02	1.45E-04	1.63E-03	2.67E-04	1.45E-04	4.22E-04	4.96E-04	-5.49E-03	1.04E-02
PED	6.49E+01	1.64E+00	4.50E+00	3.02E+00	1.64E+00	1.54E+00	2.91E+00	-1.26E+01	6.76E+01

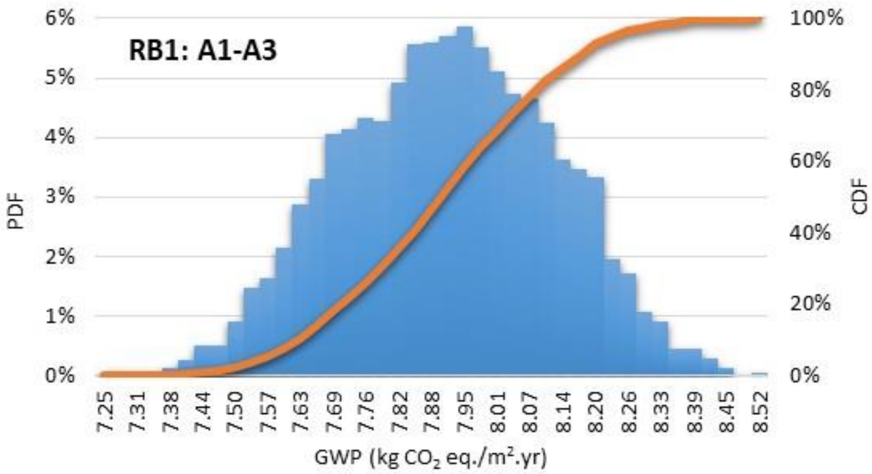
ii) Contribution of life cycle stages per environmental category



A2) Probabilistic analysis

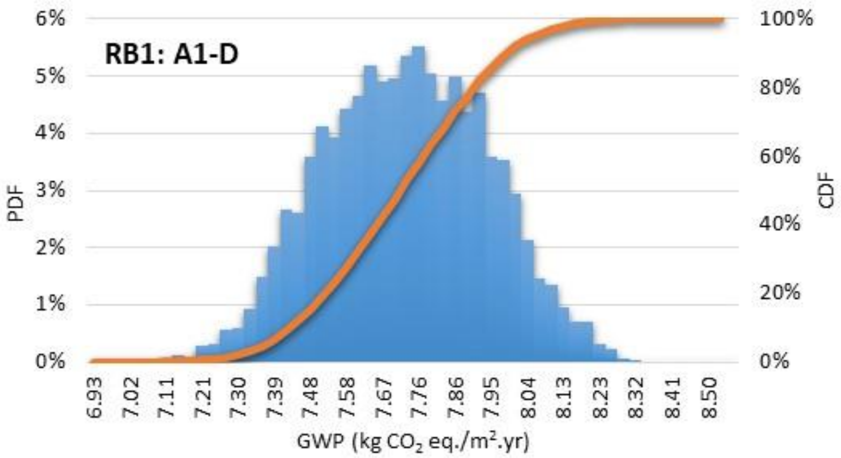
A2.1) GWP

i) Results for Modules A1-A3



Mean	***7.92***
Median	***7.90***
σ	***0.21***
CoV	***2.6%***
Q5%	***7.56***
Q95%	***8.23***

ii) Results for Modules A1-D



Mean	***7.73***
Median	***7.72***
σ	***0.21***
CoV	***2.7%***
Q5%	***7.37***
Q95%	***8.06***

A2.2) Other environmental categories

i) Results for Modules A1-A3

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	2.05E-2	2.13E-3	1.27E-3
Median	2.04E-2	2.13E-3	1.26E-3
COV	2.70%	2.73%	3.27%

ii) Results for Modules A1-D

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	2.18E-2	2.42E-3	1.07E-3
Median	2.17E-2	2.41E-3	1.07E-3
COV	2.65%	2.82%	3.97%

Building 2 (RB2)

Building properties and main characteristics

Type of building	Medium rise residential building
Type of structure (Tier 4)	Reinforced concrete structure
Total Gross Floor Area	291 m^2
Number of floors	6 (1 underground)
Number of occupants/working places	n.a.
Design working life	50 years (estimated)
Building ref. year	2017
Seismic area (PGA)	0.1529
Climatic area	Csa

Summarized BoM

Building main component	**Material**	**Quantity**
Sub-base	Concrete C30/37	15 m^3
	Steel reinforcement (S500)	1.5 ton
Super-structure	Concrete C30/37	51 m^3
	Steel reinforcement (S500)	5.5 ton
	Plywood	563 m^2
Upper floors	Concrete C30/37	62 m^3
	Steel reinforcement (S500)	6.6 ton
	Steel sections (S275 JR)	248 kg
	Plywood	527 m^2

A1) Deterministic analysis

i) LCA results per functional unit

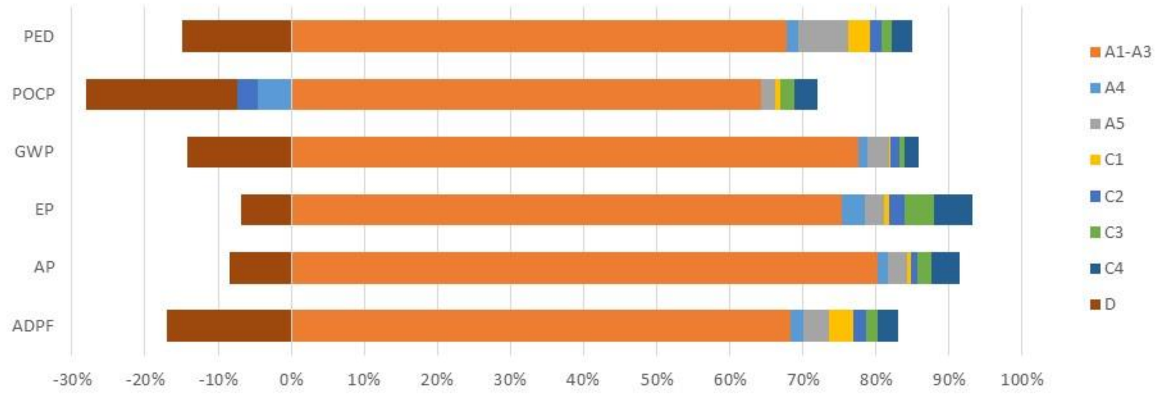
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP$_{exc}$	4.35E+00	6.16E-02	1.66E-01	1.69E-02	6.17E-02	4.09E-02	1.05E-01	-7.80E-01	4.02E+00
ADPF	3.36E+01	8.44E-01	1.77E+00	1.63E+00	8.45E-01	7.59E-01	1.37E+00	-8.39E+00	3.25E+01
AP	1.29E-02	2.06E-04	4.39E-04	7.51E-05	1.37E-04	3.20E-04	6.19E-04	-1.37E-03	1.33E-02
EP	1.21E-03	5.02E-05	4.15E-05	1.23E-05	3.19E-05	6.54E-05	8.39E-05	-1.09E-04	1.38E-03
GWP	4.24E+00	6.11E-02	1.66E-01	1.04E-02	6.11E-02	3.91E-02	1.05E-01	-7.76E-01	3.91E+00
ODP	-7.14E-09	2.05E-14	7.36E-12	3.96E-14	2.05E-14	1.95E-13	1.07E-13	3.21E-09	-3.92E-09
POCP	1.01E-03	-7.29E-05	3.02E-05	1.11E-05	-4.32E-05	3.16E-05	4.91E-05	-3.24E-04	6.91E-04

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	1.77E-06	4.45E-08	1.18E-09	8.59E-08	4.45E-08	2.32E-08	2.24E-08	-3.60E-07	1.63E-06
NHWD	8.52E-01	6.48E-05	1.91E-03	1.25E-04	6.48E-05	3.42E-04	6.55E+00	6.10E-02	7.47E+00
RWD	5.19E-04	1.16E-06	4.52E-04	2.23E-06	1.16E-06	1.15E-05	1.93E-05	-1.65E-04	8.42E-04
PENRT	3.51E+01	8.47E-01	2.91E+00	1.64E+00	8.48E-01	7.88E-01	1.41E+00	-8.60E+00	3.49E+01
PERT	3.67E+00	4.25E-02	9.91E-01	8.21E-02	4.26E-02	4.69E-02	1.65E-01	2.79E-02	5.06E+00
FW	5.92E-03	7.87E-05	1.41E-03	1.52E-04	7.88E-05	2.29E-04	2.69E-04	-4.09E-03	4.05E-03
PED	3.87E+01	8.90E-01	3.90E+00	1.72E+00	8.91E-01	8.34E-01	1.58E+00	-8.57E+00	4.00E+01

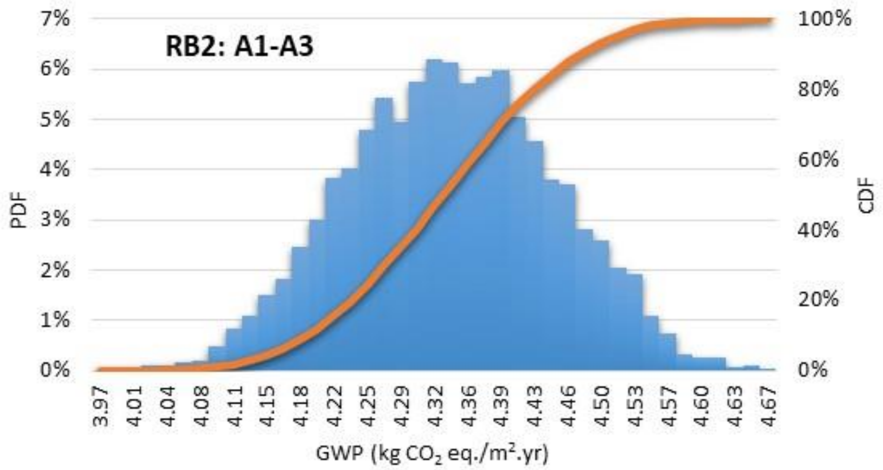
ii) Contribution of life cycle stages per environmental category



A2) Probabilistic analysis

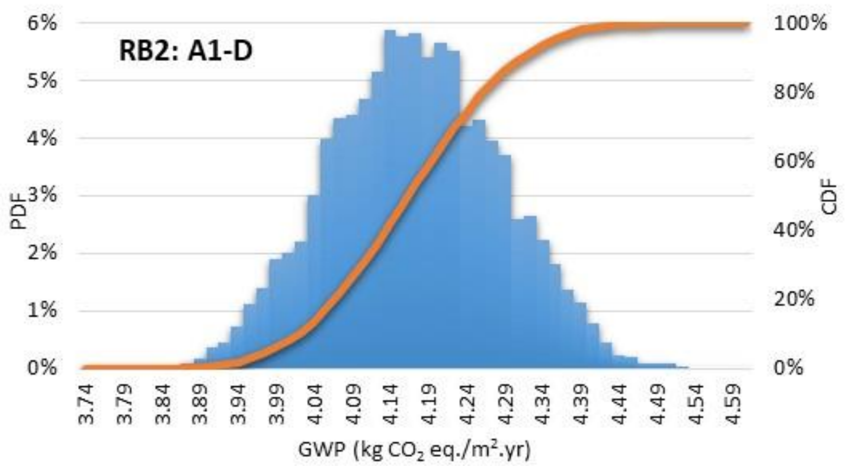
A2.1) GWP

i) Results for Modules A1-A3



Mean	***4.34***
Median	***4.33***
σ	***0.11***
CoV	***2.5%***
$Q_{5\%}$	***4.15***
$Q_{95\%}$	***4.51***

ii) Results for Modules A1-D



Mean	***4.17***
Median	***4.16***
σ	***0.11***
CoV	***2.7%***
$Q_{5\%}$	***3.98***
$Q_{95\%}$	***4.35***

A2.2) Other environmental categories

i) Results for Modules A1-A3

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	1.28E-2	1.23E-3	8.58E-4
Median	1.28E-2	1.23E-3	8.55E-4
COV	2.66%	2.50%	3.22%

ii) Results for Modules A1-D

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	1.33E-2	1.38E-3	6.94E-4
Median	1.33E-2	1.38E-3	6.90E-4
COV	2.60%	2.60%	3.99%

Building 3 (RB3)

Building properties and main characteristics

Type of building	Medium rise residential building
Type of structure (Tier 4)	Reinforced concrete structure
Total Gross Floor Area	6218 m^2
Number of floors	6 (1 underground)
Number of occupants/working places	n.a.
Design working life	50 years (estimated)
Building ref. year	2017
Seismic area (PGA)	0.0357
Climatic area	Csb

Summarized BoM

Building main component	Material	Quantity
Sub-base	Concrete C30/37	239 m^3
	Steel reinforcement (S500)	13.9 ton
Super-structure	Concrete C30/37	534 m^3
	Steel reinforcement (S500)	46.9 ton
	Plywood	4917 m^2
Upper floors	Concrete C30/37	1852 m^3
	Steel reinforcement (S500)	120.2 ton
	Concrete blocks	14528 unid.
	Plywood	8672 m^2

A1) Deterministic analysis

i) LCA results per functional unit

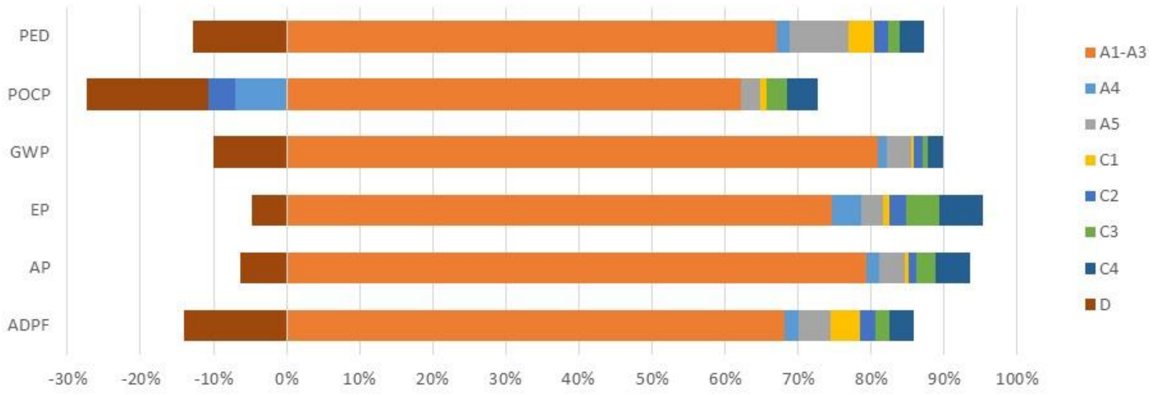
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	3.98E+00	6.08E-02	1.63E-01	1.66E-02	6.06E-02	4.02E-02	1.03E-01	-4.89E-01	3.94E+00
ADPF	2.71E+01	8.33E-01	1.73E+00	1.60E+00	8.31E-01	7.46E-01	1.34E+00	-5.62E+00	2.85E+01
AP	9.93E-03	2.26E-04	4.29E-04	7.39E-05	1.34E-04	3.15E-04	6.08E-04	-7.97E-04	1.09E-02
EP	1.04E-03	5.54E-05	4.06E-05	1.21E-05	3.14E-05	6.43E-05	8.24E-05	-6.65E-05	1.26E-03
GWP	3.92E+00	6.03E-02	1.62E-01	1.02E-02	6.01E-02	3.84E-02	1.04E-01	-4.87E-01	3.86E+00
ODP	-4.36E-09	2.02E-14	7.20E-12	3.90E-14	2.02E-14	1.92E-13	1.05E-13	1.61E-09	-2.75E-09
POCP	7.16E-04	-8.15E-05	2.96E-05	1.09E-05	-4.24E-05	3.11E-05	4.83E-05	-1.91E-04	5.21E-04

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	1.13E-06	4.39E-08	1.15E-09	8.45E-08	4.38E-08	2.28E-08	2.20E-08	-1.72E-07	1.18E-06
NHWD	8.14E-01	6.39E-05	1.87E-03	1.23E-04	6.37E-05	3.36E-04	6.44E+00	3.01E-02	7.28E+00
RWD	6.24E-04	1.14E-06	4.42E-04	2.20E-06	1.14E-06	1.13E-05	1.90E-05	-1.63E-04	9.38E-04
PENRT	2.87E+01	8.36E-01	2.84E+00	1.61E+00	8.34E-01	7.75E-01	1.39E+00	-5.92E+00	3.11E+01
PERT	3.27E+00	4.19E-02	9.69E-01	8.08E-02	4.18E-02	4.62E-02	1.62E-01	-1.52E-01	4.46E+00
FW	6.83E-03	7.77E-05	1.38E-03	1.50E-04	7.75E-05	2.25E-04	2.64E-04	-2.50E-03	6.51E-03
PED	3.20E+01	8.78E-01	3.81E+00	1.69E+00	8.76E-01	8.21E-01	1.55E+00	-6.07E+00	3.55E+01

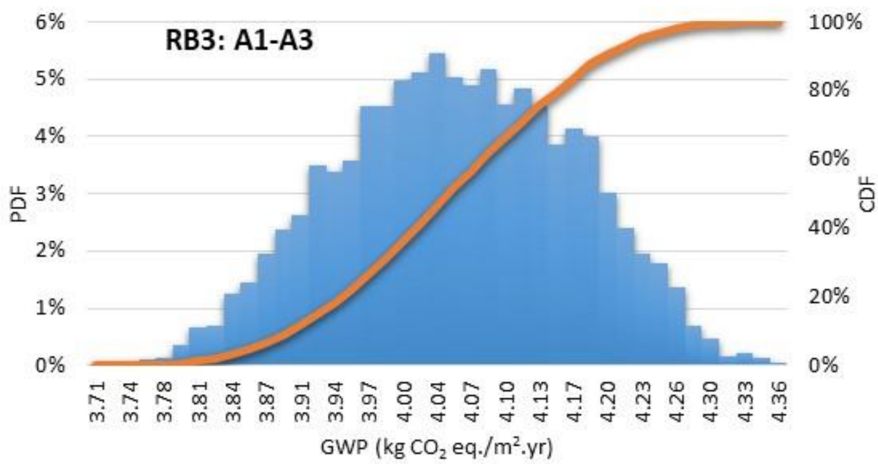
ii) Contribution of life cycle stages per environmental category



A2) Probabilistic analysis

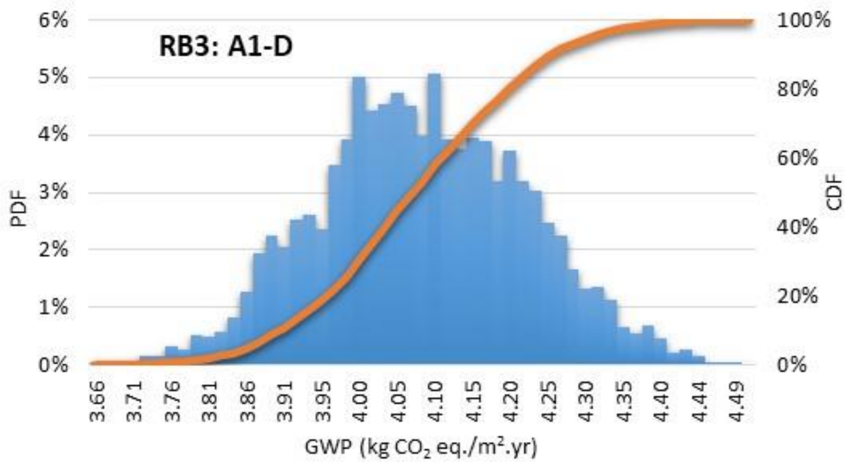
A2.1) GWP

i) Results for Modules A1-A3



Mean	***4.06***
Median	***4.05***
σ	***0.11***
CoV	***2.8%***
$Q_{5\%}$	***3.86***
$Q_{95\%}$	***4.23***

ii) Results for Modules A1-D



Mean	***4.08***
Median	***4.07***
σ	***0.14***
CoV	***3.3%***
$Q_{5\%}$	***3.86***
$Q_{95\%}$	***4.30***

A2.2) Other environmental categories

i) Results for Modules A1-A3

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	9.98E-3	1.08E-3	5.88E-4
Median	9.63E-3	1.08E-3	5.86E-4
COV	2.77%	2.91%	3.29%

ii) Results for Modules A1-D

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	1.09E-2	1.26E-3	5.21E-4
Median	1.09E-2	1.26E-3	5.18E-4
COV	3.21%	3.26%	7.86%

Building 4 (RB4)

Building properties and main characteristics

Type of building	Single family house
Type of structure (Tier 4)	Reinforced concrete structure
Total Gross Floor Area	313 m^2
Number of floors	3
Number of occupants/working places	n.a.
Design working life	50 years (estimated)
Building ref. year	2016
Seismic area (PGA)	0.0357
Climatic area	Csb

Summarized BoM

Building main component	**Material**	**Quantity**
Sub-base	Concrete C30/37	39.4 m^3
	Steel reinforcement (S500)	1.0 ton
Super-structure	Concrete C30/37	59 m^3
	Steel reinforcement (S500)	3.6 ton
	Plywood	537.5 m^2
Upper floors	Concrete C30/37	65.1 m^3
	Steel reinforcement (S500)	3.1 ton
	Steel sections (S275 JR)	13.9 ton
	Galvanized steel deck	234 m^2
	Plywood	203 m^2

A1) Deterministic analysis

i) LCA results per functional unit

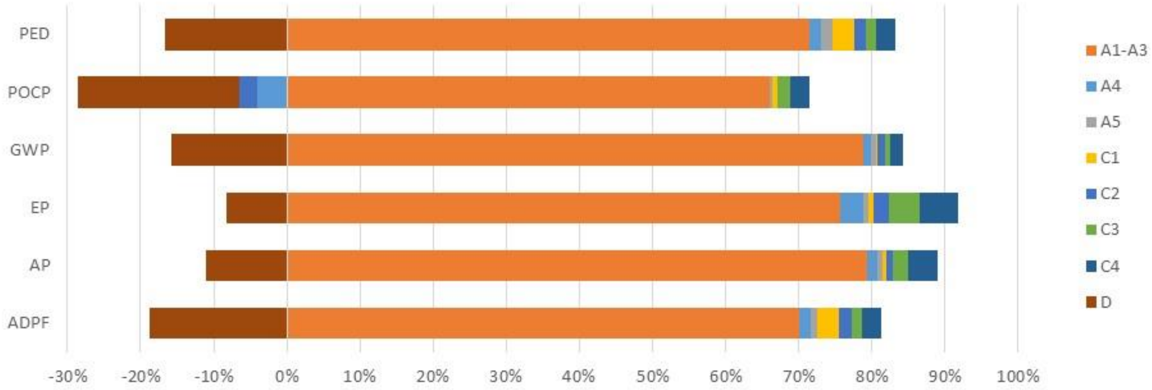
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	5.69E+00	7.37E-02	5.18E-02	2.05E-02	7.53E-02	5.05E-02	1.25E-01	-1.13E+00	4.96E+00
ADPF	4.44E+01	1.01E+00	5.50E-01	1.98E+00	1.03E+00	9.37E-01	1.62E+00	-1.19E+01	3.97E+01
AP	1.46E-02	2.53E-04	1.36E-04	9.14E-05	1.67E-04	3.96E-04	7.37E-04	-2.02E-03	1.44E-02
EP	1.45E-03	6.17E-05	1.29E-05	1.49E-05	3.90E-05	8.08E-05	9.98E-05	-1.59E-04	1.60E-03
GWP	5.61E+00	7.31E-02	5.15E-02	1.27E-02	7.47E-02	4.83E-02	1.26E-01	-1.12E+00	4.87E+00
ODP	-1.01E-08	2.45E-14	2.29E-12	4.82E-14	2.51E-14	2.41E-13	1.28E-13	4.95E-09	-5.17E-09
POCP	1.44E-03	-8.98E-05	9.40E-06	1.35E-05	-5.27E-05	3.90E-05	5.85E-05	-4.79E-04	9.36E-04

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	2.61E-06	5.32E-08	3.66E-10	1.05E-07	5.44E-08	2.86E-08	2.66E-08	-5.60E-07	2.32E-06
NHWD	1.16E+00	7.75E-05	5.95E-04	1.52E-04	7.92E-05	4.22E-04	7.80E+00	9.42E-02	9.05E+00
RWD	5.95E-04	1.38E-06	1.41E-04	2.72E-06	1.41E-06	1.42E-05	2.30E-05	-1.95E-04	5.84E-04
PENRT	4.66E+01	1.01E+00	9.04E-01	1.99E+00	1.04E+00	9.73E-01	1.68E+00	-1.21E+01	4.22E+01
PERT	4.19E+00	5.09E-02	3.08E-01	9.99E-02	5.20E-02	5.80E-02	1.96E-01	1.65E-01	5.12E+00
FW	5.15E-03	9.42E-05	4.39E-04	1.85E-04	9.63E-05	2.83E-04	3.20E-04	-5.97E-03	5.91E-04
PED	5.08E+01	1.06E+00	1.21E+00	2.09E+00	1.09E+00	1.03E+00	1.88E+00	-1.19E+01	4.73E+01

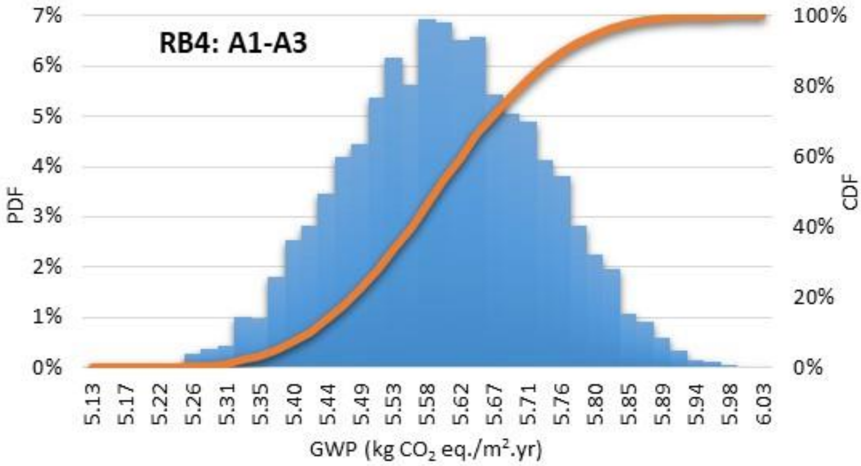
ii) Contribution of life cycle stages per environmental category



A2) Probabilistic analysis

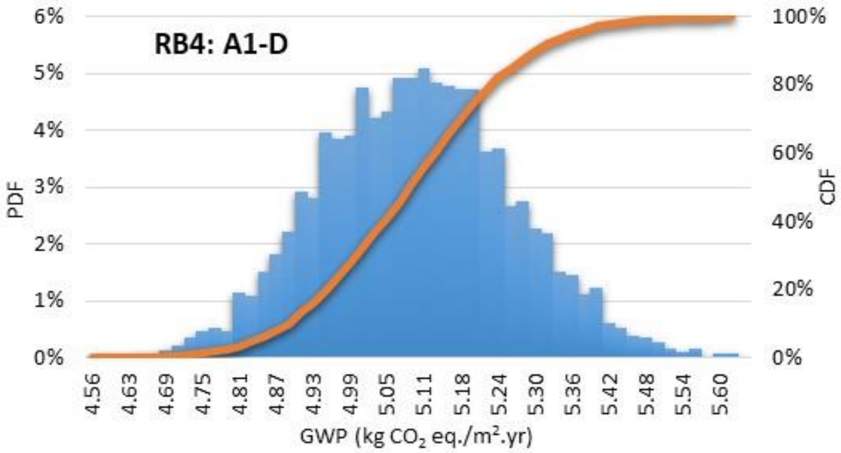
A2.1) GWP

i) Results for Modules A1-A3



Mean	***5.60***
Median	***5.59***
σ	***0.13***
CoV	***2.3%***
$Q_{5\%}$	***5.38***
$Q_{95\%}$	***5.80***

ii) Results for Modules A1-D



Mean	***5.10***
Median	***5.09***
σ	***0.16***
CoV	***3.1%***
$Q_{5\%}$	***4.84***
$Q_{95\%}$	***5.36***

A2.2) Other environmental categories

i) Results for Modules A1-A3

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	1.43E-2	1.48E-3	1.22E-3
Median	1.43E-2	1.48E-3	1.22E-3
COV	2.25%	2.28%	3.01%

ii) Results for Modules A1-D

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	1.44E-2	1.61E-3	9.38E-4
Median	1.44E-2	1.60E-3	9.32E-4
COV	2.77%	2.71%	5.93%

Building 5 (RB5)

Building properties and main characteristics

Type of building	Medium rise residential building
Type of structure (Tier 4)	Reinforced concrete structure
Total Gross Floor Area	11262 m^2
Number of floors	8 (3 underground)
Number of occupants/working places	n.a.
Design working life	50 years (estimated)
Building ref. year	2006
Seismic area (PGA)	0.0357
Climatic area	Csb

Summarized BoM

Building main component	Material	Quantity
Sub-base	Concrete C12/15	60 m^3
	Concrete C25/30	414 m^3
	Steel reinforcement (S500)	33 ton
Super-structure	Concrete C20/25	292 m^3
	Concrete C25/30	540 m^3
	Steel reinforcement (S500)	79 ton
	Plywood	7715 m^2
Upper floors	Concrete C20/25	2781 m^3
	Steel reinforcement (S500)	188 ton
	Concrete blocks	25780 unid.
	Plywood	13857 m^2

A1) Deterministic analysis

i) LCA results per functional unit

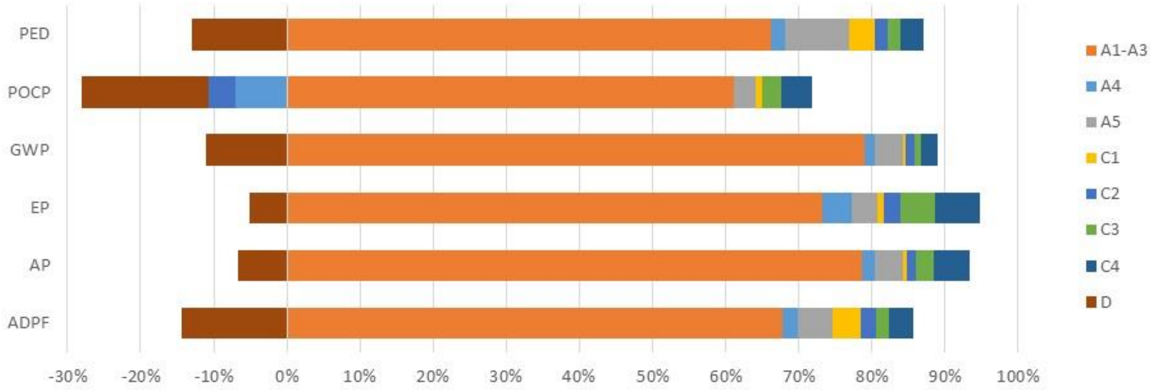
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	3.16E+00	5.18E-02	1.56E-01	1.41E-02	5.17E-02	3.43E-02	8.78E-02	-4.36E-01	3.11E+00
ADPF	2.35E+01	7.09E-01	1.65E+00	1.37E+00	7.08E-01	6.36E-01	1.14E+00	-4.96E+00	2.48E+01
AP	8.41E-03	1.92E-04	4.10E-04	6.30E-05	1.14E-04	2.68E-04	5.18E-04	-7.17E-04	9.26E-03
EP	8.41E-04	4.72E-05	3.88E-05	1.03E-05	2.67E-05	5.48E-05	7.02E-05	-5.94E-05	1.03E-03
GWP	3.10E+00	5.13E-02	1.55E-01	8.73E-03	5.12E-02	3.27E-02	8.83E-02	-4.34E-01	3.05E+00
ODP	-3.98E-09	1.72E-14	6.88E-12	3.32E-14	1.72E-14	1.63E-13	8.97E-14	1.48E-09	-2.50E-09
POCP	6.01E-04	-6.91E-05	2.83E-05	9.26E-06	-3.62E-05	2.64E-05	4.11E-05	-1.71E-04	4.30E-04

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	1.02E-06	3.74E-08	1.10E-09	7.20E-08	3.73E-08	1.94E-08	1.87E-08	-1.59E-07	1.05E-06
NHWD	7.11E-01	5.44E-05	1.79E-03	1.05E-04	5.43E-05	2.86E-04	5.48E+00	2.77E-02	6.22E+00
RWD	4.52E-04	9.71E-07	4.23E-04	1.87E-06	9.69E-07	9.63E-06	1.62E-05	-1.38E-04	7.66E-04
PENRT	2.47E+01	7.12E-01	2.72E+00	1.37E+00	7.10E-01	6.60E-01	1.18E+00	-5.22E+00	2.69E+01
PERT	2.67E+00	3.57E-02	9.27E-01	6.88E-02	3.56E-02	3.93E-02	1.38E-01	-1.17E-01	3.79E+00
FW	5.55E-03	6.62E-05	1.32E-03	1.27E-04	6.60E-05	1.92E-04	2.25E-04	-2.23E-03	5.32E-03
PED	2.74E+01	7.48E-01	3.64E+00	1.44E+00	7.46E-01	6.99E-01	1.32E+00	-5.33E+00	3.07E+01

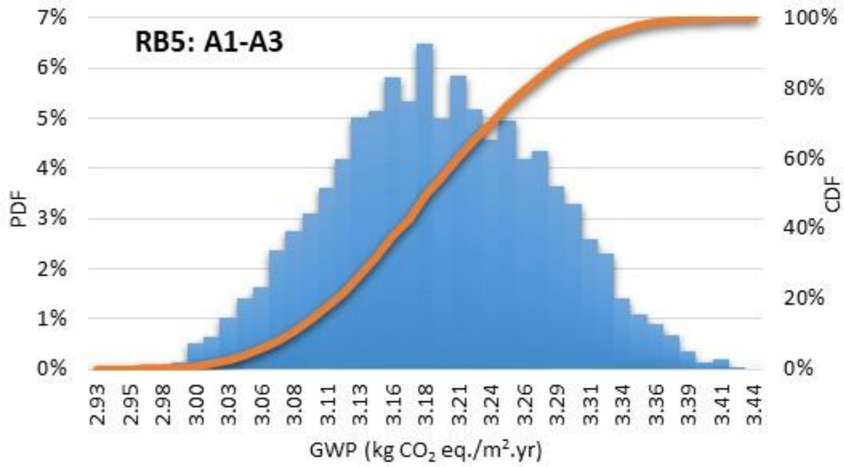
ii) Contribution of life cycle stages per environmental category



A2) Probabilistic analysis

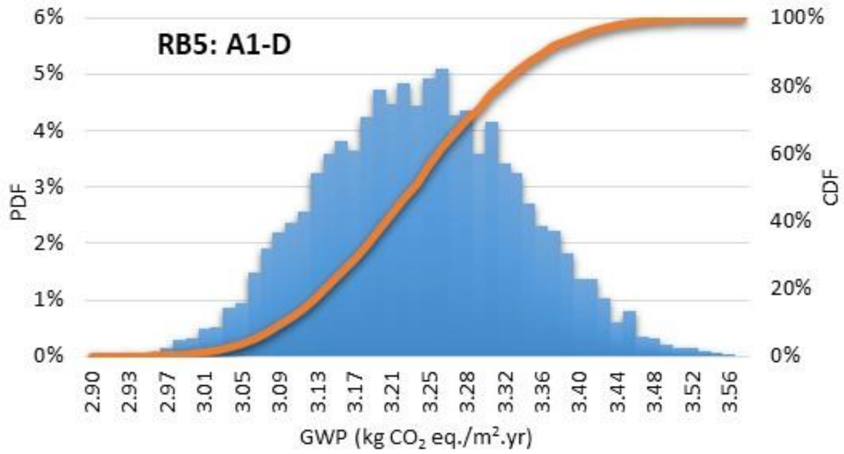
A2.1) GWP

i) Results for Modules A1-A3



Mean	***3.19***
Median	***3.19***
σ	***0.08***
CoV	***2.6%***
$Q_{5\%}$	***3.0***
$Q_{95\%}$	***3.32***

ii) Results for Modules A1-D



Mean	***3.24***
Median	***3.23***
σ	***0.10***
CoV	***3.2%***
$Q_{5\%}$	***3.06***
$Q_{95\%}$	***3.40***

A2.2) Other environmental categories

i) Results for Modules A1-A3

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	8.43E-3	8.75E-4	4.88E-4
Median	8.41E-3	8.72E-4	4.86E-4
COV	2.62%	2.71%	3.26%

ii) Results for Modules A1-D

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	9.28E-3	1.03E-3	4.30E-4
Median	9.26E-3	1.03E-3	4.28E-4
COV	3.03%	3.04%	8.25%

Building 6 (RB6)

Building properties and main characteristics

Type of building	Medium rise residential building
Type of structure (Tier 4)	Reinforced concrete structure
Total Gross Floor Area	2808 m^2
Number of floors	9 (2 underground)
Number of occupants/working places	n.a.
Design working life	50 years (estimated)
Building ref. year	2007
Seismic area (PGA)	0.0357
Climatic area	Csb

Summarized BoM

Building main component	Material	Quantity
Sub-base	Concrete C25/30	137 m^3
	Steel reinforcement (S500)	12 ton
Super-structure	Concrete C25/30	328 m^3
	Steel reinforcement (S500)	48 ton
	Plywood	1572 m^2
Upper floors	Concrete C20/25	732 m^3
	Steel reinforcement (S500)	55 ton
	Concrete blocks	5823 unid.
	Plywood	3263 m^2

A1) Deterministic analysis

i) LCA results per functional unit

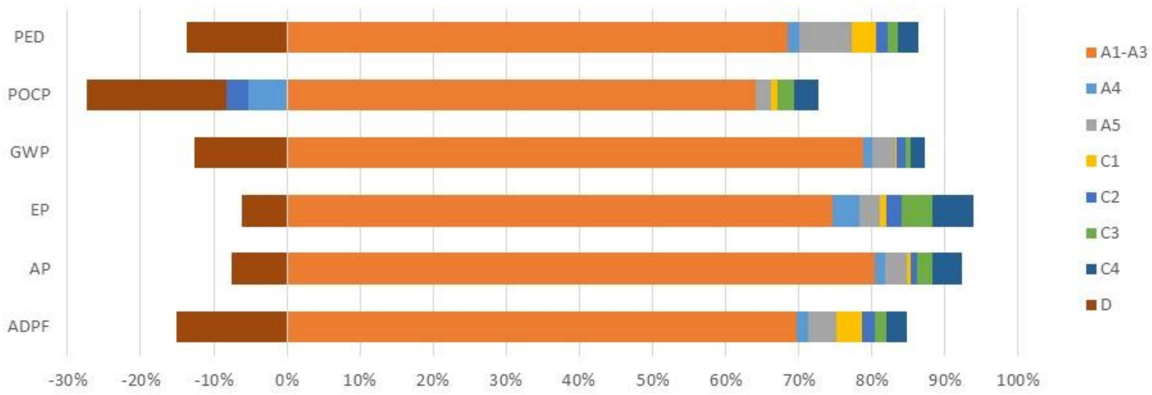
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	3.92E+00	5.71E-02	1.59E-01	1.68E-02	5.73E-02	3.80E-02	9.74E-02	-6.25E-01	3.72E+00
ADPF	3.14E+01	7.82E-01	1.69E+00	1.63E+00	7.85E-01	7.05E-01	1.27E+00	-6.84E+00	3.14E+01
AP	1.14E-02	2.02E-04	4.19E-04	7.51E-05	1.27E-04	2.98E-04	5.74E-04	-1.07E-03	1.20E-02
EP	1.05E-03	4.94E-05	3.97E-05	1.22E-05	2.96E-05	6.08E-05	7.78E-05	-8.66E-05	1.24E-03
GWP	3.87E+00	5.66E-02	1.58E-01	1.04E-02	5.68E-02	3.63E-02	9.78E-02	-6.22E-01	3.66E+00
ODP	-6.06E-09	1.90E-14	7.03E-12	3.96E-14	1.91E-14	1.81E-13	9.95E-14	2.44E-09	-3.61E-09
POCP	8.64E-04	-7.22E-05	2.89E-05	1.10E-05	-4.01E-05	2.93E-05	4.56E-05	-2.56E-04	6.11E-04

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	1.56E-06	4.12E-08	1.13E-09	8.58E-08	4.14E-08	2.15E-08	2.07E-08	-2.71E-07	1.50E-06
NHWD	8.19E-01	6.00E-05	1.83E-03	1.25E-04	6.02E-05	3.17E-04	6.08E+00	4.62E-02	6.95E+00
RWD	4.86E-04	1.07E-06	4.32E-04	2.23E-06	1.07E-06	1.07E-05	1.79E-05	-1.51E-04	7.99E-04
PENRT	3.27E+01	7.85E-01	2.78E+00	1.63E+00	7.88E-01	7.32E-01	1.31E+00	-7.06E+00	3.37E+01
PERT	2.99E+00	3.94E-02	9.46E-01	8.20E-02	3.95E-02	4.36E-02	1.53E-01	-3.22E-02	4.26E+00
FW	6.30E-03	7.29E-05	1.35E-03	1.52E-04	7.32E-05	2.13E-04	2.50E-04	-3.26E-03	5.15E-03
PED	3.57E+01	8.24E-01	3.72E+00	1.72E+00	8.27E-01	7.76E-01	1.46E+00	-7.10E+00	3.80E+01

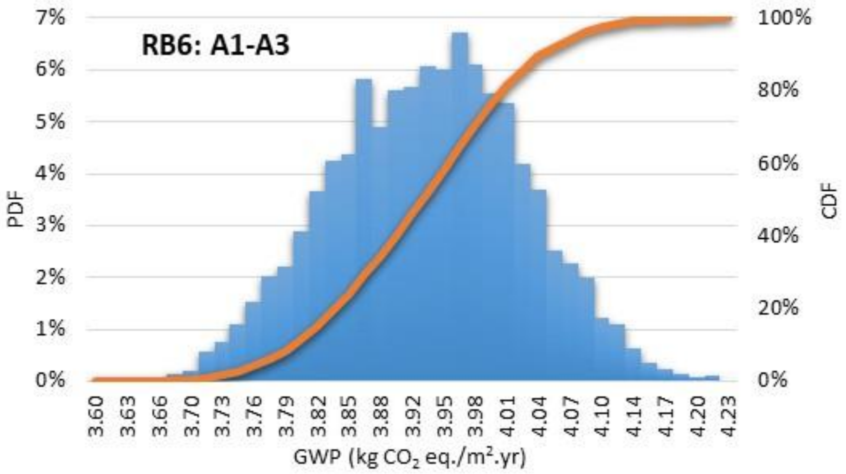
ii) Contribution of life cycle stages per environmental category



A2) Probabilistic analysis

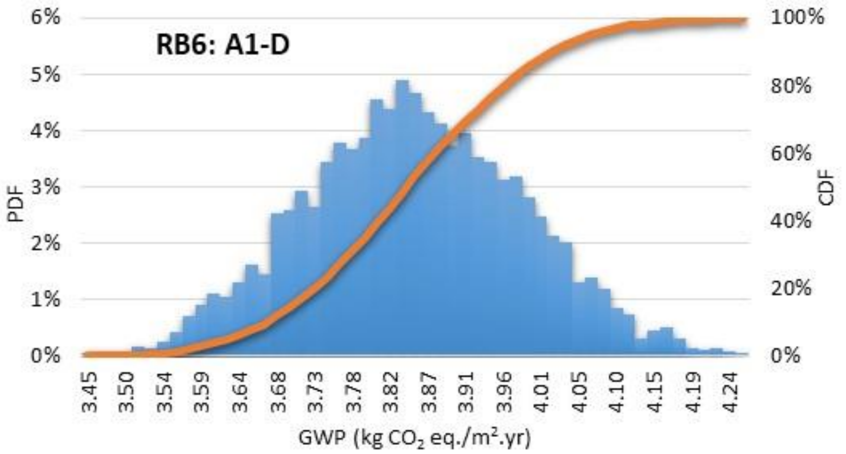
A2.1) GWP

i) Results for Modules A1-A3



Mean	***3.93***
Median	***3.93***
σ	***0.10***
CoV	***2.4%***
$Q_{5\%}$	***3.76***
$Q_{95\%}$	***4.08***

ii) Results for Modules A1-D



Mean	***3.85***
Median	***3.84***
σ	***0.13***
CoV	***3.5%***
$Q_{5\%}$	***3.62***
$Q_{95\%}$	***4.07***

A2.2) Other environmental categories

i) Results for Modules A1-A3

	AP	**EP**	**POCP**
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	1.13E-2	1.08E-3	7.26E-4
Median	1.13E-2	1.08E-3	7.23E-4
COV	2.68%	2.50%	3.36%

ii) Results for Modules A1-D

	AP	**EP**	**POCP**
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	1.20E-2	1.23E-3	6.10E-4
Median	1.20E-2	1.23E-3	6.07E-4
COV	3.08%	2.94%	8.18%

Building 7 (RB7)

Building properties and main characteristics

Type of building	Medium rise residential building
Type of structure (Tier 4)	Reinforced concrete structure
Total Gross Floor Area	3073 m^2
Number of floors	8 (3 underground)
Number of occupants/working places	n.a.
Design working life	50 years (estimated)
Building ref. year	2017
Seismic area (PGA)	0.0357
Climatic area	Csb

Summarized BoM

Building main component	**Material**	**Quantity**
Sub-base	Concrete C25/30	282 m^3
	Steel reinforcement (S500)	15.5 ton
Super-structure	Concrete C25/30	159 m^3
	Concrete C30/37	165 m^3
	Steel reinforcement (S500)	23 ton
	Plywood	2798 m^2
Upper floors	Concrete C25/30	732 m^3
	Concrete C30/37	164 m^3
	Steel reinforcement (S500)	54 ton
	Concrete blocks	5882 unid.
	Plywood	4100 m^2

A1) Deterministic analysis

i) LCA results per functional unit

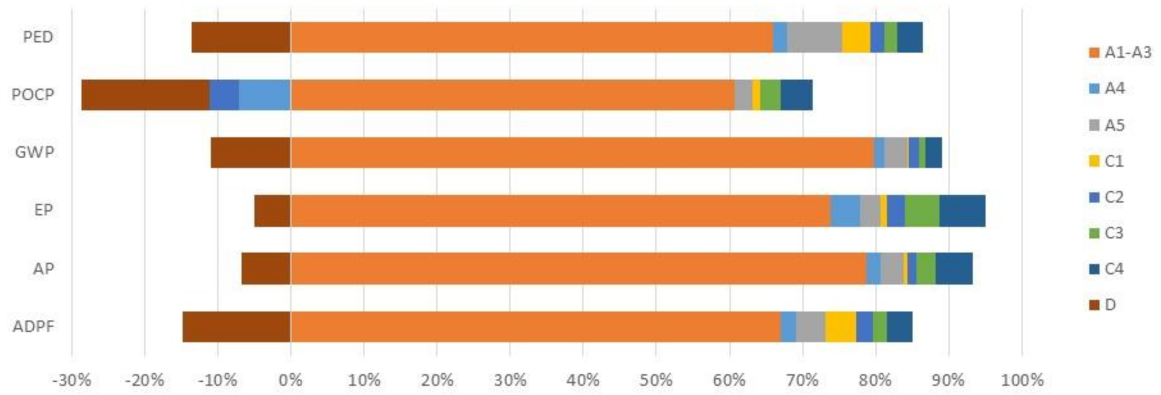
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	3.95E+00	6.47E-02	1.56E-01	1.79E-02	6.54E-02	4.34E-02	1.11E-01	-5.32E-01	3.87E+00
ADPF	2.74E+01	8.87E-01	1.66E+00	1.73E+00	8.97E-01	8.05E-01	1.45E+00	-6.10E+00	2.87E+01
AP	1.02E-02	2.37E-04	4.12E-04	7.97E-05	1.45E-04	3.40E-04	6.56E-04	-8.68E-04	1.12E-02
EP	1.06E-03	5.81E-05	3.90E-05	1.30E-05	3.38E-05	6.94E-05	8.89E-05	-7.23E-05	1.29E-03
GWP	3.88E+00	6.42E-02	1.55E-01	1.11E-02	6.49E-02	4.15E-02	1.12E-01	-5.29E-01	3.80E+00
ODP	-4.46E-09	2.15E-14	6.91E-12	4.20E-14	2.18E-14	2.07E-13	1.14E-13	1.76E-09	-2.70E-09
POCP	7.18E-04	-8.52E-05	2.84E-05	1.17E-05	-4.58E-05	3.35E-05	5.20E-05	-2.07E-04	5.06E-04

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	1.18E-06	4.67E-08	1.11E-09	9.12E-08	4.72E-08	2.46E-08	2.37E-08	-1.88E-07	1.22E-06
NHWD	8.69E-01	6.80E-05	1.80E-03	1.33E-04	6.88E-05	3.62E-04	6.94E+00	3.28E-02	7.85E+00
RWD	5.97E-04	1.21E-06	4.24E-04	2.37E-06	1.23E-06	1.22E-05	2.05E-05	-1.75E-04	8.84E-04
PENRT	2.89E+01	8.90E-01	2.73E+00	1.74E+00	9.00E-01	8.36E-01	1.50E+00	-6.43E+00	3.11E+01
PERT	3.13E+00	4.47E-02	9.30E-01	8.71E-02	4.51E-02	4.98E-02	1.75E-01	-1.62E-01	4.30E+00
FW	6.65E-03	8.27E-05	1.33E-03	1.61E-04	8.36E-05	2.43E-04	2.85E-04	-2.72E-03	6.12E-03
PED	3.21E+01	9.35E-01	3.66E+00	1.82E+00	9.45E-01	8.86E-01	1.67E+00	-6.59E+00	3.54E+01

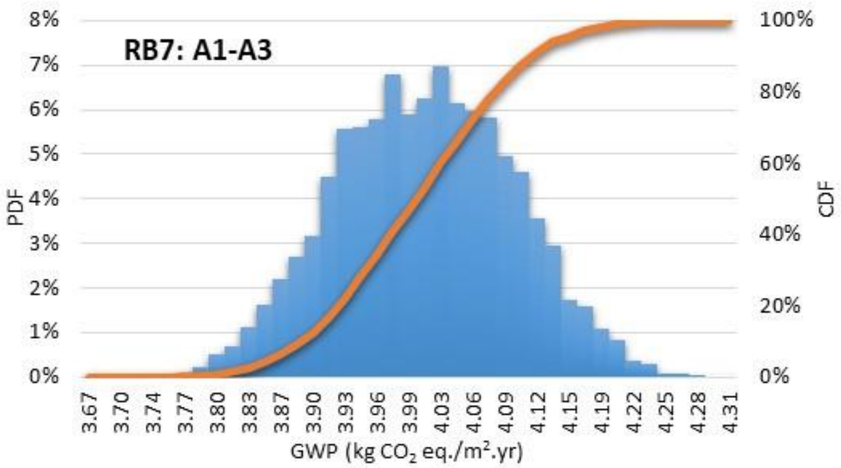
ii) Contribution of life cycle stages per environmental category



A1) Deterministic analysis

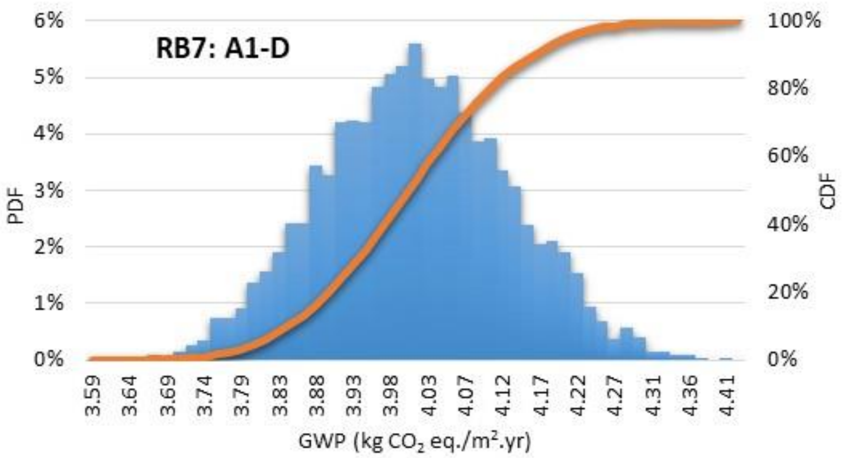
A2.1) GWP

i) LCA results per functional unit



Mean	***4.01***
Median	***4.00***
σ	***0.09***
CoV	***2.2%***
$Q_{5\%}$	***3.85***
$Q_{95\%}$	***4.15***

ii) Results for Modules A1-D



Mean	***4.01***
Median	***4.00***
σ	***0.12***
CoV	***3.0%***
$Q_{5\%}$	***3.80***
$Q_{95\%}$	***4.20***

A2.2) Other environmental categories

i) Results for Modules A1-A3

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	1.02E-2	1.11E-3	5.85E-4
Median	1.02E-2	1.10E-3	5.82E-4
COV	2.40%	2.28%	3.16%

ii) Results for Modules A1-D

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	1.11E-2	1.29E-3	5.06E-4
Median	1.11E-2	1.29E-3	5.03E-4
COV	2.82%	2.67%	7.66%

Building 8 (RB8)

Building properties and main characteristics

Type of building	Medium rise residential building
Type of structure (Tier 4)	Reinforced concrete structure
Total Gross Floor Area	3073 m^2
Number of floors	8 (3 underground)
Number of occupants/working places	n.a.
Design working life	50 years (estimated)
Building ref. year	2017
Seismic area (PGA)	0.0357
Climatic area	Csb

Summarized BoM

Building main component	Material	Quantity
Sub-base	Concrete C25/30	269 m^3
	Steel reinforcement (S500)	22.6 ton
Super-structure	Concrete C25/30	317 m^3
	Steel reinforcement (S500)	54 ton
	Plywood	2798 m^2
Upper floors	Concrete C25/30	887 m^3
	Steel reinforcement (S500)	154 ton
	Concrete blocks	4864 unid.
	Plywood	4100 m^2

A1) Deterministic analysis

i) LCA results per functional unit

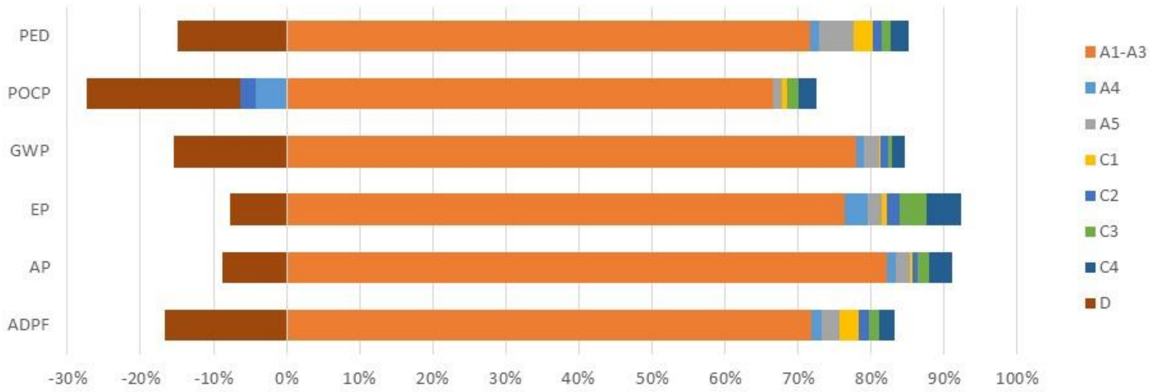
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	5.62E+00	6.98E-02	1.57E-01	1.92E-02	7.03E-02	4.66E-02	1.19E-01	-1.10E+00	5.01E+00
ADPF	4.95E+01	9.57E-01	1.66E+00	1.86E+00	9.63E-01	8.65E-01	1.55E+00	-1.15E+01	4.58E+01
AP	1.83E-02	2.57E-04	4.12E-04	8.57E-05	1.56E-04	3.65E-04	7.05E-04	-1.97E-03	1.83E-02
EP	1.54E-03	6.31E-05	3.91E-05	1.40E-05	3.64E-05	7.46E-05	9.55E-05	-1.54E-04	1.71E-03
GWP	5.54E+00	6.92E-02	1.56E-01	1.19E-02	6.97E-02	4.46E-02	1.20E-01	-1.09E+00	4.92E+00
ODP	-1.12E-08	2.32E-14	6.92E-12	4.52E-14	2.34E-14	2.22E-13	1.22E-13	4.85E-09	-6.33E-09
POCP	1.48E-03	-9.26E-05	2.84E-05	1.26E-05	-4.92E-05	3.60E-05	5.59E-05	-4.66E-04	1.00E-03

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	2.77E-06	5.04E-08	1.11E-09	9.80E-08	5.08E-08	2.64E-08	2.54E-08	-5.50E-07	2.47E-06
NHWD	1.06E+00	7.34E-05	1.80E-03	1.43E-04	7.39E-05	3.89E-04	7.46E+00	9.24E-02	8.62E+00
RWD	5.32E-04	1.31E-06	4.25E-04	2.55E-06	1.32E-06	1.31E-05	2.20E-05	-1.81E-04	8.16E-04
PENRT	5.10E+01	9.60E-01	2.73E+00	1.87E+00	9.67E-01	8.98E-01	1.61E+00	-1.17E+01	4.84E+01
PERT	4.08E+00	4.82E-02	9.32E-01	9.36E-02	4.85E-02	5.35E-02	1.88E-01	1.82E-01	5.63E+00
FW	7.70E-03	8.92E-05	1.33E-03	1.73E-04	8.98E-05	2.61E-04	3.06E-04	-5.80E-03	4.15E-03
PED	5.51E+01	1.01E+00	3.67E+00	1.96E+00	1.02E+00	9.52E-01	1.80E+00	-1.15E+01	5.40E+01

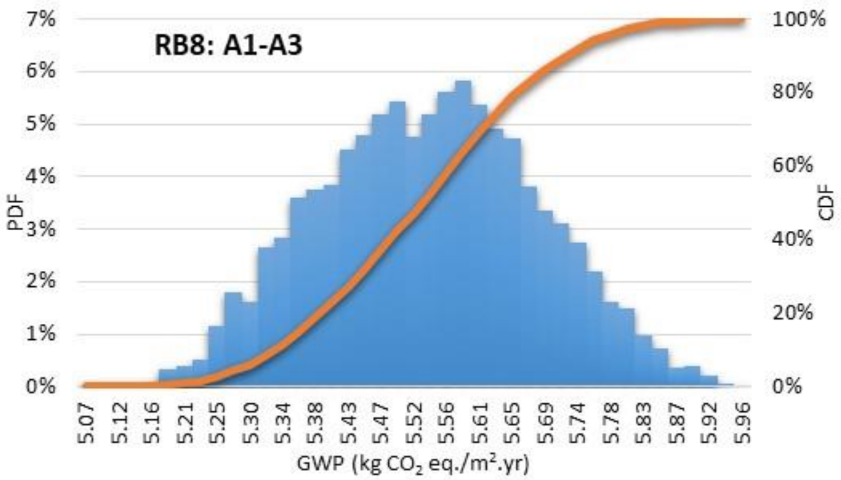
ii) Contribution of life cycle stages per environmental category



A2) Probabilistic analysis

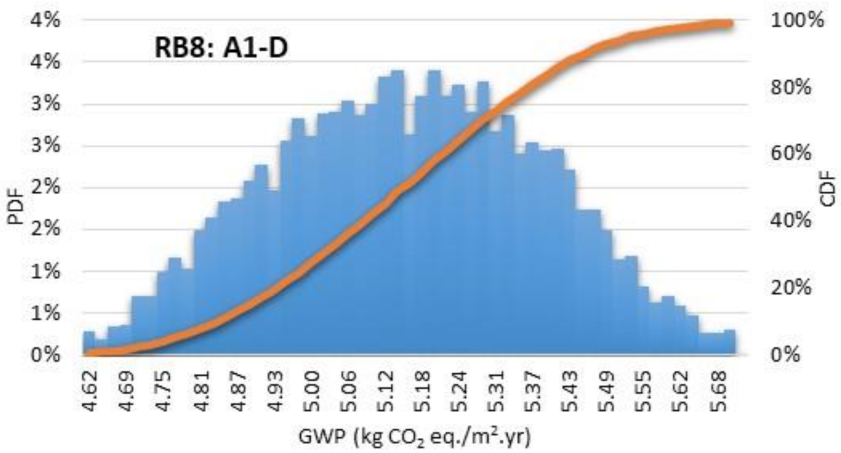
A2.1) GWP

i) Results for Modules A1-A3



Mean	***5.54***
Median	***5.53***
σ	***0.15***
CoV	***2.7%***
$Q_{5\%}$	***5.28***
$Q_{95\%}$	***5.77***

ii) Results for Modules A1-D



Mean	***5.16***
Median	***5.15***
σ	***0.23***
CoV	***4.5%***
$Q_{5\%}$	***4.78***
$Q_{95\%}$	***5.53***

A2.2) Other environmental categories

i) Results for Modules A1-A3

	AP *(kg SO_2 eq./m^2.yr)*	***EP*** *(kg PO_4^{3-} eq./m^2.yr)*	***POCP*** *(kg C_2H_4 eq./m^2.yr)*
Mean value	1.80E-2	1.56E-3	1.26E-3
Median	1.80E-2	1.56E-3	1.26E-3
COV	3.16%	2.71%	3.90%

ii) Results for Modules A1-D

	AP *(kg SO_2 eq./m^2.yr)*	***EP*** *(kg PO_4^{3-} eq./m^2.yr)*	***POCP*** *(kg C_2H_4 eq./m^2.yr)*
Mean value	1.83E-2	1.71E-3	9.62E-4
Median	1.82E-2	1.70E-3	9.64E-4
COV	3.63%	3.21%	11.15%

Building 9 (RB8)

Building properties and main characteristics

Type of building	Medium rise residential building
Type of structure (Tier 4)	Reinforced concrete structure
Total Gross Floor Area	2280 m^2
Number of floors	9 (1 underground)
Number of occupants/working places	n.a.
Design working life	50 years (estimated)
Building ref. year	2004
Seismic area (PGA)	0.0357
Climatic area	Csb

Summarized BoM

Building main component	Material	Quantity
Sub-base	Concrete C25/30	144 m^3
	Steel reinforcement (S500)	10.7 ton
Super-structure	Concrete C25/30	500 m^3
	Steel reinforcement (S500)	47.8 ton
	Plywood	4096 m^2
Upper floors	Concrete C25/30	873 m^3
	Steel reinforcement (S500)	71.4 ton
	Concrete blocks	5448 unid.
	Plywood	4919 m^2

A1) Deterministic analysis

i) LCA results per functional unit

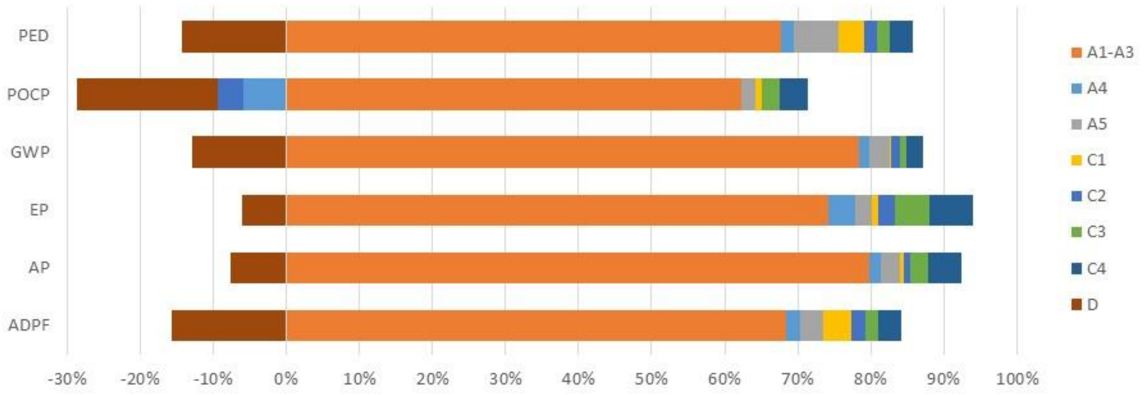
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	5.81E+00	9.46E-02	2.03E-01	2.58E-02	9.45E-02	6.27E-02	1.61E-01	-9.42E-01	5.51E+00
ADPF	4.53E+01	1.30E+00	2.16E+00	2.50E+00	1.30E+00	1.16E+00	2.09E+00	-1.05E+01	4.53E+01
AP	1.67E-02	3.30E-04	5.35E-04	1.15E-04	2.09E-04	4.91E-04	9.48E-04	-1.60E-03	1.77E-02
EP	1.60E-03	8.05E-05	5.07E-05	1.88E-05	4.89E-05	1.00E-04	1.28E-04	-1.30E-04	1.89E-03
GWP	5.69E+00	9.38E-02	2.02E-01	1.60E-02	9.37E-02	5.99E-02	1.62E-01	-9.38E-01	5.38E+00
ODP	-8.42E-09	3.15E-14	8.98E-12	6.07E-14	3.15E-14	2.99E-13	1.64E-13	3.52E-09	-4.90E-09
POCP	1.23E-03	-1.17E-04	3.69E-05	1.69E-05	-6.61E-05	4.84E-05	7.52E-05	-3.80E-04	8.40E-04

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	2.20E-06	6.83E-08	1.44E-09	1.32E-07	6.82E-08	3.55E-08	3.42E-08	-3.86E-07	2.15E-06
NHWD	1.30E+00	9.94E-05	2.34E-03	1.92E-04	9.93E-05	5.23E-04	1.00E+01	6.63E-02	1.14E+01
RWD	7.48E-04	1.77E-06	5.52E-04	3.42E-06	1.77E-06	1.76E-05	2.96E-05	-2.52E-04	1.10E-03
PENRT	4.73E+01	1.30E+00	3.55E+00	2.51E+00	1.30E+00	1.21E+00	2.16E+00	-1.09E+01	4.84E+01
PERT	4.68E+00	6.53E-02	1.21E+00	1.26E-01	6.52E-02	7.19E-02	2.52E-01	-1.19E-01	6.35E+00
FW	9.33E-03	1.21E-04	1.72E-03	2.33E-04	1.21E-04	3.51E-04	4.12E-04	-4.88E-03	7.41E-03
PED	5.20E+01	1.37E+00	4.76E+00	2.63E+00	1.36E+00	1.28E+00	2.42E+00	-1.10E+01	5.48E+01

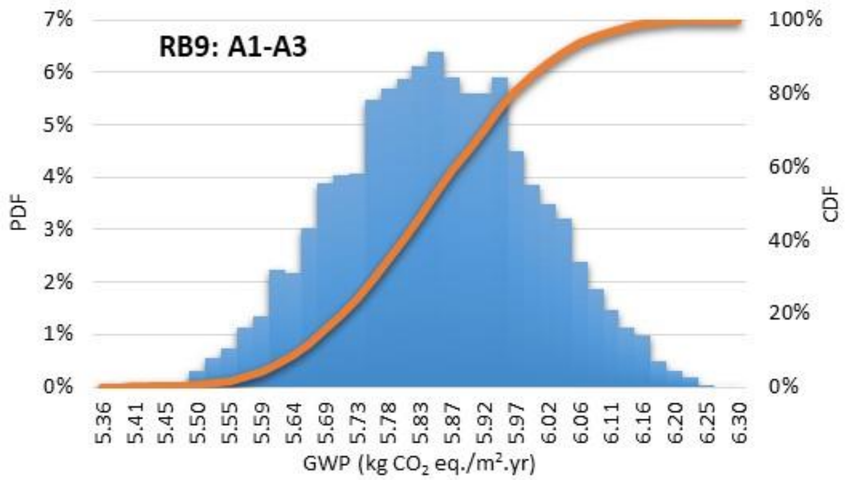
ii) Contribution of life cycle stages per environmental category



A2) Probabilistic analysis

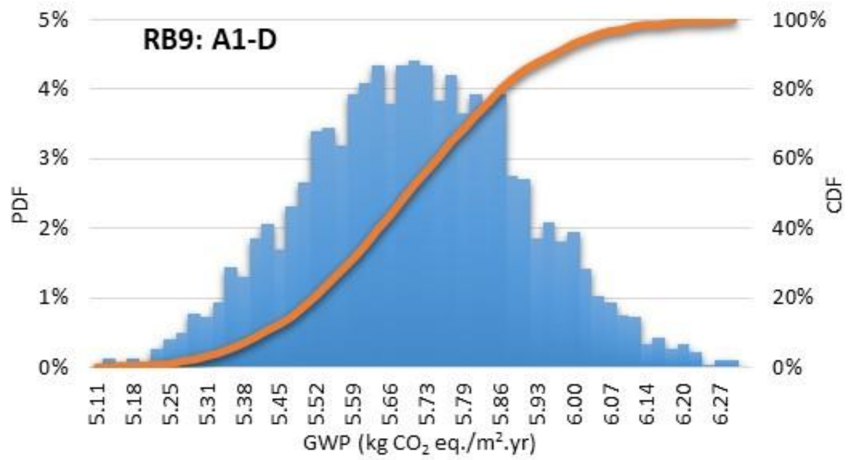
A2.1) GWP

i) Results for Modules A1-A3



Mean	***5.85***
Median	***5.84***
σ	***0.14***
CoV	***2.5%***
$Q_{5\%}$	***5.60***
$Q_{95\%}$	***6.08***

ii) Results for Modules A1-D



Mean	***5.70***
Median	***5.69***
σ	***0.21***
CoV	***3.6%***
$Q_{5\%}$	***5.35***
$Q_{95\%}$	***6.03***

A2.2) Other environmental categories

i) Results for Modules A1-A3

	AP *(kg SO_2 eq./m^2.yr)*	**EP** *(kg PO_4^{3-} eq./m^2.yr)*	**POCP** *(kg C_2H_4 eq./m^2.yr)*
Mean value	1.67E-2	1.65E-3	1.02E-3
Median	1.66E-2	1.65E-3	1.01E-3
COV	2.67%	2.57%	3.14%

ii) Results for Modules A1-D

	AP *(kg SO_2 eq./m^2.yr)*	**EP** *(kg PO_4^{3-} eq./m^2.yr)*	**POCP** *(kg C_2H_4 eq./m^2.yr)*
Mean value	1.77E-2	1.89E-3	8.41E-4
Median	1.77E-2	1.89E-3	8.37E-4
COV	3.18%	3.10%	8.65%

Annex C: Office buildings

Building 1 (OB1)

Building properties and main characteristics

Type of building	Low rise office building
Type of structure (Tier 4)	Reinforced concrete structure
Total Gross Floor Area	10500 m^2
Number of floors	4 (1 underground)
Number of occupants/working places	265 people
Design working life	50 years (Estimated)
Building ref. year	2016
Seismic area (PGA)	0.038
Climatic area	Cfb

Summarized BoM

Building main component	Material	Quantity
Sub-base	Concrete C12/15	1485 ton
	Concrete C16/20	15 ton
	Concrete C25/30	9890 ton
	Steel reinforcement (S400)	301 ton
	Plywood	534 m^2
Super-structure	Concrete C35/45	11407 ton
	Steel reinforcement (S400)	1055 ton
	Plywood	9219 m^2
Upper floors	Concrete C30/37	237 ton
	Steel reinforcement (S400)	22 ton
	Structural steel	0.3 ton
	Galvanized steel	11 ton
	Plywood	8177 m^2

A1) Deterministic analysis

i) LCA results per functional unit

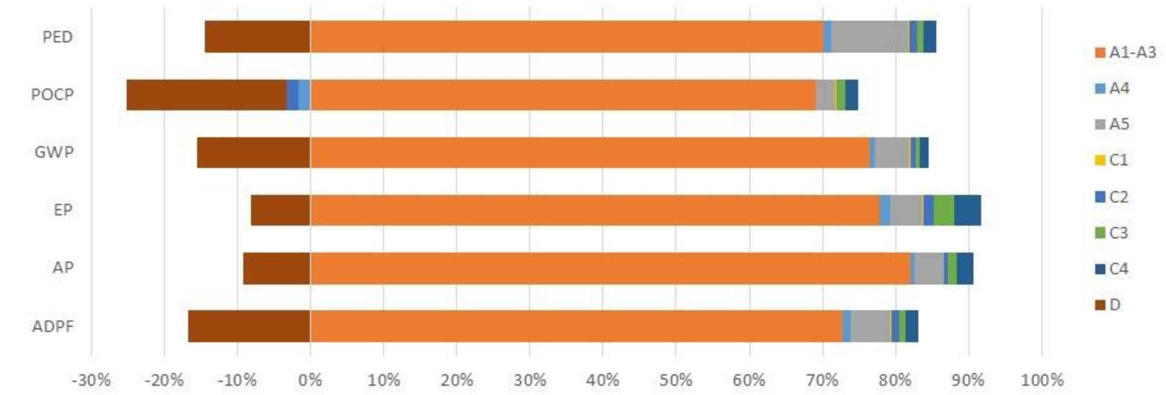
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	7,24E+00	6,89E-02	4,52E-01	8,96E-03	6,89E-02	4,57E-02	1,17E-01	-1,46E+00	6,54E+00
ADPF	6,40E+01	9,44E-01	4,81E+00	9,52E-02	9,44E-01	8,48E-01	1,52E+00	-1,48E+01	5,84E+01
AP	2,42E-02	1,55E-04	1,19E-03	2,36E-05	1,53E-04	3,58E-04	6,90E-04	-2,73E-03	2,40E-02
EP	1,97E-03	3,64E-05	1,13E-04	2,24E-06	3,56E-05	7,31E-05	9,35E-05	-2,08E-04	2,11E-03
GWP	7,15E+00	6,83E-02	4,50E-01	8,91E-03	6,83E-02	4,37E-02	1,18E-01	-1,45E+00	6,45E+00
ODP	-1,55E-08	2,29E-14	2,00E-11	3,96E-13	2,29E-14	2,18E-13	1,20E-13	7,07E-09	-8,42E-09
POCP	2,04E-03	-4,94E-05	8,21E-05	1,63E-06	-4,82E-05	3,53E-05	5,48E-05	-6,45E-04	1,47E-03

Indicators describing input/output flows

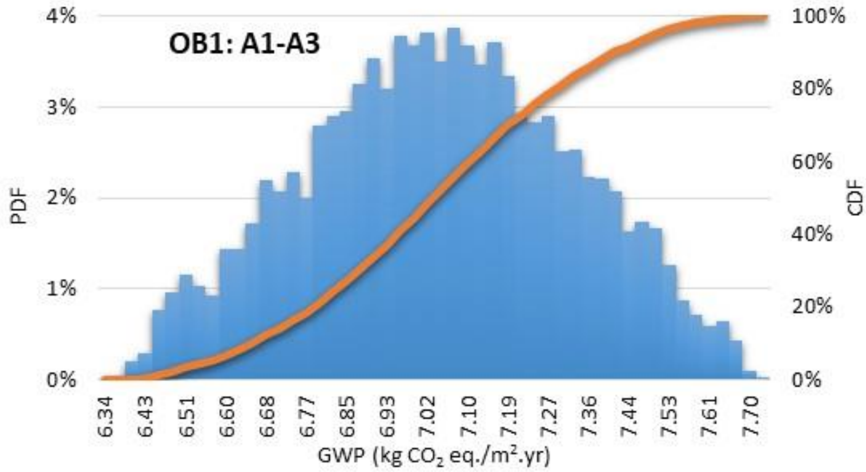
	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	3,80E-06	4,97E-08	3,20E-09	6,34E-11	4,97E-08	2,59E-08	2,49E-08	-8,12E-07	3,14E-06
NHWD	1,06E+00	7,24E-05	5,20E-03	1,03E-04	7,24E-05	3,82E-04	7,31E+00	1,35E-01	8,51E+00
RWD	5,96E-04	1,29E-06	1,23E-03	2,43E-05	1,29E-06	1,28E-05	2,15E-05	-1,93E-04	1,69E-03
PENRT	6,57E+01	9,48E-01	7,90E+00	1,56E-01	9,47E-01	8,80E-01	1,58E+00	-1,48E+01	6,33E+01
PERT	4,57E+00	4,75E-02	2,69E+00	5,33E-02	4,75E-02	5,24E-02	1,84E-01	4,08E-01	8,06E+00
FW	8,83E-03	8,80E-05	3,84E-03	7,61E-05	8,80E-05	2,56E-04	3,00E-04	-7,93E-03	5,54E-03
PED	7,03E+01	9,95E-01	1,06E+01	2,10E-01	9,95E-01	9,33E-01	1,76E+00	-1,44E+01	7,14E+01

ii) Contribution of life cycle stages per environmental category



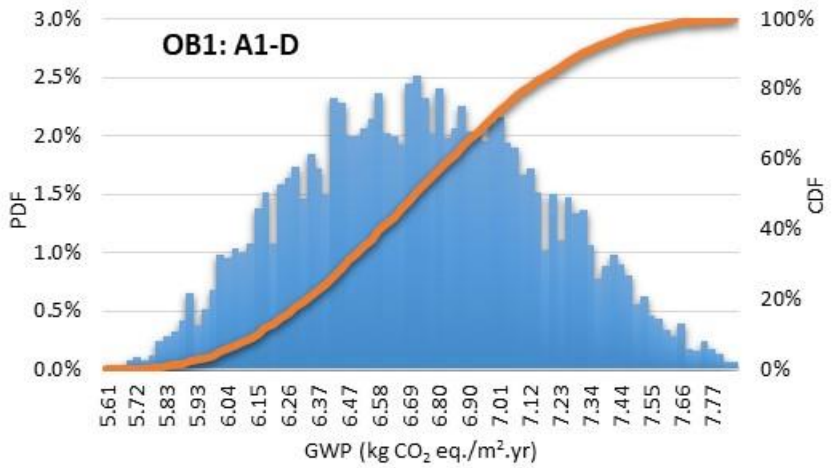
A2) Probabilistic analysis

i) Results for Modules A1-A3



Mean	***7.05***
Median	***7.03***
σ	***0.28***
CoV	***4.0%***
$Q_{5\%}$	***6.56***
$Q_{95\%}$	***7.49***

ii) Results for Modules A1-D



Mean	***6.73***
Median	***6.71***
σ	***0.44***
CoV	***6.5%***
$Q_{5\%}$	***6.01***
$Q_{95\%}$	***7.44***

A2.2) Other environmental categories

i) Results for Modules A1-A3

	AP (kg SO_2 eq./m^2.yr)	***EP*** (kg PO_4^{3-} eq./m^2.yr)	***POCP*** (kg C_2H_4 eq./m^2.yr)
Mean value	2.36E-2	1.94E-3	1.82E-3
Median	2.36E-2	1.94E-3	1.81E-3
COV	4.53%	3.98%	5.10%

ii) Results for Modules A1-D

	AP (kg SO_2 eq./m^2.yr)	***EP*** (kg PO_4^{3-} eq./m^2.yr)	***POCP*** (kg C_2H_4 eq./m^2.yr)
Mean value	2.40E-2	2.11E-3	1.47E-3
Median	2.39E-2	2.11E-3	1.46E-3
COV	5.16%	4.66%	12.42%

Building 2 (OB2)

Building properties and main characteristics

Type of building	Low rise office building
Type of structure (Tier 4)	Reinforced concrete structure
Total Gross Floor Area	2068 m^2
Number of floors	3
Number of occupants/working places	n.a.
Design working life	50 years (Estimated)
Building ref. year	2006
Seismic area (PGA)	0.1529
Climatic area	Csa

Summarized BoM

Building main component	**Material**	**Quantity**
Sub-base	Concrete C25/30	213.6 ton
	Steel reinforcement (S400)	9.3 ton
Super-structure	Concrete C25/30	499.2 ton
	Steel reinforcement (S400)	30.7 ton
Upper floors	Concrete C25/30	598.8 ton
	Steel reinforcement (S400)	45.6 ton

A1) Deterministic analysis

i) LCA results per functional unit

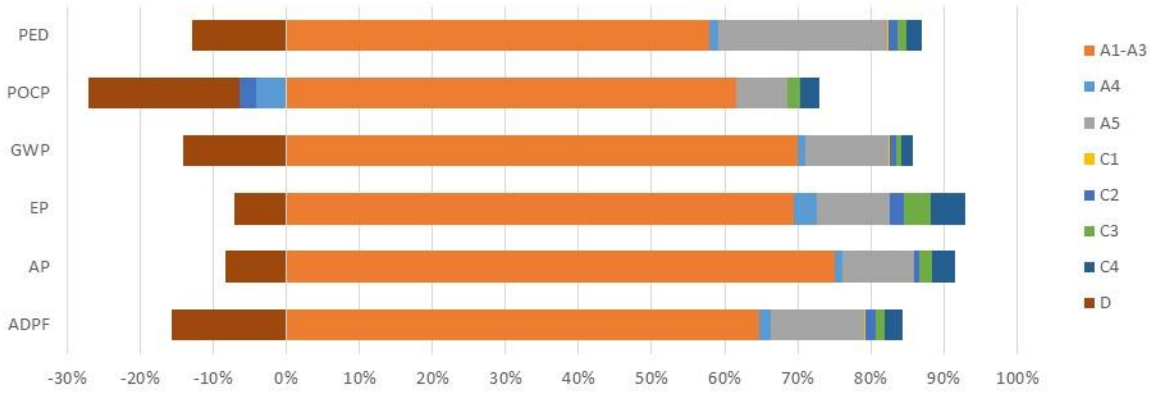
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	2,76E+00	4,04E-02	4,49E-01	3,07E-03	3,91E-02	2,60E-02	6,63E-02	-5,58E-01	2,83E+00
ADPF	2,41E+01	5,53E-01	4,78E+00	3,26E-02	5,36E-01	4,81E-01	8,62E-01	-5,84E+00	2,55E+01
AP	9,10E-03	1,39E-04	1,18E-03	8,08E-06	8,65E-05	2,03E-04	3,91E-04	-1,02E-03	1,01E-02
EP	7,76E-04	3,38E-05	1,12E-04	7,66E-07	2,02E-05	4,15E-05	5,30E-05	-7,86E-05	9,59E-04
GWP	2,75E+00	4,00E-02	4,47E-01	3,05E-03	3,87E-02	2,48E-02	6,66E-02	-5,55E-01	2,81E+00
ODP	-5,48E-09	1,34E-14	1,99E-11	1,36E-13	1,30E-14	1,24E-13	6,77E-14	2,49E-09	-2,97E-09
POCP	7,20E-04	-4,81E-05	8,16E-05	5,57E-07	-2,74E-05	2,00E-05	3,10E-05	-2,41E-04	5,36E-04

Indicators describing input/output flows

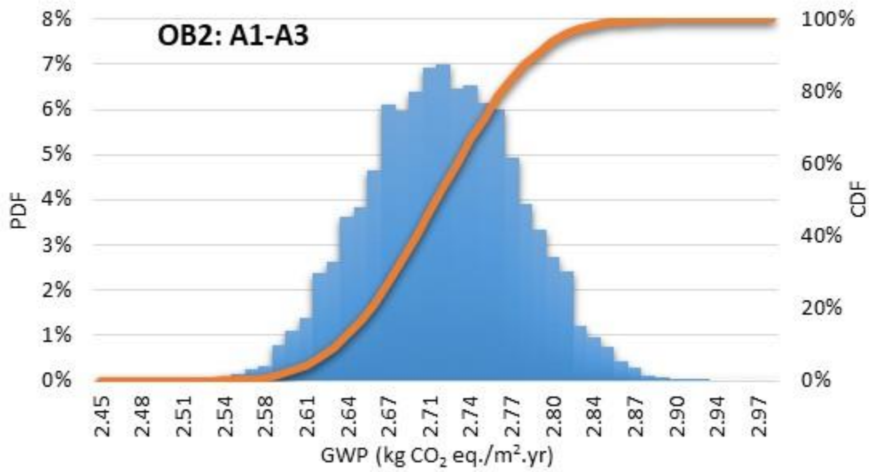
	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	1,37E-06	2,91E-08	3,18E-09	2,17E-11	2,82E-08	1,47E-08	1,41E-08	-2,83E-07	1,17E-06
NHWD	5,67E-01	4,24E-05	5,17E-03	3,53E-05	4,11E-05	2,17E-04	4,14E+00	4,74E-02	4,76E+00
RWD	2,48E-04	7,57E-07	1,22E-03	8,33E-06	7,33E-07	7,30E-06	1,22E-05	-1,12E-04	1,39E-03
PENRT	2,48E+01	5,55E-01	7,85E+00	5,36E-02	5,37E-01	5,00E-01	8,93E-01	-5,96E+00	2,92E+01
PERT	1,54E+00	2,78E-02	2,68E+00	1,83E-02	2,70E-02	2,98E-02	1,04E-01	5,17E-02	4,48E+00
FW	3,57E-03	5,16E-05	3,82E-03	2,60E-05	4,99E-05	1,45E-04	1,70E-04	-3,02E-03	4,81E-03
PED	2,63E+01	5,83E-01	1,05E+01	7,18E-02	5,64E-01	5,30E-01	9,97E-01	-5,91E+00	3,37E+01

ii) Contribution of life cycle stages per environmental category



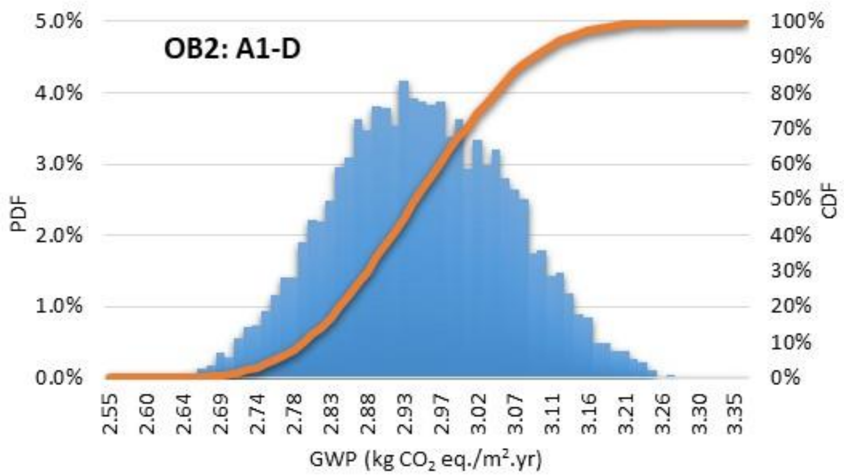
A2) Probabilistic analysis

i) Results for Modules A1-A3



Mean	***2.72***
Median	***2.71***
σ	***0.06***
CoV	***2.2%***
$Q_{5\%}$	***2.61***
$Q_{95\%}$	***2.81***

ii) Results for Modules A1-D



Mean	***2.95***
Median	***2.94***
σ	***0.11***
CoV	***3.8%***
$Q_{5\%}$	***2.76***
$Q_{95\%}$	***3.13***

A2.2) Other environmental categories

i) Results for Modules A1-A3

	AP *(kg SO_2 eq./m^2.yr)*	***EP*** *(kg PO_4^{3-} eq./m^2.yr)*	***POCP*** *(kg C_2H_4 eq./m^2.yr)*
Mean value	9.00E-3	7.91E-4	6.11E-4
Median	8.98E-3	7.89E-4	6.08E-4
COV	2.57%	2.17%	3.24%

ii) Results for Modules A1-D

	AP *(kg SO_2 eq./m^2.yr)*	***EP*** *(kg PO_4^{3-} eq./m^2.yr)*	***POCP*** *(kg C_2H_4 eq./m^2.yr)*
Mean value	1.01E-2	9.58E-4	5.36E-4
Median	1.00E-2	9.56E-4	5.32E-4
COV	3.05%	2.68%	9.03%

Building 3 (OB3)

Building properties and main characteristics

Type of building	Low rise residential building
Type of structure (Tier 4)	Reinforced concrete structure
Total Gross Floor Area	10054 m^2
Number of floors	5 (1 underground)
Number of occupants/working places	n.a.
Design working life	50 years (estimated)
Building ref. year	n.a.
Seismic area (PGA)	0.02
Climatic area	Cfb

Summarized BoM

Building main component	Material	Quantity
Sub-base	Concrete C25/30	262 ton
	Concrete C30/37	120 ton
	Steel reinforcement (S400)	18 ton
	Formwork	157 m^2
Super-structure	Concrete C30/37	479 ton
	Steel reinforcement (S400)	21 ton
	Structural steel (S355)	68 ton
	Formwork	140 m^2
Upper floors	Concrete C30/37	3170 ton
	Steel reinforcement (S400)	36 ton
	Structural steel (S355)	463 ton
	Galvanized steel	139 ton
	Formwork	281 m^2

A1) Deterministic analysis

i) LCA results per functional unit

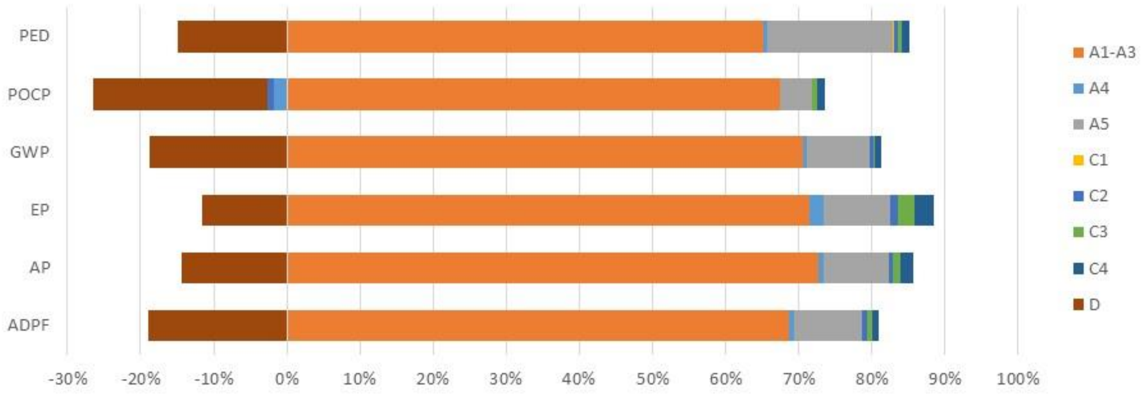
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	3,78E+00	2,43E-02	4,48E-01	1,83E-03	2,48E-02	1,70E-02	3,91E-02	-9,82E-01	3,35E+00
ADPF	3,49E+01	3,33E-01	4,76E+00	1,94E-02	3,40E-01	3,15E-01	5,09E-01	-9,66E+00	3,15E+01
AP	9,51E-03	9,39E-05	1,18E-03	4,82E-06	5,49E-05	1,33E-04	2,31E-04	-1,88E-03	9,33E-03
EP	8,73E-04	2,31E-05	1,12E-04	4,56E-07	1,28E-05	2,71E-05	3,13E-05	-1,42E-04	9,38E-04
GWP	3,68E+00	2,41E-02	4,45E-01	1,82E-03	2,46E-02	1,62E-02	3,93E-02	-9,78E-01	3,26E+00
ODP	-9,89E-09	8,09E-15	1,98E-11	8,09E-14	8,26E-15	8,08E-14	4,00E-14	5,10E-09	-4,77E-09
POCP	1,26E-03	-3,37E-05	8,13E-05	3,32E-07	-1,74E-05	1,31E-05	1,83E-05	-4,42E-04	8,80E-04

Indicators describing input/output flows

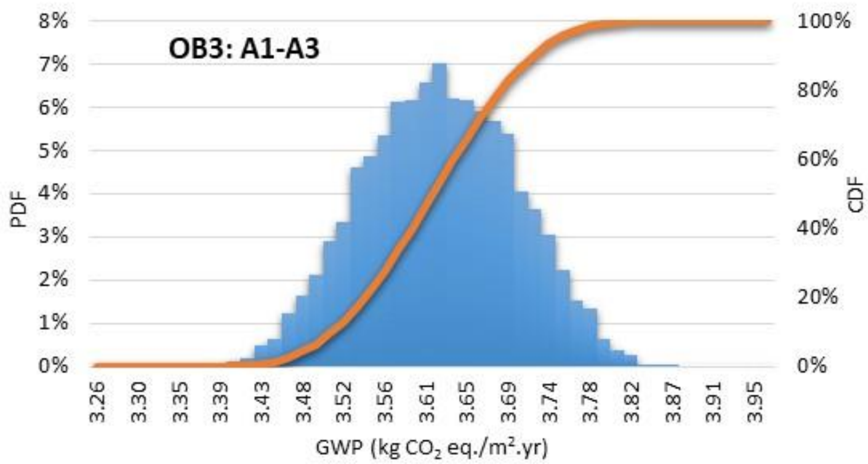
	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	2,61E-06	1,75E-08	3,17E-09	1,29E-11	1,79E-08	9,60E-09	8,33E-09	-5,92E-07	2,07E-06
NHWD	5,58E-01	2,55E-05	5,15E-03	2,10E-05	2,61E-05	1,42E-04	2,44E+00	9,78E-02	3,10E+00
RWD	2,01E-04	4,56E-07	1,22E-03	4,97E-06	4,66E-07	4,77E-06	7,20E-06	-6,75E-05	1,37E-03
PENRT	3,63E+01	3,34E-01	7,82E+00	3,19E-02	3,41E-01	3,27E-01	5,27E-01	-9,51E+00	3,62E+01
PERT	3,43E+00	1,68E-02	2,67E+00	1,09E-02	1,71E-02	1,95E-02	6,14E-02	4,44E-01	6,67E+00
FW	6,48E-03	3,10E-05	3,80E-03	1,55E-05	3,17E-05	9,49E-05	1,00E-04	-5,35E-03	5,20E-03
PED	3,97E+01	3,51E-01	1,05E+01	4,28E-02	3,58E-01	3,46E-01	5,88E-01	-9,06E+00	4,29E+01

ii) Contribution of life cycle stages per environmental category



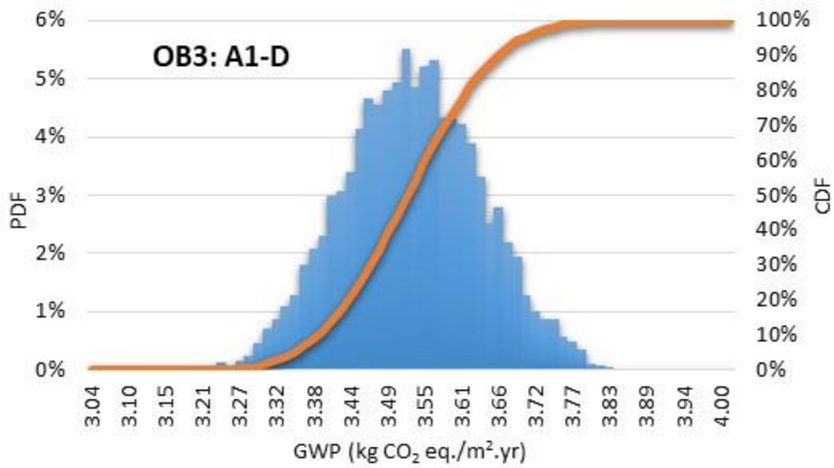
A2) Probabilistic analysis

i) Results for Modules A1-A3



Mean	***3.62***
Median	***3.61***
σ	***0.08***
CoV	***2.2%***
$Q_{5\%}$	***3.48***
$Q_{95\%}$	***3.75***

ii) Results for Modules A1-D



Mean	***3.53***
Median	***3.52***
σ	***0.11***
CoV	***3.0%***
$Q_{5\%}$	***3.35***
$Q_{95\%}$	***3.70***

A2.2) Other environmental categories

i) Results for Modules A1-A3

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	9.11E-3	8.59E-4	1.11E-3
Median	9.09E-3	8.58E-4	1.10E-3
COV	2.27%	2.16%	2.64%

ii) Results for Modules A1-D

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	9.35E-3	9.38E-4	8.84E-4
Median	9.33E-3	9.37E-4	8.79E-4
COV	2.67%	2.39%	4.95%

Building 4 (OB4)

Building properties and main characteristics

Type of building	Low rise residential building
Type of structure (Tier 4)	Composite structure
Total Gross Floor Area	10054 m^2
Number of floors	5 (1 underground)
Number of occupants/working places	n.a.
Design working life	50 years (estimated)
Building ref. year	n.a.
Seismic area (PGA)	n.a.
Climatic area	Cfb

Summarized BoM

Building main component	Material	Quantity
Sub-base	Concrete C25/30	262 ton
	Concrete C30/37	120 ton
	Steel reinforcement (S400)	18 ton
	Formwork	157 m^2
Super-structure	Concrete C30/37	357 ton
	Concrete C35/45	153 ton
	Concrete C50	55 ton
	Steel reinforcement (S400)	27 ton
	Formwork	972 m^2
Upper floors	Concrete C35/45	6114 ton
	Steel reinforcement (S400)	93 ton
	Formwork	11306 m^2

A1) Deterministic analysis

i) LCA results per functional unit

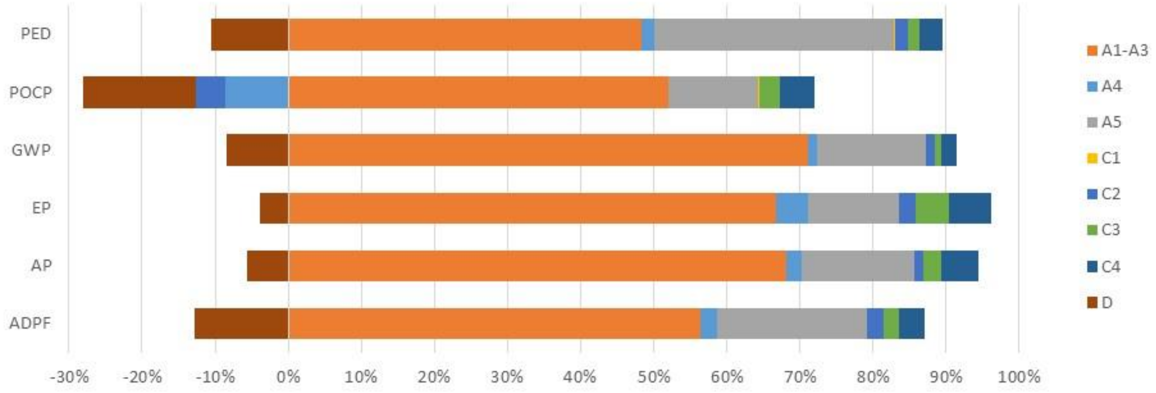
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	2,18E+00	3,91E-02	4,50E-01	2,76E-03	3,84E-02	2,55E-02	6,53E-02	-2,58E-01	2,54E+00
ADPF	1,31E+01	5,35E-01	4,78E+00	2,93E-02	5,27E-01	4,73E-01	8,49E-01	-3,00E+00	1,73E+01
AP	5,23E-03	1,58E-04	1,18E-03	7,27E-06	8,51E-05	2,00E-04	3,85E-04	-4,26E-04	6,82E-03
EP	6,03E-04	3,89E-05	1,12E-04	6,88E-07	1,99E-05	4,07E-05	5,22E-05	-3,48E-05	8,33E-04
GWP	2,14E+00	3,87E-02	4,47E-01	2,74E-03	3,81E-02	2,44E-02	6,56E-02	-2,56E-01	2,50E+00
ODP	-1,66E-09	1,30E-14	1,99E-11	1,22E-13	1,28E-14	1,22E-13	6,67E-14	8,02E-10	-8,41E-10
POCP	3,44E-04	-5,66E-05	8,17E-05	5,01E-07	-2,69E-05	1,97E-05	3,06E-05	-1,02E-04	2,91E-04

Indicators describing input/output flows

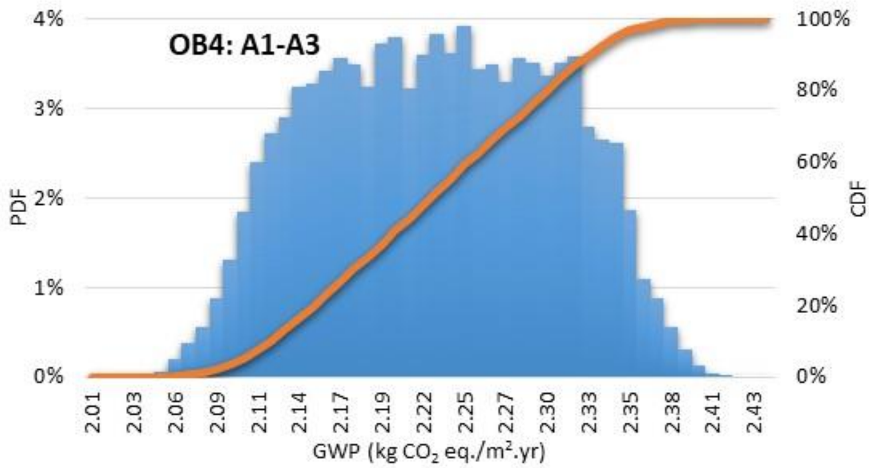
	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	5,10E-07	2,82E-08	3,18E-09	1,95E-11	2,77E-08	1,44E-08	1,39E-08	-8,43E-08	5,13E-07
NHWD	4,56E-01	4,11E-05	5,17E-03	3,17E-05	4,04E-05	2,13E-04	4,08E+00	1,48E-02	4,55E+00
RWD	3,58E-04	7,33E-07	1,22E-03	7,49E-06	7,21E-07	7,16E-06	1,20E-05	-1,16E-04	1,49E-03
PENRT	1,41E+01	5,37E-01	7,85E+00	4,82E-02	5,28E-01	4,91E-01	8,80E-01	-3,24E+00	2,12E+01
PERT	1,49E+00	2,70E-02	2,68E+00	1,64E-02	2,65E-02	2,92E-02	1,03E-01	-1,52E-01	4,21E+00
FW	3,48E-03	4,99E-05	3,82E-03	2,34E-05	4,91E-05	1,43E-04	1,67E-04	-1,37E-03	6,36E-03
PED	1,56E+01	5,64E-01	1,05E+01	6,46E-02	5,55E-01	5,20E-01	9,82E-01	-3,39E+00	2,54E+01

ii) Contribution of life cycle stages per environmental category



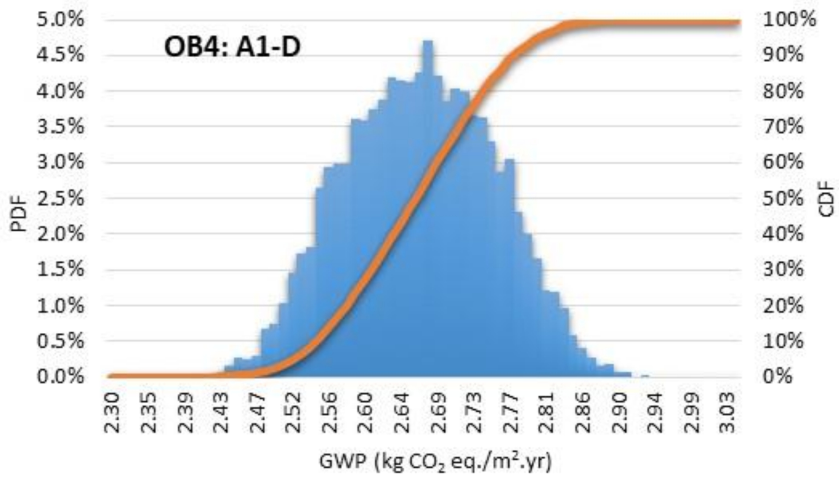
A2) Probabilistic analysis

i) Results for Modules A1-A3



Mean	***2.23***
Median	***2.22***
σ	***0.08***
CoV	***3.4%***
$Q_{5\%}$	***2.10***
$Q_{95\%}$	***2.34***

ii) Results for Modules A1-D



Mean	***2.67***
Median	***2.66***
σ	***0.08***
CoV	***3.3%***
$Q_{5\%}$	***2.52***
$Q_{95\%}$	***2.81***

A2.2) Other environmental categories

i) Results for Modules A1-A3

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	5.31E-3	6.37E-4	2.69E-4
Median	5.30E-3	6.35E-4	2.67E-4
COV	2.95%	3.46%	2.89%

ii) Results for Modules A1-D

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	6.82E-3	8.34E-4	2.90E-4
Median	6.81E-3	8.32E-4	2.89E-4
COV	3.12%	3.49%	6.44%

Building 5 (OB5)

Building properties and main characteristics

Type of building	Medium rise office building
Type of structure (Tier 4)	Reinforced concrete structure
Total Gross Floor Area	12780 m^2
Number of floors	8 (1 underground)
Number of occupants/working places	n.a.
Design working life	50 years (estimated)
Building ref. year	n.a.
Seismic area (PGA)	n.a.
Climatic area	Cfb

Summarized BoM

Building main component	Material	Quantity
Sub-base		
	Concrete C30/37	5179 ton
	Steel reinforcement (S400)	86 ton
	Formwork	1565 m^2
Super-structure	Concrete C30/37	3901 ton
	Steel reinforcement (S400)	296 ton
	Formwork	14126 m^2
Upper floors	Concrete C35/45	10380 ton
	Steel reinforcement (S400)	790 ton
	Formwork	13509 m^2

A1) Deterministic analysis

i) LCA results per functional unit

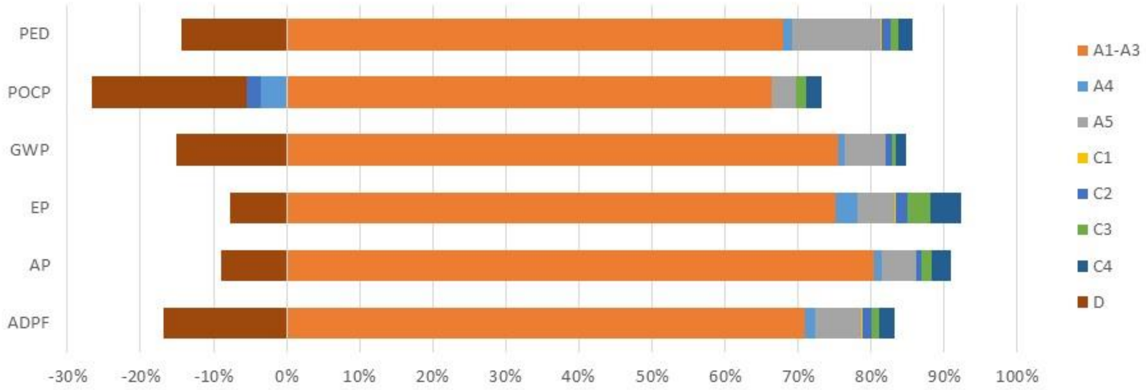
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	6,16E+00	7,37E-02	4,52E-01	6,70E-03	6,83E-02	4,53E-02	1,16E-01	-1,22E+00	5,70E+00
ADPF	5,31E+01	1,01E+00	4,81E+00	7,12E-02	9,36E-01	8,41E-01	1,51E+00	-1,26E+01	4,97E+01
AP	2,02E-02	2,74E-04	1,19E-03	1,77E-05	1,51E-04	3,55E-04	6,85E-04	-2,27E-03	2,06E-02
EP	1,69E-03	6,71E-05	1,13E-04	1,67E-06	3,53E-05	7,25E-05	9,28E-05	-1,74E-04	1,90E-03
GWP	6,07E+00	7,31E-02	4,50E-01	6,66E-03	6,77E-02	4,33E-02	1,17E-01	-1,22E+00	5,61E+00
ODP	-1,28E-08	2,45E-14	2,00E-11	2,96E-13	2,27E-14	2,16E-13	1,19E-13	5,74E-09	-7,02E-09
POCP	1,68E-03	-9,08E-05	8,21E-05	1,22E-06	-4,78E-05	3,50E-05	5,43E-05	-5,36E-04	1,17E-03

Indicators describing input/output flows

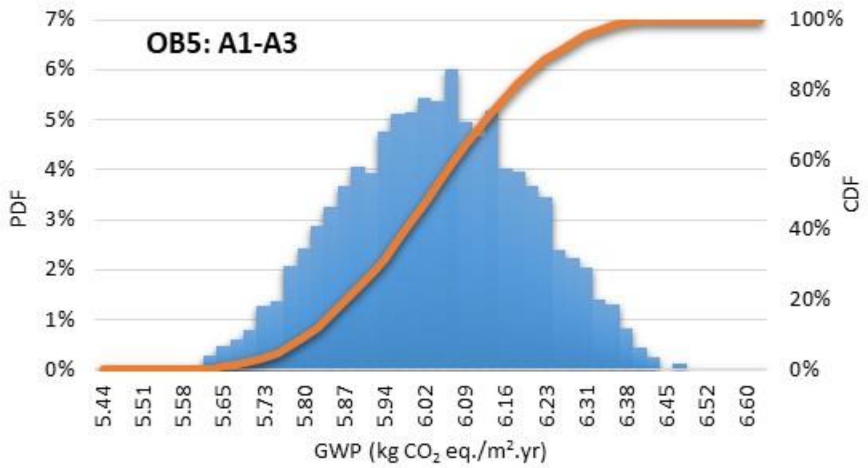
	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	3,07E-06	5,32E-08	3,20E-09	4,74E-11	4,93E-08	2,57E-08	2,47E-08	-6,57E-07	2,57E-06
NHWD	1,04E+00	7,75E-05	5,20E-03	7,70E-05	7,18E-05	3,78E-04	7,25E+00	1,10E-01	8,40E+00
RWD	5,62E-04	1,38E-06	1,23E-03	1,82E-05	1,28E-06	1,27E-05	2,14E-05	-1,95E-04	1,65E-03
PENRT	5,47E+01	1,01E+00	7,90E+00	1,17E-01	9,39E-01	8,73E-01	1,56E+00	-1,27E+01	5,44E+01
PERT	4,33E+00	5,09E-02	2,69E+00	3,99E-02	4,71E-02	5,20E-02	1,82E-01	2,51E-01	7,65E+00
FW	7,49E-03	9,42E-05	3,84E-03	5,69E-05	8,73E-05	2,54E-04	2,98E-04	-6,63E-03	5,49E-03
PED	5,90E+01	1,06E+00	1,06E+01	1,57E-01	9,87E-01	9,25E-01	1,75E+00	-1,24E+01	6,20E+01

ii) Contribution of life cycle stages per environmental category



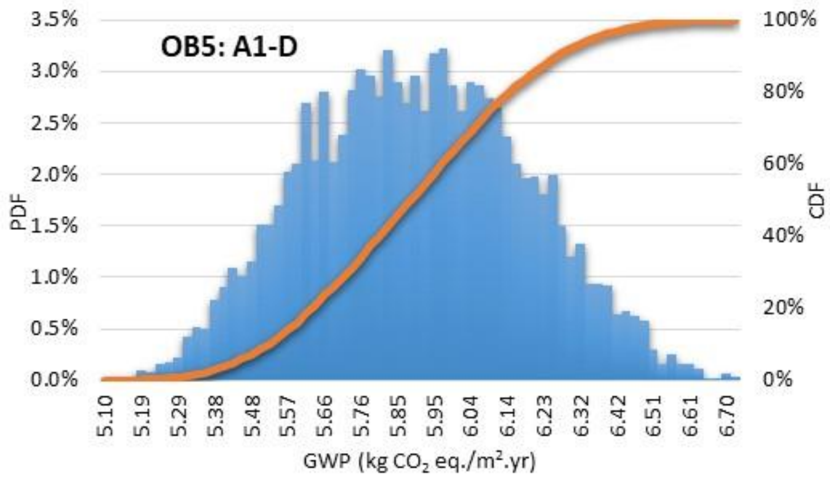
A2) Probabilistic analysis

i) Results for Modules A1-A3



Mean	***6.04***
Median	***6.03***
σ	***0.17***
CoV	***2.7%***
$Q_{5\%}$	***5.75***
$Q_{95\%}$	***6.30***

ii) Results for Modules A1-D



Mean	***5.90***
Median	***5.89***
σ	***0.28***
CoV	***4.8%***
$Q_{5\%}$	***5.43***
$Q_{95\%}$	***6.37***

A2.2) Other environmental categories

i) Results for Modules A1-A3

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	1.99E-2	1.70E-3	1.45E-3
Median	1.98E-2	1.70E-3	1.44E-3
COV	3.09%	2.74%	3.65%

ii) Results for Modules A1-D

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	2.07E-2	1.89E-3	1.17E-3
Median	2.06E-2	1.89E-3	1.17E-3
COV	3.75%	3.37%	10.28%

Building 6 (OB6)

Building properties and main characteristics

Type of building	Medium rise residential building
Type of structure (Tier 4)	Composite structure
Total Gross Floor Area	36450 m^2
Number of floors	10
Number of occupants/working places	n.a.
Design working life	50 years (estimated)
Building ref. year	2008
Seismic area (PGA)	n.a.
Climatic area	Cfb

Summarized BoM

Building main component	Material	Quantity
Sub-base	Concrete C32/40	3112 ton
	Concrete C35/45	2764 ton
	Steel reinforcement (S400)	232 ton
	Formwork	31 ton
Super-structure	Concrete C30/37	3779 ton
	Steel reinforcement (S400)	233 ton
	Structural steel (S355)	554 ton
	Formwork	153 ton
Upper floors	Concrete C20/25	5205 ton
	Concrete C30/37	2542 ton
	Steel reinforcement (S400)	333 ton
	Structural steel (S355)	2102 ton
	Galvanized steel	400 ton
	Formwork	25 ton

A1) Deterministic analysis

i) LCA results per functional unit

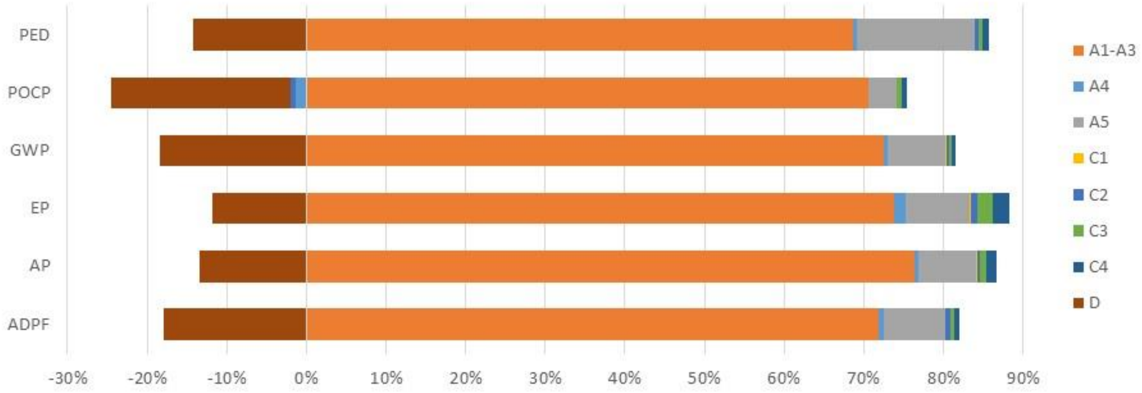
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	4,44E+00	2,32E-02	4,48E-01	2,25E-03	2,36E-02	1,65E-02	3,54E-02	-1,12E+00	3,87E+00
ADPF	4,39E+01	3,18E-01	4,76E+00	2,39E-02	3,23E-01	3,05E-01	4,60E-01	-1,09E+01	3,92E+01
AP	1,24E-02	8,31E-05	1,18E-03	5,92E-06	5,23E-05	1,29E-04	2,09E-04	-2,17E-03	1,19E-02
EP	1,02E-03	2,03E-05	1,12E-04	5,61E-07	1,22E-05	2,63E-05	2,83E-05	-1,62E-04	1,06E-03
GWP	4,40E+00	2,30E-02	4,45E-01	2,23E-03	2,34E-02	1,57E-02	3,56E-02	-1,12E+00	3,83E+00
ODP	-1,26E-08	7,71E-15	1,98E-11	9,93E-14	7,86E-15	7,84E-14	3,62E-14	5,95E-09	-6,59E-09
POCP	1,60E-03	-2,98E-05	8,13E-05	4,08E-07	-1,65E-05	1,27E-05	1,66E-05	-5,09E-04	1,16E-03

Indicators describing input/output flows

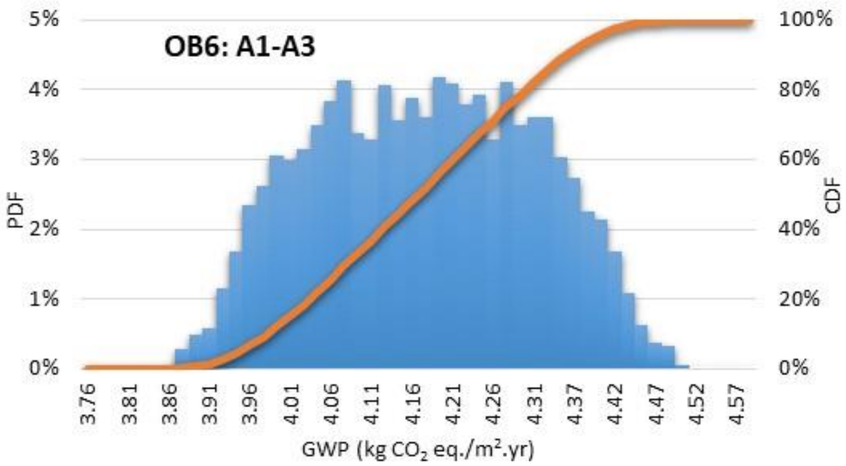
	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	3,13E-06	1,67E-08	3,17E-09	1,59E-11	1,70E-08	9,32E-09	7,54E-09	-6,92E-07	2,50E-06
NHWD	6,74E-01	2,44E-05	5,14E-03	2,58E-05	2,48E-05	1,37E-04	2,21E+00	1,14E-01	3,00E+00
RWD	1,42E-04	4,35E-07	1,22E-03	6,10E-06	4,43E-07	4,62E-06	6,51E-06	-5,47E-05	1,32E-03
PENRT	4,55E+01	3,19E-01	7,82E+00	3,92E-02	3,25E-01	3,17E-01	4,77E-01	-1,07E+01	4,41E+01
PERT	3,24E+00	1,60E-02	2,66E+00	1,34E-02	1,63E-02	1,89E-02	5,56E-02	5,69E-01	6,60E+00
FW	2,60E-03	2,96E-05	3,80E-03	1,91E-05	3,02E-05	9,20E-05	9,07E-05	-6,14E-03	5,21E-04
PED	4,87E+01	3,35E-01	1,05E+01	5,26E-02	3,41E-01	3,36E-01	5,32E-01	-1,01E+01	5,07E+01

ii) Contribution of life cycle stages per environmental category



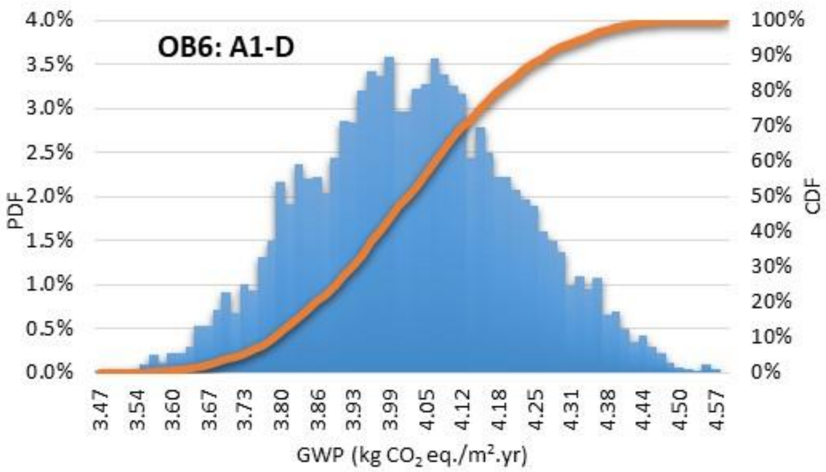
A2) Probabilistic analysis

i) Results for Modules A1-A3



Mean	***4.18***
Median	***4.17***
σ	***0.14***
CoV	***3.3%***
$Q_{5\%}$	***3.95***
$Q_{95\%}$	***4.39***

ii) Results for Modules A1-D



Mean	***4.03***
Median	***4.02***
σ	***0.18***
CoV	***4.6%***
$Q_{5\%}$	***3.72***
$Q_{95\%}$	***4.34***

A2.2) Other environmental categories

i) Results for Modules A1-A3

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	1.17E-2	9.87E-4	1.40E-3
Median	1.17E-2	9.86E-4	1.40E-3
COV	3.27%	3.03%	3.93%

ii) Results for Modules A1-D

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	1.19E-2	1.05E-3	1.16E-3
Median	1.18E-2	1.05E-3	1.16E-3
COV	3.81%	3.37%	6.98%

Building 7 (OB7)

Building properties and main characteristics

Type of building	Low rise office building
Type of structure (Tier 4)	Composite structure
Total Gross Floor Area	83760 m^2
Number of floors	<3
Number of occupants/working places	n.a.
Design working life	50 years (estimated)
Building ref. year	2016
Seismic area (PGA)	0.04
Climatic area	Cfb

Summary BoM

Building main component	**Material**	**Quantity**
Sub-base	-	-
Super-structure	Concrete C30/37	64620 m^3
	Steel reinforcement (S500)	10975 ton
	Pre-stressed steel	59 ton
	Structural steel (S355)	2320 ton
	Formwork	2491 m^2

A1) Deterministic analysis

i) LCA results per functional unit

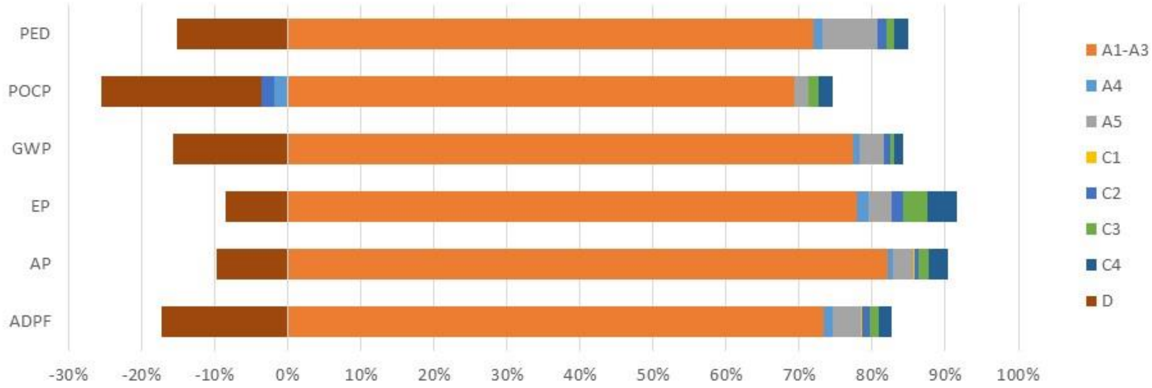
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	1,06E+01	1,10E-01	4,56E-01	7,34E-03	1,10E-01	7,32E-02	1,84E-01	-2,14E+00	9,38E+00
ADPF	9,25E+01	1,50E+00	4,85E+00	7,81E-02	1,50E+00	1,36E+00	2,40E+00	-2,18E+01	8,24E+01
AP	3,39E-02	2,45E-04	1,20E-03	1,93E-05	2,43E-04	5,73E-04	1,09E-03	-3,98E-03	3,33E-02
EP	2,82E-03	5,73E-05	1,14E-04	1,83E-06	5,68E-05	1,17E-04	1,47E-04	-3,04E-04	3,01E-03
GWP	1,05E+01	1,09E-01	4,53E-01	7,30E-03	1,09E-01	7,00E-02	1,85E-01	-2,13E+00	9,30E+00
ODP	-2,28E-08	3,64E-14	2,02E-11	3,25E-13	3,65E-14	3,49E-13	1,88E-13	1,02E-08	-1,25E-08
POCP	2,99E-03	-7,77E-05	8,28E-05	1,33E-06	-7,68E-05	5,65E-05	8,63E-05	-9,42E-04	2,12E-03

Indicators describing input/output flows

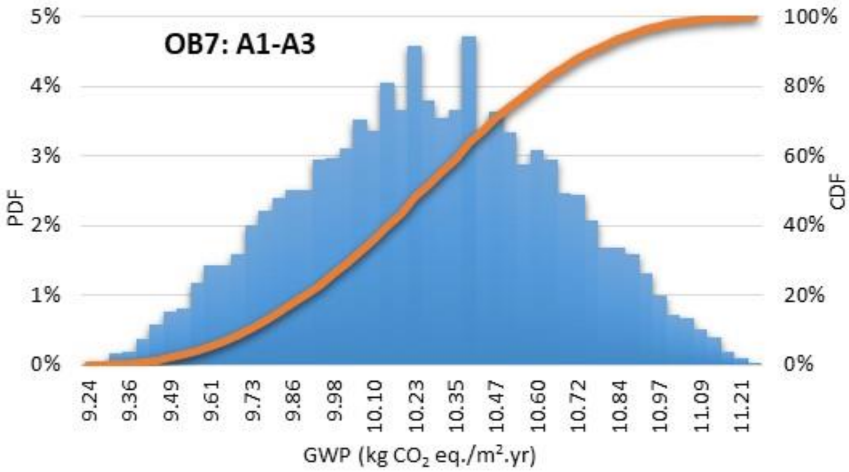
	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	5,48E-06	7,91E-08	3,23E-09	5,20E-11	7,92E-08	4,14E-08	3,93E-08	-1,17E-06	4,54E-06
NHWD	1,78E+00	1,15E-04	5,24E-03	8,44E-05	1,15E-04	6,11E-04	1,15E+01	1,95E-01	1,35E+01
RWD	8,70E-04	2,05E-06	1,24E-03	1,99E-05	2,06E-06	2,06E-05	3,39E-05	-3,05E-04	1,88E-03
PENRT	9,54E+01	1,51E+00	7,96E+00	1,28E-01	1,51E+00	1,41E+00	2,48E+00	-2,19E+01	8,85E+01
PERT	6,55E+00	7,55E-02	2,71E+00	4,37E-02	7,57E-02	8,40E-02	2,90E-01	5,37E-01	1,04E+01
FW	1,02E-02	1,40E-04	3,87E-03	6,23E-05	1,40E-04	4,09E-04	4,73E-04	-1,16E-02	3,67E-03
PED	1,02E+02	1,58E+00	1,07E+01	1,72E-01	1,58E+00	1,49E+00	2,77E+00	-2,14E+01	9,89E+01

ii) Contribution of life cycle stages per environmental category



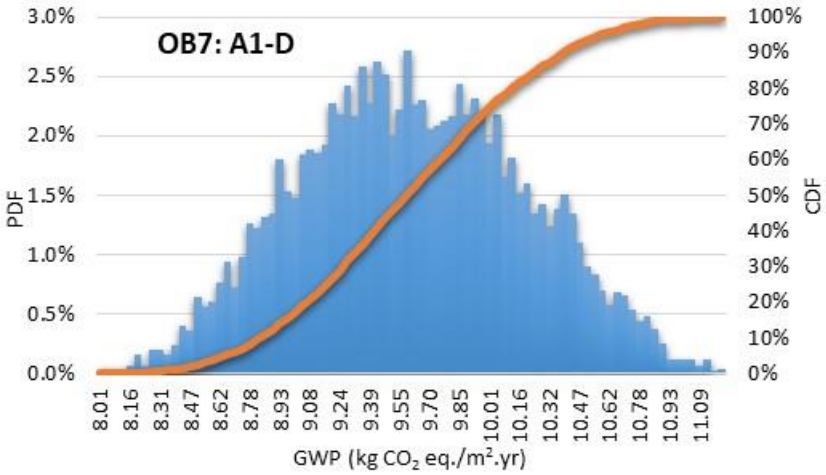
A2) Probabilistic analysis

i) Results for Modules A1-A3



Mean	***10.27***
Median	***10.25***
σ	***0.39***
CoV	***3.8%***
$Q_{5\%}$	***9.60***
$Q_{95\%}$	***10.88***

ii) Results for Modules A1-D



Mean	***9.61***
Median	***9.58***
σ	***0.59***
CoV	***6.1%***
$Q_{5\%}$	***8.64***
$Q_{95\%}$	***10.58***

A2.2) Other environmental categories

i) Results for Modules A1-A3

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	3.32E-2	2.79E-3	2.65E-3
Median	3.31E-2	2.79E-3	2.64E-3
COV	4.24%	3.82%	4.60%

ii) Results for Modules A1-D

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	3.34E-2	3.01E-3	2.12E-3
Median	3.33E-2	3.00E-3	2.10E-3
COV	5.02%	4.59%	11.49%

Building 8 (OB8)

Building properties and main characteristics

Type of building	Low rise office building
Type of structure (Tier 4)	Composite structure
Total Gross Floor Area	35000 m^2
Number of floors	3
Number of occupants/working places	n.a.
Design working life	50 years (estimated)
Building ref. year	2017
Seismic area (PGA)	0.10
Climatic area	Cfb

Summary BoM

Building main component	Material	Quantity
Sub-base	Concrete C30/37	12692 m^3
	Steel reinforcement (S500)	1579 ton
	Formwork	6471 m^2
Super-structure	Concrete C30/37	21830 m^3
	Steel reinforcement (S500)	3458 ton
	Formwork	68450 m^2

A1) Deterministic analysis

i) LCA results per functional unit

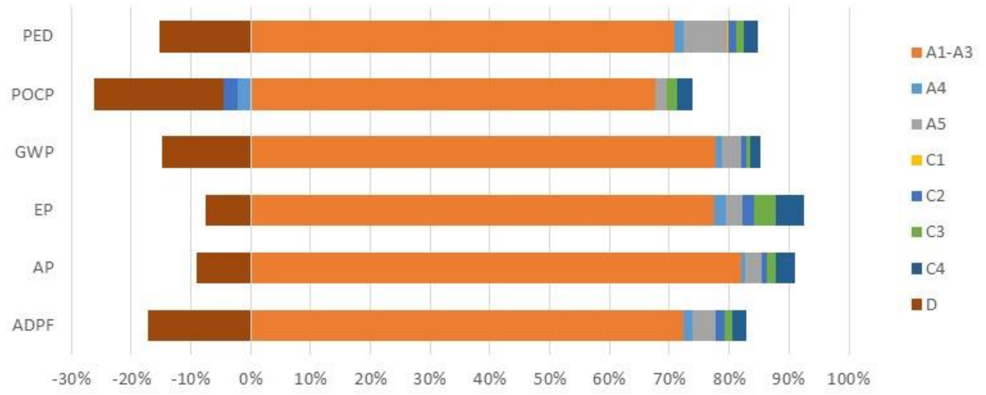
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	1,13E+01	1,37E-01	4,59E-01	9,29E-03	1,37E-01	9,10E-02	2,33E-01	-2,13E+00	1,02E+01
ADPF	9,33E+01	1,88E+00	4,88E+00	9,88E-02	1,88E+00	1,69E+00	3,02E+00	-2,22E+01	8,46E+01
AP	3,56E-02	3,03E-04	1,21E-03	2,45E-05	3,03E-04	7,12E-04	1,37E-03	-3,92E-03	3,57E-02
EP	3,09E-03	7,08E-05	1,14E-04	2,32E-06	7,08E-05	1,45E-04	1,86E-04	-3,01E-04	3,38E-03
GWP	1,12E+01	1,36E-01	4,56E-01	9,24E-03	1,36E-01	8,69E-02	2,34E-01	-2,12E+00	1,01E+01
ODP	-2,16E-08	4,56E-14	2,03E-11	4,11E-13	4,56E-14	4,34E-13	2,38E-13	9,72E-09	-1,19E-08
POCP	2,90E-03	-9,59E-05	8,33E-05	1,69E-06	-9,59E-05	7,02E-05	1,09E-04	-9,27E-04	2,04E-03

Indicators describing input/output flows

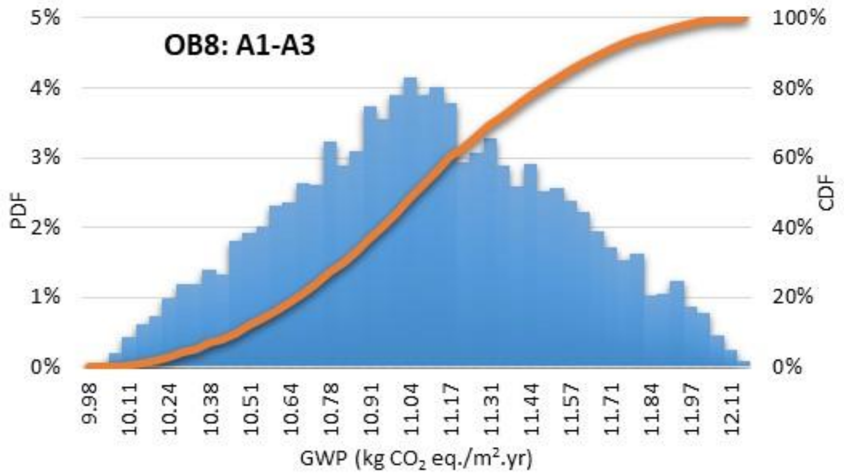
	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	5,24E-06	9,89E-08	3,25E-09	6,58E-11	9,89E-08	5,15E-08	4,95E-08	-1,11E-06	4,43E-06
NHWD	2,00E+00	1,44E-04	5,27E-03	1,07E-04	1,44E-04	7,59E-04	1,45E+01	1,85E-01	1,67E+01
RWD	1,13E-03	2,57E-06	1,25E-03	2,52E-05	2,57E-06	2,56E-05	4,28E-05	-3,93E-04	2,08E-03
PENRT	9,65E+01	1,88E+00	8,01E+00	1,62E-01	1,88E+00	1,75E+00	3,13E+00	-2,25E+01	9,08E+01
PERT	7,33E+00	9,45E-02	2,73E+00	5,53E-02	9,45E-02	1,04E-01	3,65E-01	2,94E-01	1,11E+01
FW	1,42E-02	1,75E-04	3,90E-03	7,89E-05	1,75E-04	5,09E-04	5,96E-04	-1,15E-02	8,10E-03
PED	1,04E+02	1,98E+00	1,07E+01	2,18E-01	1,98E+00	1,86E+00	3,50E+00	-2,22E+01	1,02E+02

ii) Contribution of life cycle stages per environmental category



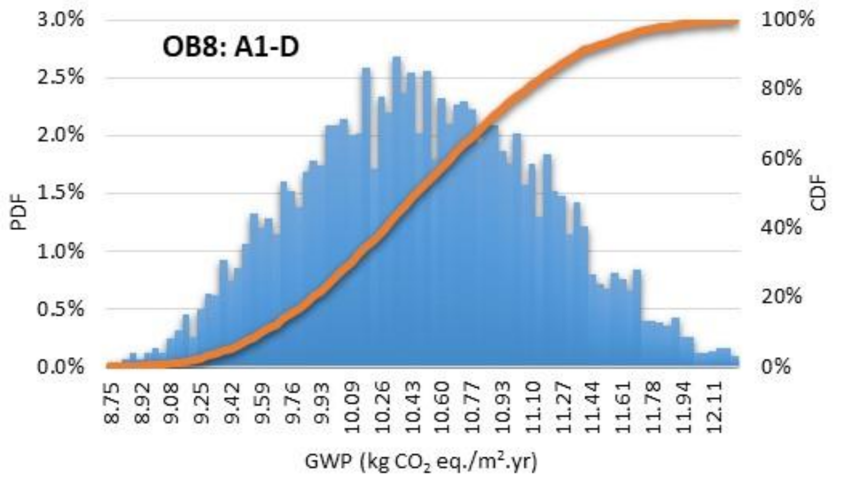
A2) Probabilistic analysis

i) Results for Modules A1-A3



Mean	***11.09***
Median	***11.06***
σ	***0.45***
CoV	***4.0%***
$Q_{5\%}$	***10.32***
$Q_{95\%}$	***11.83***

ii) Results for Modules A1-D



Mean	***10.50***
Median	***10.46***
σ	***0.67***
CoV	***6.4%***
$Q_{5\%}$	***9.40***
$Q_{95\%}$	***11.60***

A2.2) Other environmental categories

i) Results for Modules A1-A3

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	3.50E-2	3.09E-3	2.57E-3
Median	3.49E-2	3.08E-3	2.55E-3
COV	4.44%	4.04%	5.14%

ii) Results for Modules A1-D

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	3.56E-2	3.37E-3	2.04E-3
Median	3.55E-2	3.36E-3	2.02E-3
COV	5.23%	4.81%	13.11%

Building 9 (OB9)

Building properties and main characteristics

Type of building	Low rise office building
Type of structure (Tier 4)	Composite structure
Total Gross Floor Area	17500 m^2
Number of floors	<3
Number of occupants/working places	n.a.
Design working life	50 years (estimated)
Building ref. year	2015
Seismic area (PGA)	0.10
Climatic area	Cfb

Summary BoM

Building main component	**Material**	**Quantity**
Sub-base	Concrete C30/37	2053 ton
	Steel reinforcement (S500)	246 ton
	Formwork	6223 m^2
Super-structure	Concrete C30/37	7227 m^3
	Steel reinforcement (S500)	1089 ton
	Structural steel (S355)	357 ton
	Formwork	44326 m^2

A1) Deterministic analysis

i) LCA results per functional unit

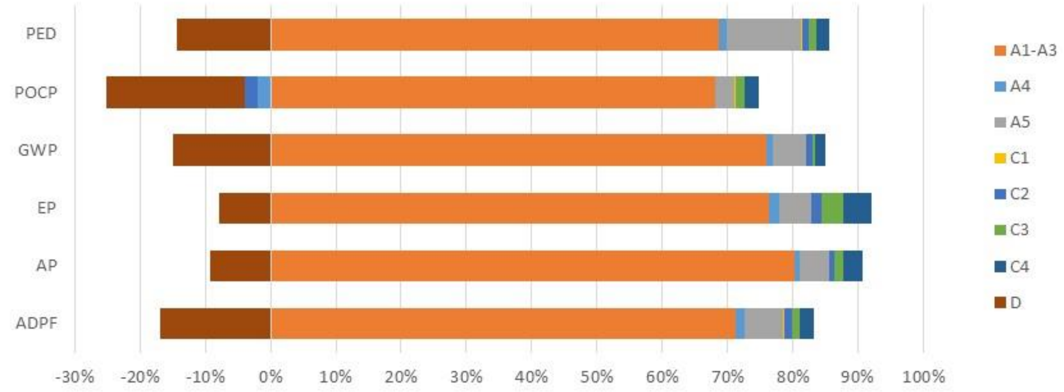
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	6,72E+00	7,46E-02	4,53E-01	5,07E-03	7,48E-02	4,98E-02	1,26E-01	-1,31E+00	6,19E+00
ADPF	5,71E+01	1,02E+00	4,81E+00	5,39E-02	1,03E+00	9,24E-01	1,64E+00	-1,35E+01	5,31E+01
AP	2,09E-02	1,67E-04	1,19E-03	1,34E-05	1,66E-04	3,90E-04	7,43E-04	-2,43E-03	2,11E-02
EP	1,80E-03	3,91E-05	1,13E-04	1,27E-06	3,87E-05	7,97E-05	1,01E-04	-1,86E-04	1,98E-03
GWP	6,61E+00	7,40E-02	4,50E-01	5,04E-03	7,41E-02	4,76E-02	1,27E-01	-1,30E+00	6,08E+00
ODP	-1,37E-08	2,48E-14	2,00E-11	2,24E-13	2,49E-14	2,38E-13	1,29E-13	6,13E-09	-7,52E-09
POCP	1,83E-03	-5,30E-05	8,22E-05	9,21E-07	-5,24E-05	3,85E-05	5,89E-05	-5,73E-04	1,34E-03

Indicators describing input/output flows

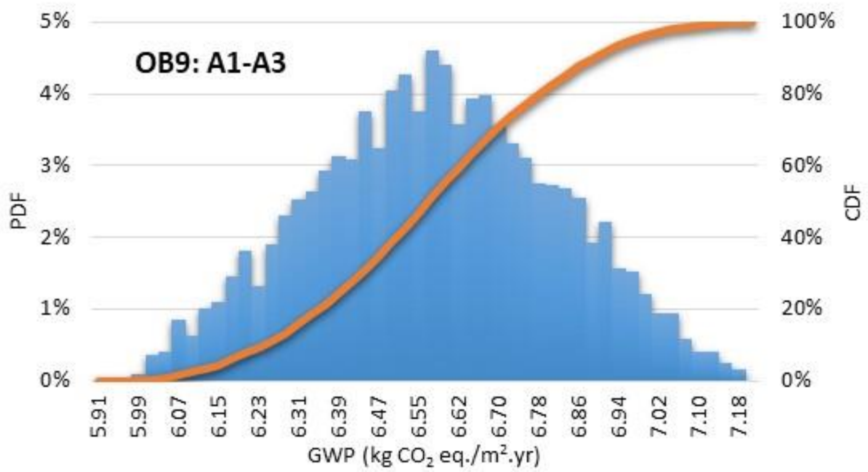
	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	3,30E-06	5,39E-08	3,20E-09	3,59E-11	5,40E-08	2,82E-08	2,68E-08	-7,01E-07	2,77E-06
NHWD	1,18E+00	7,84E-05	5,20E-03	5,83E-05	7,86E-05	4,16E-04	7,86E+00	1,17E-01	9,16E+00
RWD	6,16E-04	1,40E-06	1,23E-03	1,38E-05	1,40E-06	1,40E-05	2,32E-05	-2,14E-04	1,69E-03
PENRT	5,91E+01	1,03E+00	7,91E+00	8,85E-02	1,03E+00	9,60E-01	1,70E+00	-1,36E+01	5,82E+01
PERT	5,03E+00	5,15E-02	2,70E+00	3,02E-02	5,16E-02	5,72E-02	1,98E-01	2,56E-01	8,37E+00
FW	6,60E-03	9,53E-05	3,84E-03	4,30E-05	9,56E-05	2,79E-04	3,23E-04	-7,10E-03	4,17E-03
PED	6,42E+01	1,08E+00	1,06E+01	1,19E-01	1,08E+00	1,02E+00	1,89E+00	-1,34E+01	6,66E+01

ii) Contribution of life cycle stages per environmental category



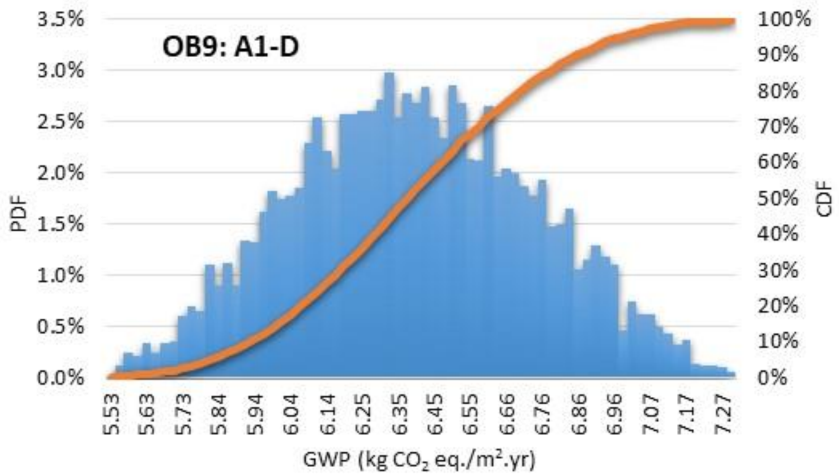
A2) Probabilistic analysis

i) Results for Modules A1-A3



Mean	***6.58***
Median	***6.56***
σ	***0.24***
CoV	***3.7%***
$Q_{5\%}$	***6.16***
$Q_{95\%}$	***6.96***

ii) Results for Modules A1-D



Mean	***6.39***
Median	***6.37***
σ	***0.35***
CoV	***5.5%***
$Q_{5\%}$	***5.81***
$Q_{95\%}$	***6.96***

A2.2) Other environmental categories

i) Results for Modules A1-A3

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	2.04E-2	1.80E-3	1.62E-3
Median	2.03E-2	1.79E-3	1.61E-3
COV	4.09%	3.73%	4.45%

ii) Results for Modules A1-D

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	2.11E-2	1.99E-3	1.33E-3
Median	2.11E-2	1.98E-3	1.32E-3
COV	4.66%	4.33%	10.61%

Building 10 (OB10)

Building properties and main characteristics

Type of building	Low rise office building
Type of structure (Tier 4)	Composite structure
Total Gross Floor Area	25000 m^2
Number of floors	<3
Number of occupants/working places	n.a.
Design working life	50 years (estimated)
Building ref. year	2017
Seismic area (PGA)	0.04
Climatic area	Cfb

Summary BoM

Building main component	**Material**	**Quantity**
Sub-base	Concrete C30/37	9756 ton
	Steel reinforcement (S500)	1492 ton
	Formwork	7002 m^2
Super-structure	Concrete C30/37	7724 m^3
	Steel reinforcement (S500)	1526 ton
	Pre-stressed steel	25 ton
	Structural steel (S355)	400 ton
	Formwork	51121 m^2

A1) Deterministic analysis

i) LCA results per functional unit

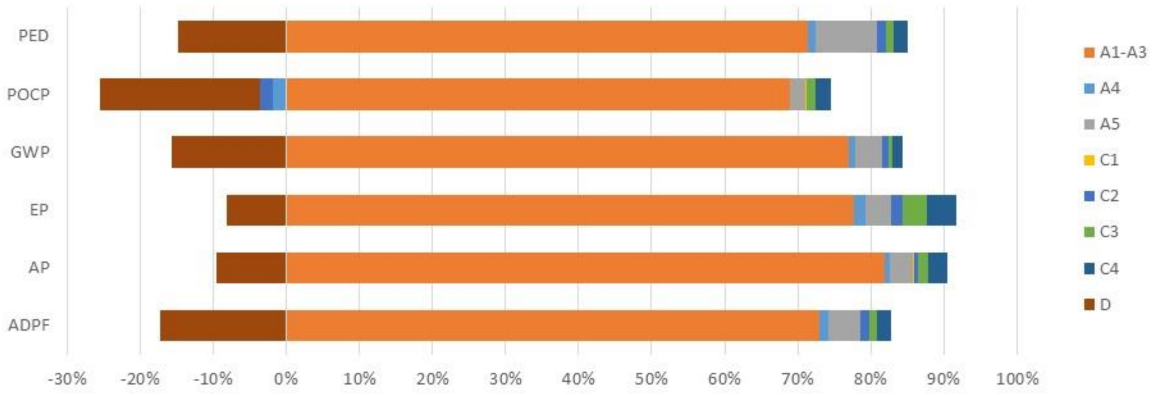
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	9,38E+00	9,90E-02	4,55E-01	6,73E-03	9,92E-02	6,60E-02	1,67E-01	-1,89E+00	8,39E+00
ADPF	8,19E+01	1,36E+00	4,84E+00	7,15E-02	1,36E+00	1,22E+00	2,18E+00	-1,93E+01	7,36E+01
AP	3,04E-02	2,21E-04	1,20E-03	1,77E-05	2,20E-04	5,17E-04	9,88E-04	-3,52E-03	3,00E-02
EP	2,53E-03	5,16E-05	1,14E-04	1,68E-06	5,13E-05	1,05E-04	1,34E-04	-2,69E-04	2,72E-03
GWP	9,27E+00	9,81E-02	4,52E-01	6,69E-03	9,83E-02	6,31E-02	1,68E-01	-1,88E+00	8,27E+00
ODP	-2,00E-08	3,30E-14	2,01E-11	2,97E-13	3,30E-14	3,15E-13	1,71E-13	8,99E-09	-1,10E-08
POCP	2,63E-03	-6,99E-05	8,26E-05	1,22E-06	-6,94E-05	5,09E-05	7,84E-05	-8,31E-04	1,87E-03

Indicators describing input/output flows

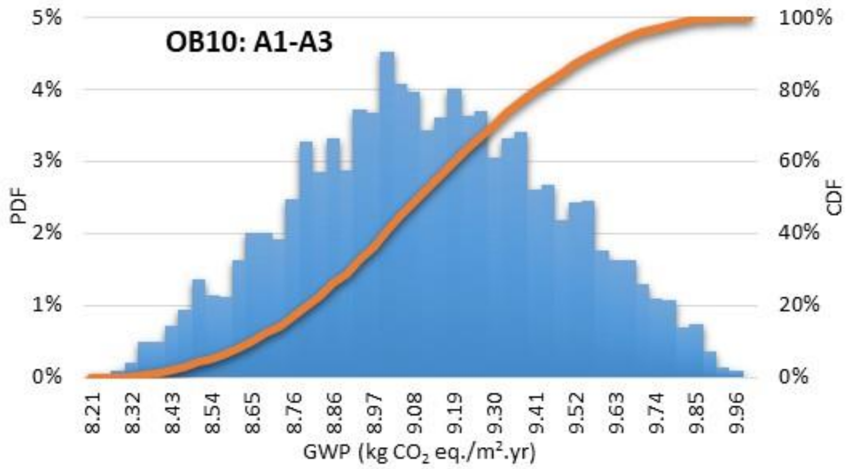
	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	4,81E-06	7,15E-08	3,22E-09	4,76E-11	7,16E-08	3,74E-08	3,57E-08	-1,03E-06	4,00E-06
NHWD	1,57E+00	1,04E-04	5,23E-03	7,73E-05	1,04E-04	5,51E-04	1,05E+01	1,72E-01	1,22E+01
RWD	8,03E-04	1,86E-06	1,24E-03	1,83E-05	1,86E-06	1,85E-05	3,08E-05	-2,80E-04	1,83E-03
PENRT	8,44E+01	1,36E+00	7,95E+00	1,17E-01	1,36E+00	1,27E+00	2,25E+00	-1,94E+01	7,93E+01
PERT	6,44E+00	6,83E-02	2,71E+00	4,00E-02	6,84E-02	7,57E-02	2,63E-01	4,47E-01	1,01E+01
FW	9,88E-03	1,27E-04	3,86E-03	5,71E-05	1,27E-04	3,69E-04	4,29E-04	-1,03E-02	4,59E-03
PED	9,08E+01	1,43E+00	1,07E+01	1,57E-01	1,43E+00	1,35E+00	2,52E+00	-1,90E+01	8,94E+01

ii) Contribution of life cycle stages per environmental category



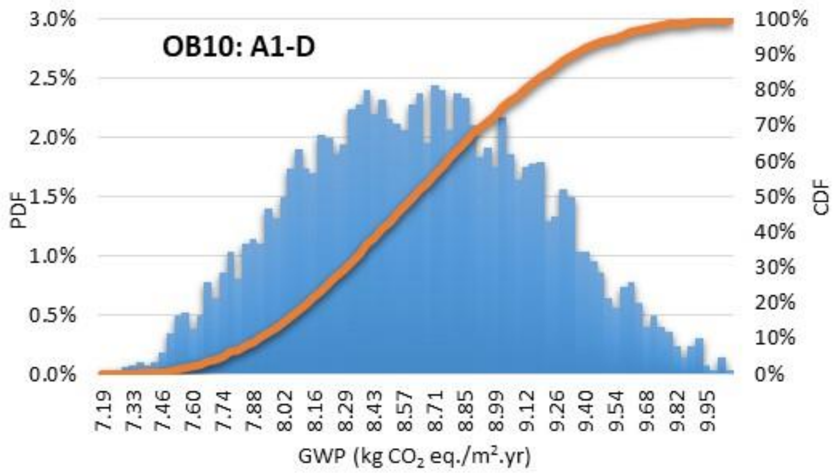
A2) Probabilistic analysis

i) Results for Modules A1-A3



Mean	***9.12***
Median	***9.10***
σ	***0.35***
CoV	***3.8%***
$Q_{5\%}$	***8.52***
$Q_{95\%}$	***9.68***

ii) Results for Modules A1-D



Mean	***8.64***
Median	***8.61***
σ	***0.55***
CoV	***6.3%***
$Q_{5\%}$	***7.74***
$Q_{95\%}$	***9.54***

A2.2) Other environmental categories

i) Results for Modules A1-A3

	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	2.97E-2	2.51E-3	2.34E-3
Median	2.96E-2	2.51E-3	2.32E-3
COV	4.32%	3.83%	4.79%

ii) Results for Modules A1-D

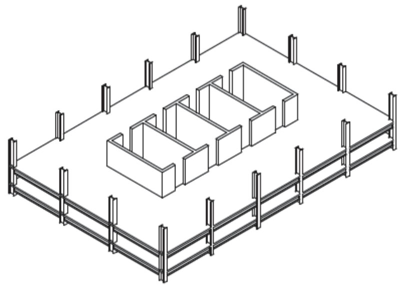
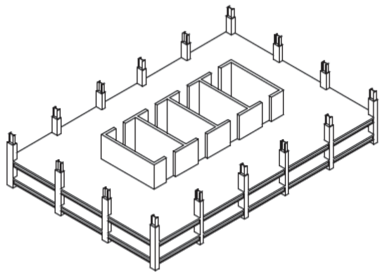
	AP	***EP***	***POCP***
	(kg SO_2 eq./m^2.yr)	*(kg PO_4^{3-} eq./m^2.yr)*	*(kg C_2H_4 eq./m^2.yr)*
Mean value	3.00E-2	2.72E-3	1.87E-3
Median	2.99E-2	2.71E-3	1.86E-3
COV	5.13%	4.69%	12.02%

Annex D: Tall buildings

Buildings with 60 floors

Building properties and main characteristics

Detailed data about buildings geometry and inventory of materials are given in CTBUH [54]. The following results are relative to BoM1.

Scenario	Type of structure	
1a	Normal steel frame and concrete core	
1b	High strenght steel frame and concrete core	
1c	Composite frame and concrete core	

A1) Scenario 1a

i) LCA results per functional unit

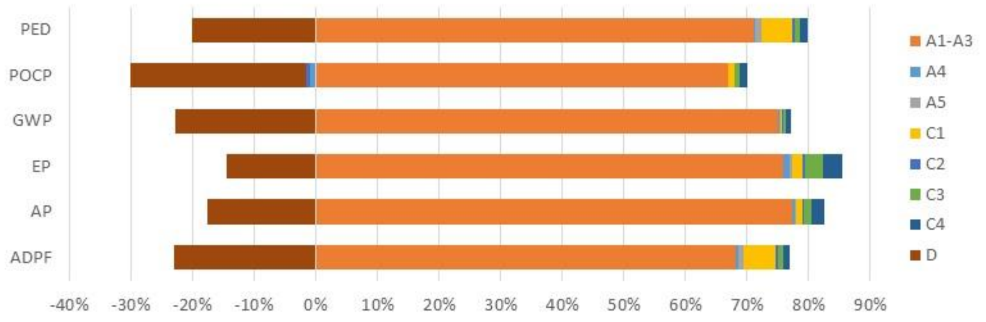
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	1,76E+02	5,84E-01	3,10E-01	1,22E+00	5,99E-01	9,58E-01	2,04E+00	-5,34E+01	1,29E+02
ADPF	1,56E+03	8,01E+00	1,96E+01	1,18E+02	8,21E+00	1,78E+01	2,65E+01	-5,25E+02	1,23E+03
AP	4,52E-01	2,39E-03	1,16E-03	5,44E-03	1,33E-03	7,50E-03	1,20E-02	-1,02E-01	3,79E-01
EP	4,01E-02	5,90E-04	1,68E-04	8,88E-04	3,10E-04	1,53E-03	1,63E-03	-7,69E-03	3,76E-02
GWP	1,75E+02	5,79E-01	2,37E-01	7,54E-01	5,94E-01	9,15E-01	2,05E+00	-5,31E+01	1,27E+02
ODP	-3,50E-07	1,94E-13	5,78E-12	2,87E-12	1,99E-13	4,56E-12	2,08E-12	2,77E-07	-7,34E-08
POCP	5,65E-02	-8,76E-04	1,46E-04	8,01E-04	-4,19E-04	7,39E-04	9,54E-04	-2,41E-02	3,38E-02

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	1,05E-04	4,22E-07	9,68E-07	6,22E-06	4,33E-07	5,42E-07	4,34E-07	-3,22E-05	8,14E-05
NHWD	2,48E+01	6,14E-04	2,79E-03	9,06E-03	6,30E-04	8,00E-03	1,27E+02	5,32E+00	1,57E+02
RWD	1,15E-02	1,10E-05	3,53E-04	1,62E-04	1,12E-05	2,69E-04	3,75E-04	-3,59E-03	9,07E-03
PENRT	1,62E+03	8,03E+00	2,05E+01	1,18E+02	8,24E+00	1,84E+01	2,75E+01	-5,16E+02	1,31E+03
PERT	1,11E+02	4,03E-01	1,64E+00	5,94E+00	4,13E-01	1,10E+00	3,20E+00	2,44E+01	1,48E+02
FW	1,76E-01	7,47E-04	2,74E-03	1,10E-02	7,66E-04	5,36E-03	5,23E-03	-2,91E-01	-8,90E-02
PED	1,73E+03	8,44E+00	2,22E+01	1,24E+02	8,65E+00	1,95E+01	3,07E+01	-4,92E+02	1,45E+03

ii) Contribution of life cycle stages per environmental category



A2) Scenario 1b

i) LCA results per functional unit

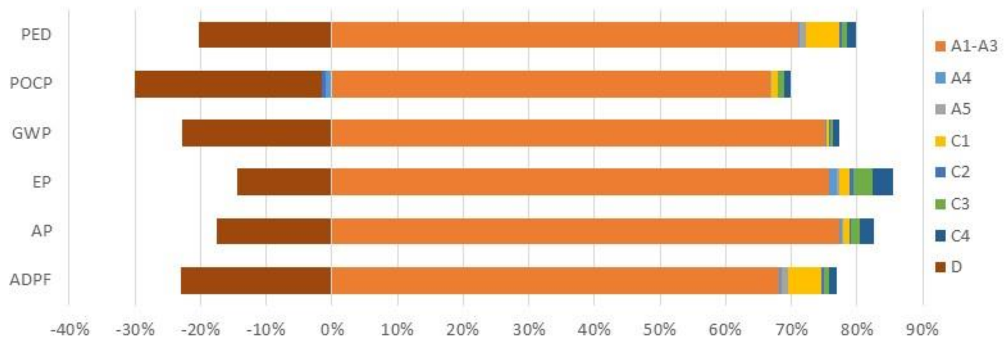
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP$_{exc}$	1,75E+02	5,77E-01	3,10E-01	1,22E+00	5,99E-01	9,55E-01	2,04E+00	-5,28E+01	1,27E+02
ADPF	1,54E+03	7,91E+00	1,96E+01	1,18E+02	8,20E+00	1,77E+01	2,65E+01	-5,20E+02	1,22E+03
AP	4,47E-01	2,36E-03	1,16E-03	5,44E-03	1,33E-03	7,48E-03	1,20E-02	-1,01E-01	3,76E-01
EP	3,98E-02	5,82E-04	1,68E-04	8,88E-04	3,10E-04	1,53E-03	1,63E-03	-7,61E-03	3,73E-02
GWP	1,74E+02	5,72E-01	2,37E-01	7,54E-01	5,93E-01	9,13E-01	2,05E+00	-5,26E+01	1,26E+02
ODP	-3,46E-07	1,92E-13	5,78E-12	2,87E-12	1,99E-13	4,55E-12	2,08E-12	2,74E-07	-7,14E-08
POCP	5,58E-02	-8,65E-04	1,46E-04	8,01E-04	-4,19E-04	7,37E-04	9,54E-04	-2,38E-02	3,34E-02

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	1,03E-04	4,17E-07	9,68E-07	6,22E-06	4,32E-07	5,41E-07	4,34E-07	-3,18E-05	8,06E-05
NHWD	2,45E+01	6,07E-04	2,79E-03	9,06E-03	6,29E-04	7,98E-03	1,27E+02	5,26E+00	1,57E+02
RWD	1,15E-02	1,08E-05	3,53E-04	1,62E-04	1,12E-05	2,68E-04	3,75E-04	-3,59E-03	9,07E-03
PENRT	1,60E+03	7,94E+00	2,05E+01	1,18E+02	8,23E+00	1,84E+01	2,75E+01	-5,11E+02	1,29E+03
PERT	1,10E+02	3,98E-01	1,64E+00	5,94E+00	4,13E-01	1,10E+00	3,20E+00	2,40E+01	1,47E+02
FW	1,79E-01	7,37E-04	2,74E-03	1,10E-02	7,65E-04	5,34E-03	5,23E-03	-2,88E-01	-8,37E-02
PED	1,71E+03	8,33E+00	2,22E+01	1,24E+02	8,65E+00	1,95E+01	3,07E+01	-4,87E+02	1,44E+03

ii) Contribution of life cycle stages per environmental category



A3) Scenario 1c

i) LCA results per functional unit

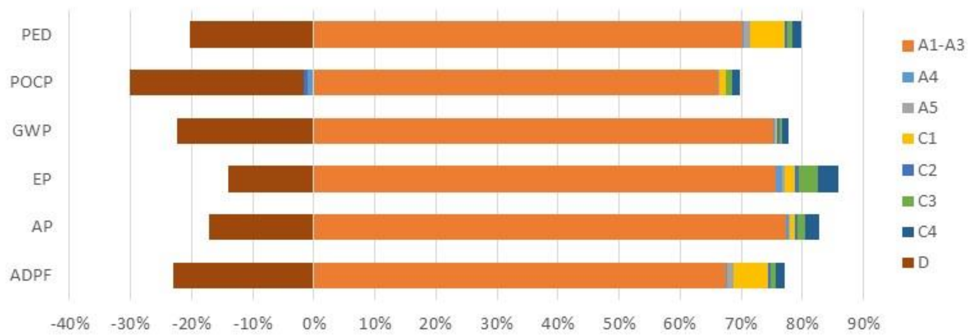
Indicators describing environmental impacts

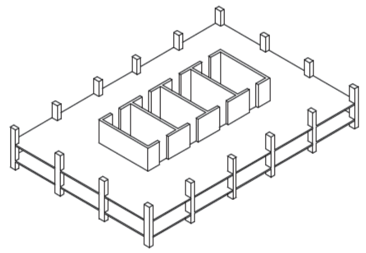
	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	1,68E+02	5,38E-01	3,19E-01	1,28E+00	6,34E-01	9,95E-01	2,18E+00	-5,00E+01	1,24E+02
ADPF	1,45E+03	7,38E+00	1,97E+01	1,23E+02	8,69E+00	1,84E+01	2,84E+01	-4,94E+02	1,16E+03
AP	4,30E-01	2,20E-03	1,19E-03	5,69E-03	1,40E-03	7,79E-03	1,29E-02	-9,55E-02	3,65E-01
EP	3,88E-02	5,42E-04	1,70E-04	9,28E-04	3,28E-04	1,59E-03	1,74E-03	-7,20E-03	3,69E-02
GWP	1,67E+02	5,34E-01	2,46E-01	7,88E-01	6,29E-01	9,50E-01	2,19E+00	-4,98E+01	1,23E+02
ODP	-3,09E-07	1,79E-13	6,16E-12	3,00E-12	2,11E-13	4,74E-12	2,23E-12	2,57E-07	-5,17E-08
POCP	5,20E-02	-8,05E-04	1,48E-04	8,37E-04	-4,44E-04	7,68E-04	1,02E-03	-2,25E-02	3,10E-02

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	9,60E-05	3,89E-07	9,68E-07	6,50E-06	4,58E-07	5,63E-07	4,65E-07	-2,98E-05	7,55E-05
NHWD	2,35E+01	5,66E-04	2,89E-03	9,47E-03	6,67E-04	8,30E-03	1,36E+02	4,93E+00	1,65E+02
RWD	1,23E-02	1,01E-05	3,76E-04	1,69E-04	1,19E-05	2,80E-04	4,01E-04	-3,85E-03	9,72E-03
PENRT	1,51E+03	7,40E+00	2,07E+01	1,24E+02	8,72E+00	1,91E+01	2,94E+01	-4,87E+02	1,23E+03
PERT	1,02E+02	3,71E-01	1,69E+00	6,21E+00	4,38E-01	1,14E+00	3,43E+00	2,15E+01	1,37E+02
FW	2,07E-01	6,88E-04	2,81E-03	1,15E-02	8,10E-04	5,56E-03	5,59E-03	-2,73E-01	-3,86E-02
PED	1,61E+03	7,78E+00	2,24E+01	1,30E+02	9,16E+00	2,03E+01	3,28E+01	-4,66E+02	1,37E+03

ii) Contribution of life cycle stages per environmental category



Scenario	Type of structure	
2a	All concrete wide and shallow beams	
2b	All concrete narrow and deep beams	

B1) Scenario 2a

i) LCA results per functional unit

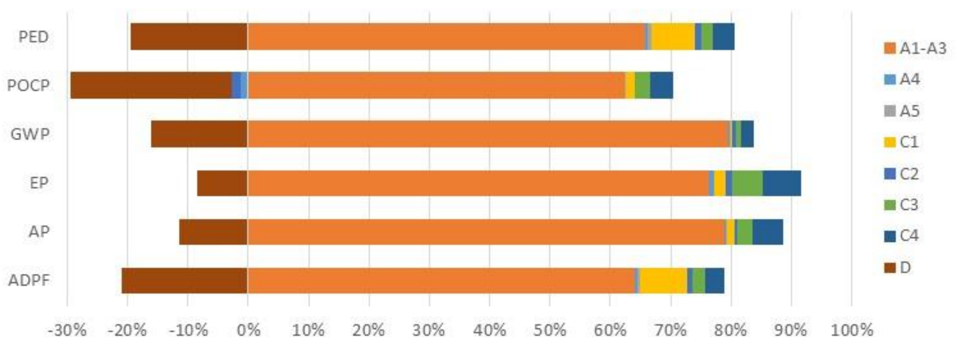
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	1,61E+02	4,42E-01	2,89E-01	1,33E+00	1,19E+00	1,73E+00	4,28E+00	-3,28E+01	1,37E+02
ADPF	1,06E+03	6,06E+00	6,06E+00	1,29E+02	1,63E+01	3,21E+01	5,56E+01	-3,48E+02	9,58E+02
AP	4,07E-01	1,77E-03	8,25E-04	5,94E-03	2,64E-03	1,36E-02	2,52E-02	-5,91E-02	3,98E-01
EP	4,16E-02	4,36E-04	8,87E-05	9,68E-04	6,17E-04	2,77E-03	3,42E-03	-4,59E-03	4,53E-02
GWP	1,60E+02	4,39E-01	2,75E-01	8,23E-01	1,18E+00	1,65E+00	4,30E+00	-3,26E+01	1,36E+02
ODP	-8,99E-08	1,47E-13	1,13E-11	3,13E-12	3,97E-13	8,25E-12	4,37E-12	1,41E-07	5,09E-08
POCP	3,27E-02	-6,46E-04	6,90E-05	8,73E-04	-8,35E-04	1,34E-03	2,00E-03	-1,40E-02	2,15E-02

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	4,73E-05	3,19E-07	1,78E-07	6,79E-06	8,61E-07	9,80E-07	9,11E-07	-1,59E-05	4,15E-05
NHWD	2,81E+01	4,65E-04	3,18E-03	9,88E-03	1,25E-03	1,45E-02	2,67E+02	2,67E+00	2,98E+02
RWD	2,35E-02	8,30E-06	6,96E-04	1,76E-04	2,24E-05	4,87E-04	7,87E-04	-7,60E-03	1,80E-02
PENRT	1,12E+03	6,08E+00	7,81E+00	1,29E+02	1,64E+01	3,33E+01	5,76E+01	-3,58E+02	1,02E+03
PERT	8,41E+01	3,05E-01	1,68E+00	6,49E+00	8,23E-01	1,99E+00	6,71E+00	2,55E-01	1,02E+02
FW	2,31E-01	5,65E-04	2,47E-03	1,20E-02	1,52E-03	9,69E-03	1,10E-02	-1,77E-01	9,13E-02
PED	1,21E+03	6,39E+00	9,49E+00	1,36E+02	1,72E+01	3,53E+01	6,43E+01	-3,57E+02	1,12E+03

ii) Contribution of life cycle stages per environmental category



B2) Scenario 2b

i) LCA results per functional unit

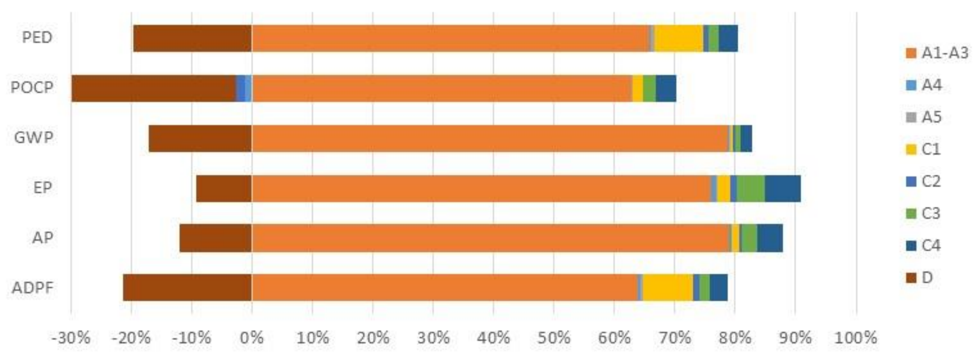
Indicators describing environmental impacts

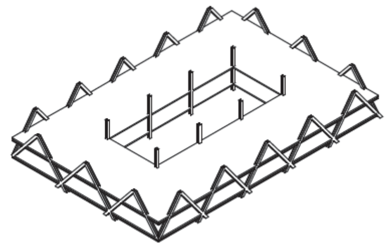
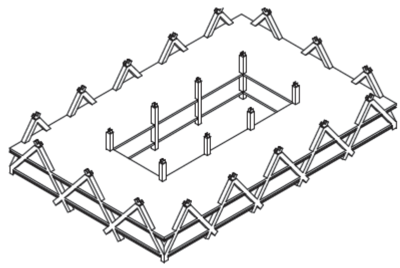
	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	1,43E+02	4,20E-01	2,45E-01	1,33E+00	9,88E-01	1,44E+00	3,53E+00	-3,11E+01	1,20E+02
ADPF	9,79E+02	5,75E+00	5,58E+00	1,29E+02	1,35E+01	2,67E+01	4,59E+01	-3,26E+02	8,80E+02
AP	3,72E-01	1,68E-03	7,08E-04	5,94E-03	2,19E-03	1,13E-02	2,08E-02	-5,67E-02	3,58E-01
EP	3,65E-02	4,13E-04	7,76E-05	9,68E-04	5,11E-04	2,30E-03	2,82E-03	-4,38E-03	3,92E-02
GWP	1,42E+02	4,16E-01	2,30E-01	8,23E-01	9,79E-01	1,38E+00	3,55E+00	-3,10E+01	1,18E+02
ODP	-8,73E-08	1,40E-13	9,37E-12	3,13E-12	3,29E-13	6,86E-12	3,61E-12	1,39E-07	5,16E-08
POCP	3,11E-02	-6,12E-04	6,09E-05	8,73E-04	-6,91E-04	1,11E-03	1,65E-03	-1,34E-02	2,01E-02

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	4,59E-05	3,03E-07	1,78E-07	6,79E-06	7,13E-07	8,15E-07	7,52E-07	-1,57E-05	3,97E-05
NHWD	2,30E+01	4,41E-04	2,67E-03	9,88E-03	1,04E-03	1,20E-02	2,21E+02	2,64E+00	2,46E+02
RWD	1,97E-02	7,87E-06	5,75E-04	1,76E-04	1,85E-05	4,05E-04	6,50E-04	-6,27E-03	1,52E-02
PENRT	1,03E+03	5,77E+00	7,03E+00	1,29E+02	1,36E+01	2,77E+01	4,76E+01	-3,32E+02	9,30E+02
PERT	7,43E+01	2,90E-01	1,42E+00	6,49E+00	6,81E-01	1,65E+00	5,55E+00	2,81E+00	9,32E+01
FW	1,98E-01	5,36E-04	2,10E-03	1,20E-02	1,26E-03	8,05E-03	9,06E-03	-1,68E-01	6,24E-02
PED	1,11E+03	6,06E+00	8,45E+00	1,36E+02	1,43E+01	2,94E+01	5,31E+01	-3,30E+02	1,02E+03

ii) Contribution of life cycle stages per environmental category



Scenario	Type of structure	
3a	All steel diagrid normal steel	
3b	All steel diagrid HS steel	
3c	Composite diagrid	

C1) Scenario 3a

i) LCA results per functional unit

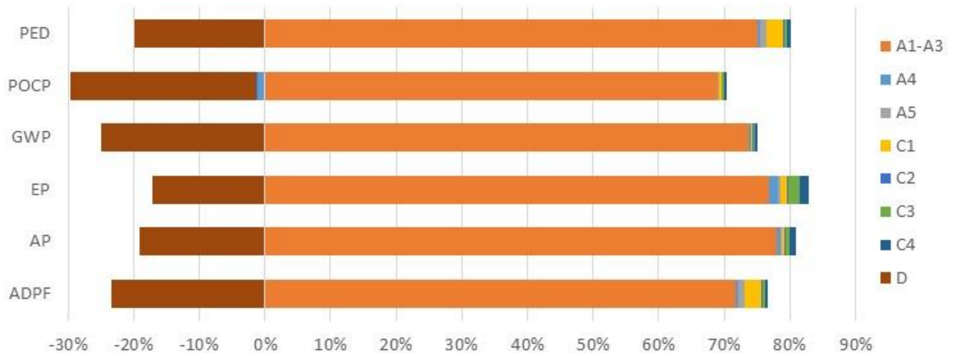
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	2,10E+02	8,28E-01	3,47E-01	7,77E-01	3,34E-01	6,51E-01	9,92E-01	-7,12E+01	1,43E+02
ADPF	2,11E+03	1,13E+01	2,86E+01	7,51E+01	4,58E+00	1,21E+01	1,29E+01	-6,85E+02	1,57E+03
AP	5,63E-01	3,42E-03	1,44E-03	3,46E-03	7,40E-04	5,10E-03	5,85E-03	-1,38E-01	4,45E-01
EP	4,61E-02	8,45E-04	2,25E-04	5,65E-04	1,73E-04	1,04E-03	7,92E-04	-1,03E-02	3,94E-02
GWP	2,09E+02	8,20E-01	2,36E-01	4,80E-01	3,31E-01	6,22E-01	9,97E-01	-7,08E+01	1,42E+02
ODP	-6,12E-07	2,75E-13	3,24E-12	1,83E-12	1,11E-13	3,10E-12	1,01E-12	3,86E-07	-2,26E-07
POCP	7,93E-02	-1,26E-03	2,00E-04	5,10E-04	-2,34E-04	5,02E-04	4,64E-04	-3,25E-02	4,70E-02

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	1,52E-04	5,98E-07	1,48E-06	3,96E-06	2,41E-07	3,69E-07	2,11E-07	-4,51E-05	1,13E-04
NHWD	3,18E+01	8,70E-04	2,81E-03	5,76E-03	3,51E-04	5,43E-03	6,19E+01	7,43E+00	1,01E+02
RWD	4,98E-03	1,55E-05	1,95E-04	1,03E-04	6,27E-06	1,83E-04	1,82E-04	-1,71E-03	3,96E-03
PENRT	2,19E+03	1,14E+01	2,91E+01	7,54E+01	4,60E+00	1,25E+01	1,34E+01	-6,65E+02	1,67E+03
PERT	1,57E+02	5,71E-01	1,75E+00	3,78E+00	2,31E-01	7,47E-01	1,56E+00	4,09E+01	2,07E+02
FW	-6,96E-04	1,06E-03	3,10E-03	7,01E-03	4,27E-04	3,64E-03	2,54E-03	-3,89E-01	-3,72E-01
PED	2,35E+03	1,20E+01	3,09E+01	7,92E+01	4,83E+00	1,33E+01	1,49E+01	-6,24E+02	1,88E+03

ii) Contribution of life cycle stages per environmental category



C2) Scenario 3b

i) LCA results per functional unit

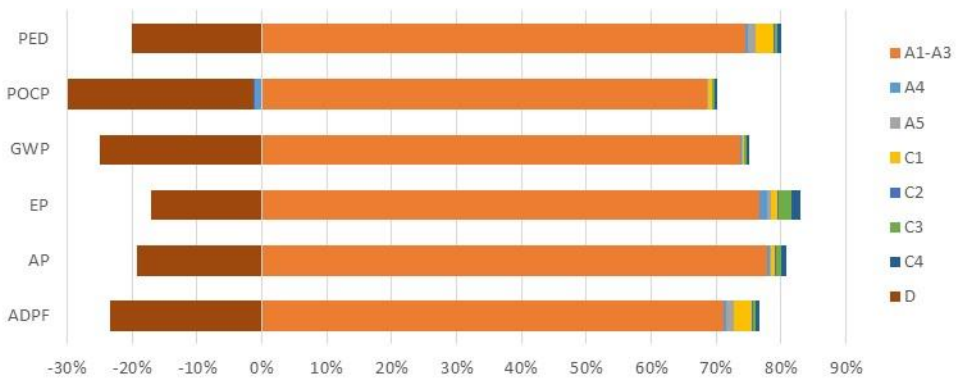
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	1,89E+02	7,29E-01	3,47E-01	7,77E-01	3,26E-01	6,17E-01	9,90E-01	-6,39E+01	1,29E+02
ADPF	1,88E+03	9,98E+00	2,86E+01	7,51E+01	4,47E+00	1,14E+01	1,29E+01	-6,16E+02	1,41E+03
AP	5,04E-01	3,01E-03	1,44E-03	3,46E-03	7,22E-04	4,83E-03	5,84E-03	-1,24E-01	3,99E-01
EP	4,17E-02	7,44E-04	2,25E-04	5,65E-04	1,69E-04	9,86E-04	7,91E-04	-9,27E-03	3,59E-02
GWP	1,88E+02	7,22E-01	2,36E-01	4,80E-01	3,23E-01	5,90E-01	9,95E-01	-6,36E+01	1,27E+02
ODP	-5,43E-07	2,43E-13	3,24E-12	1,83E-12	1,09E-13	2,94E-12	1,01E-12	3,46E-07	-1,98E-07
POCP	7,02E-02	-1,11E-03	2,00E-04	5,10E-04	-2,28E-04	4,76E-04	4,63E-04	-2,92E-02	4,14E-02

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	1,35E-04	5,26E-07	1,48E-06	3,96E-06	2,35E-07	3,49E-07	2,11E-07	-4,04E-05	1,02E-04
NHWD	2,85E+01	7,66E-04	2,81E-03	5,76E-03	3,43E-04	5,15E-03	6,18E+01	6,65E+00	9,69E+01
RWD	4,97E-03	1,37E-05	1,95E-04	1,03E-04	6,12E-06	1,73E-04	1,82E-04	-1,71E-03	3,94E-03
PENRT	1,95E+03	1,00E+01	2,91E+01	7,54E+01	4,48E+00	1,19E+01	1,33E+01	-5,98E+02	1,50E+03
PERT	1,39E+02	5,03E-01	1,75E+00	3,78E+00	2,25E-01	7,08E-01	1,55E+00	3,62E+01	1,84E+02
FW	3,32E-02	9,31E-04	3,10E-03	7,01E-03	4,17E-04	3,45E-03	2,54E-03	-3,50E-01	-2,99E-01
PED	2,09E+03	1,05E+01	3,09E+01	7,92E+01	4,71E+00	1,26E+01	1,49E+01	-5,62E+02	1,68E+03

ii) Contribution of life cycle stages per environmental category



C3) Scenario 3c

i) LCA results per functional unit

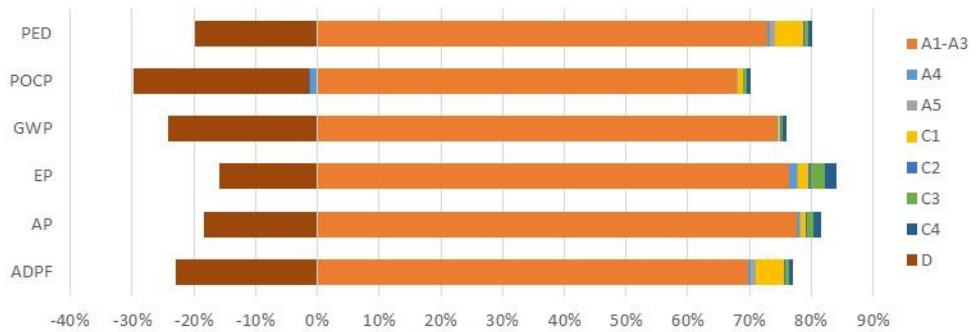
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	1,94E+02	7,12E-01	2,75E-01	1,28E+00	4,51E-01	7,85E-01	1,45E+00	-6,27E+01	1,36E+02
ADPF	1,85E+03	9,75E+00	1,93E+01	1,23E+02	6,18E+00	1,46E+01	1,89E+01	-6,08E+02	1,44E+03
AP	5,11E-01	2,94E-03	1,07E-03	5,69E-03	9,98E-04	6,15E-03	8,57E-03	-1,21E-01	4,16E-01
EP	4,37E-02	7,26E-04	1,59E-04	9,28E-04	2,33E-04	1,26E-03	1,16E-03	-9,07E-03	3,91E-02
GWP	1,92E+02	7,05E-01	2,02E-01	7,88E-01	4,47E-01	7,50E-01	1,46E+00	-6,24E+01	1,34E+02
ODP	-5,20E-07	2,37E-13	4,23E-12	3,00E-12	1,50E-13	3,74E-12	1,48E-12	3,34E-07	-1,86E-07
POCP	6,80E-02	-1,08E-03	1,40E-04	8,37E-04	-3,15E-04	6,06E-04	6,80E-04	-2,85E-02	4,04E-02

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	1,31E-04	5,14E-07	9,68E-07	6,50E-06	3,25E-07	4,45E-07	3,09E-07	-3,90E-05	1,01E-04
NHWD	3,01E+01	7,48E-04	2,39E-03	9,47E-03	4,74E-04	6,56E-03	9,07E+01	6,43E+00	1,27E+02
RWD	7,50E-03	1,34E-05	2,57E-04	1,69E-04	8,46E-06	2,21E-04	2,67E-04	-2,54E-03	5,90E-03
PENRT	1,93E+03	9,79E+00	1,99E+01	1,24E+02	6,20E+00	1,51E+01	1,96E+01	-5,93E+02	1,53E+03
PERT	1,37E+02	4,91E-01	1,43E+00	6,21E+00	3,11E-01	9,01E-01	2,28E+00	3,32E+01	1,82E+02
FW	7,50E-02	9,09E-04	2,44E-03	1,15E-02	5,76E-04	4,39E-03	3,72E-03	-3,43E-01	-2,44E-01
PED	2,07E+03	1,03E+01	2,13E+01	1,30E+02	6,51E+00	1,60E+01	2,19E+01	-5,60E+02	1,71E+03

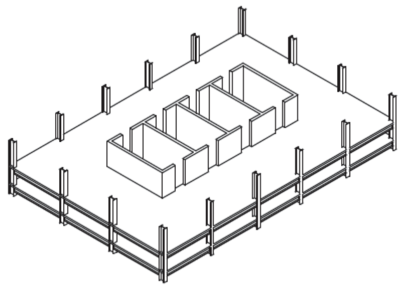
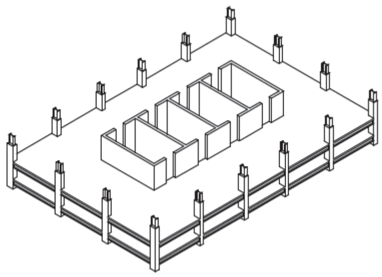
ii) Contribution of life cycle stages per environmental category



Buildings with 120 floors

Building properties and main characteristics

Detailed data about buildings geometry and inventory of materials are given in CTBUH [54]. The following results are relative to BoM1.

Scenario	Type of structure	
4a	Normal steel frame and concrete core	
4b	High strenght steel frame and concrete core	
4c	Composite frame and concrete core	

A1) Scenario 4a

i) LCA results per functional unit

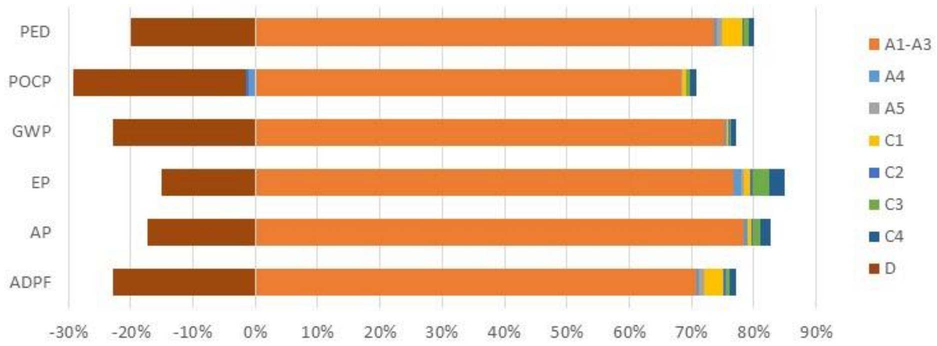
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	2,87E+02	1,05E+00	4,56E-01	1,22E+00	8,16E-01	1,36E+00	2,71E+00	-8,71E+01	2,07E+02
ADPF	2,63E+03	1,44E+01	3,03E+01	1,18E+02	1,12E+01	2,52E+01	3,52E+01	-8,52E+02	2,02E+03
AP	7,57E-01	4,30E-03	1,74E-03	5,44E-03	1,81E-03	1,06E-02	1,60E-02	-1,68E-01	6,29E-01
EP	6,46E-02	1,06E-03	2,55E-04	8,88E-04	4,22E-04	2,17E-03	2,16E-03	-1,26E-02	5,90E-02
GWP	2,85E+02	1,04E+00	3,42E-01	7,54E-01	8,08E-01	1,30E+00	2,72E+00	-8,67E+01	2,05E+02
ODP	-6,25E-07	3,50E-13	7,77E-12	2,87E-12	2,71E-13	6,46E-12	2,77E-12	4,58E-07	-1,67E-07
POCP	9,72E-02	-1,58E-03	2,23E-04	8,01E-04	-5,71E-04	1,05E-03	1,27E-03	-3,94E-02	5,89E-02

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	1,76E-04	7,60E-07	1,51E-06	6,22E-06	5,89E-07	7,68E-07	5,77E-07	-5,33E-05	1,33E-04
NHWD	4,15E+01	1,11E-03	4,03E-03	9,06E-03	8,57E-04	1,13E-02	1,69E+02	8,80E+00	2,19E+02
RWD	1,54E-02	1,97E-05	4,73E-04	1,62E-04	1,53E-05	3,81E-04	4,98E-04	-4,75E-03	1,22E-02
PENRT	2,74E+03	1,45E+01	3,15E+01	1,18E+02	1,12E+01	2,61E+01	3,65E+01	-8,34E+02	2,15E+03
PERT	1,95E+02	7,26E-01	2,39E+00	5,94E+00	5,63E-01	1,56E+00	4,25E+00	4,28E+01	2,53E+02
FW	8,14E-02	1,34E-03	4,02E-03	1,10E-02	1,04E-03	7,59E-03	6,94E-03	-4,76E-01	-3,63E-01
PED	2,94E+03	1,52E+01	3,39E+01	1,24E+02	1,18E+01	2,77E+01	4,07E+01	-7,92E+02	2,40E+03

ii) Contribution of life cycle stages per environmental category



A2) Scenario 4b

i) LCA results per functional unit

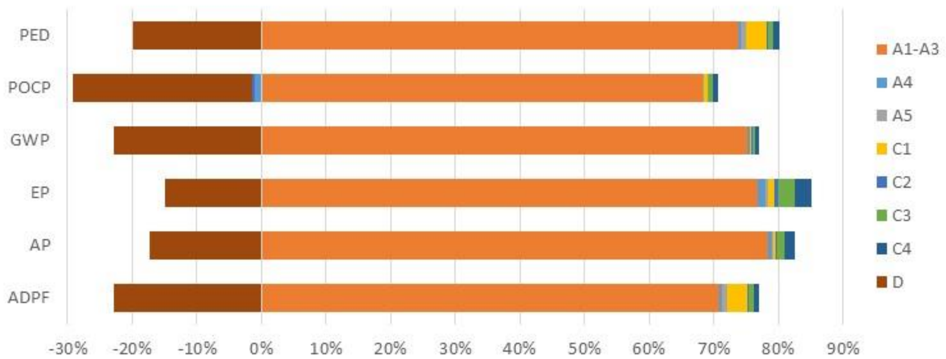
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	2,87E+02	1,05E+00	4,56E-01	1,22E+00	8,16E-01	1,36E+00	2,71E+00	-8,71E+01	2,07E+02
ADPF	2,63E+03	1,44E+01	3,03E+01	1,18E+02	1,12E+01	2,52E+01	3,52E+01	-8,52E+02	2,02E+03
AP	7,57E-01	4,30E-03	1,74E-03	5,44E-03	1,81E-03	1,06E-02	1,60E-02	-1,68E-01	6,29E-01
EP	6,46E-02	1,06E-03	2,55E-04	8,88E-04	4,22E-04	2,17E-03	2,16E-03	-1,26E-02	5,90E-02
GWP	2,85E+02	1,04E+00	3,42E-01	7,54E-01	8,08E-01	1,30E+00	2,72E+00	-8,67E+01	2,05E+02
ODP	-6,25E-07	3,50E-13	7,77E-12	2,87E-12	2,71E-13	6,46E-12	2,77E-12	4,58E-07	-1,67E-07
POCP	9,72E-02	-1,58E-03	2,23E-04	8,01E-04	-5,71E-04	1,05E-03	1,27E-03	-3,94E-02	5,89E-02

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	1,76E-04	7,60E-07	1,51E-06	6,22E-06	5,89E-07	7,68E-07	5,77E-07	-5,33E-05	1,33E-04
NHWD	4,15E+01	1,11E-03	4,03E-03	9,06E-03	8,57E-04	1,13E-02	1,69E+02	8,80E+00	2,19E+02
RWD	1,54E-02	1,97E-05	4,73E-04	1,62E-04	1,53E-05	3,81E-04	4,98E-04	-4,75E-03	1,22E-02
PENRT	2,74E+03	1,45E+01	3,15E+01	1,18E+02	1,12E+01	2,61E+01	3,65E+01	-8,34E+02	2,15E+03
PERT	1,95E+02	7,26E-01	2,39E+00	5,94E+00	5,63E-01	1,56E+00	4,25E+00	4,28E+01	2,53E+02
FW	8,14E-02	1,34E-03	4,02E-03	1,10E-02	1,04E-03	7,59E-03	6,94E-03	-4,76E-01	-3,63E-01
PED	2,94E+03	1,52E+01	3,39E+01	1,24E+02	1,18E+01	2,77E+01	4,07E+01	-7,92E+02	2,40E+03

ii) Contribution of life cycle stages per environmental category



A3) Scenario 4c

i) LCA results per functional unit

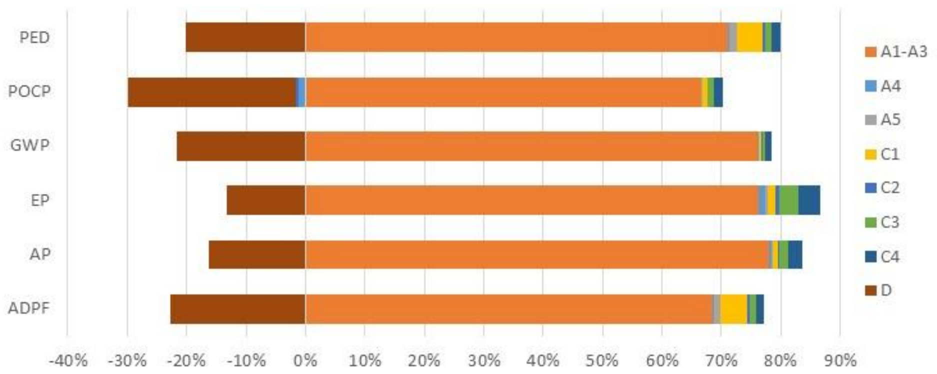
Indicators describing environmental impacts

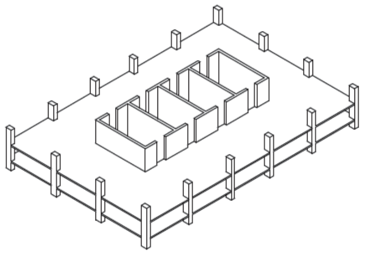
	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	2,23E+02	7,25E-01	4,78E-01	1,28E+00	8,92E-01	1,39E+00	3,08E+00	-6,31E+01	1,67E+02
ADPF	1,88E+03	9,93E+00	3,05E+01	1,23E+02	1,22E+01	2,57E+01	4,01E+01	-6,26E+02	1,49E+03
AP	5,74E-01	2,94E-03	1,80E-03	5,69E-03	1,97E-03	1,09E-02	1,82E-02	-1,20E-01	4,95E-01
EP	5,19E-02	7,25E-04	2,61E-04	9,28E-04	4,61E-04	2,22E-03	2,46E-03	-9,06E-03	4,99E-02
GWP	2,21E+02	7,18E-01	3,64E-01	7,88E-01	8,84E-01	1,32E+00	3,10E+00	-6,28E+01	1,66E+02
ODP	-3,75E-07	2,41E-13	8,77E-12	3,00E-12	2,97E-13	6,61E-12	3,15E-12	3,21E-07	-5,36E-08
POCP	6,70E-02	-1,08E-03	2,27E-04	8,37E-04	-6,24E-04	1,07E-03	1,44E-03	-2,83E-02	4,06E-02

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	1,20E-04	5,23E-07	1,51E-06	6,50E-06	6,44E-07	7,85E-07	6,56E-07	-3,72E-05	9,30E-05
NHWD	3,16E+01	7,62E-04	4,29E-03	9,47E-03	9,37E-04	1,16E-02	1,92E+02	6,15E+00	2,30E+02
RWD	1,77E-02	1,36E-05	5,35E-04	1,69E-04	1,67E-05	3,90E-04	5,67E-04	-5,44E-03	1,39E-02
PENRT	1,96E+03	9,96E+00	3,19E+01	1,24E+02	1,23E+01	2,67E+01	4,15E+01	-6,19E+02	1,59E+03
PERT	1,35E+02	5,00E-01	2,53E+00	6,21E+00	6,15E-01	1,59E+00	4,84E+00	2,55E+01	1,77E+02
FW	2,23E-01	9,26E-04	4,22E-03	1,15E-02	1,14E-03	7,76E-03	7,90E-03	-3,44E-01	-8,76E-02
PED	2,10E+03	1,05E+01	3,44E+01	1,30E+02	1,29E+01	2,83E+01	4,64E+01	-5,94E+02	1,76E+03

ii) Contribution of life cycle stages per environmental category



Scenario	Type of structure	
5a	All concrete wide and shallow beams	
5b	All concrete narrow and deep beams	

B1) Scenario 5a

i) LCA results per functional unit

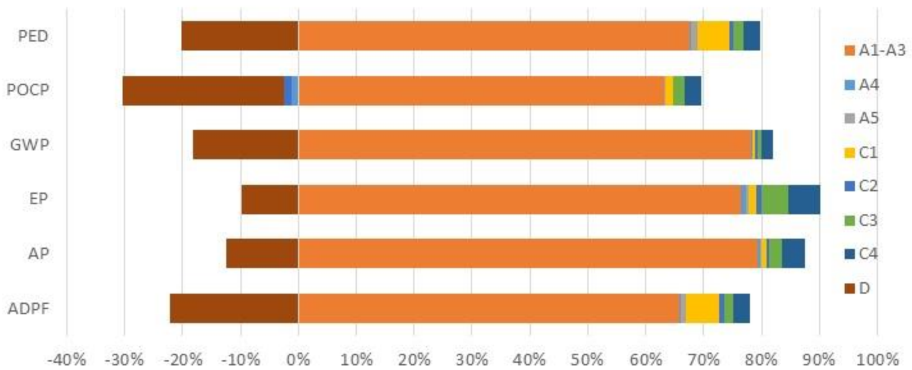
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	2,09E+02	6,52E-01	4,51E-01	1,33E+00	1,36E+00	1,99E+00	4,86E+00	-4,83E+01	1,71E+02
ADPF	1,49E+03	8,93E+00	1,87E+01	1,29E+02	1,87E+01	3,70E+01	6,33E+01	-5,01E+02	1,26E+03
AP	5,64E-01	2,61E-03	1,48E-03	5,94E-03	3,02E-03	1,56E-02	2,87E-02	-8,89E-02	5,32E-01
EP	5,34E-02	6,44E-04	1,90E-04	9,68E-04	7,05E-04	3,19E-03	3,89E-03	-6,83E-03	5,61E-02
GWP	2,07E+02	6,46E-01	3,88E-01	8,23E-01	1,35E+00	1,91E+00	4,89E+00	-4,81E+01	1,69E+02
ODP	-1,56E-07	2,17E-13	1,32E-11	3,13E-12	4,54E-13	9,51E-12	4,97E-12	2,22E-07	6,61E-08
POCP	4,79E-02	-9,53E-04	1,59E-04	8,73E-04	-9,54E-04	1,54E-03	2,28E-03	-2,11E-02	2,98E-02

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	7,28E-05	4,70E-07	8,28E-07	6,79E-06	9,84E-07	1,13E-06	1,04E-06	-2,53E-05	5,88E-05
NHWD	3,22E+01	6,85E-04	4,53E-03	9,88E-03	1,43E-03	1,67E-02	3,04E+02	4,22E+00	3,40E+02
RWD	2,72E-02	1,22E-05	8,06E-04	1,76E-04	2,56E-05	5,61E-04	8,95E-04	-8,63E-03	2,11E-02
PENRT	1,56E+03	8,96E+00	2,08E+01	1,29E+02	1,87E+01	3,84E+01	6,55E+01	-5,08E+02	1,33E+03
PERT	1,09E+02	4,50E-01	2,51E+00	6,49E+00	9,40E-01	2,29E+00	7,64E+00	7,42E+00	1,37E+02
FW	2,81E-01	8,33E-04	3,92E-03	1,20E-02	1,74E-03	1,12E-02	1,25E-02	-2,62E-01	6,14E-02
PED	1,67E+03	9,41E+00	2,33E+01	1,36E+02	1,97E+01	4,07E+01	7,32E+01	-5,01E+02	1,47E+03

ii) Contribution of life cycle stages per environmental category



B2) Scenario 5b

i) LCA results per functional unit

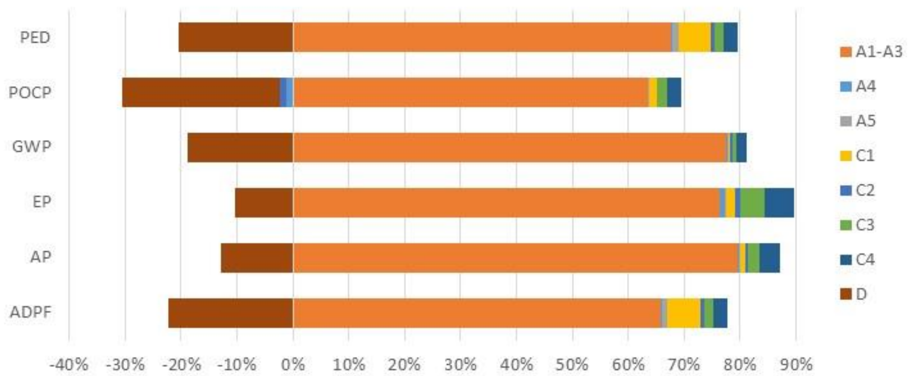
Indicators describing environmental impacts

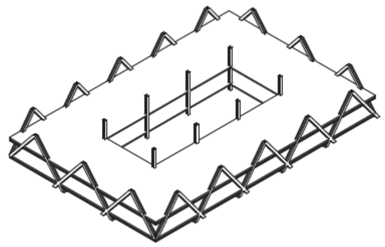
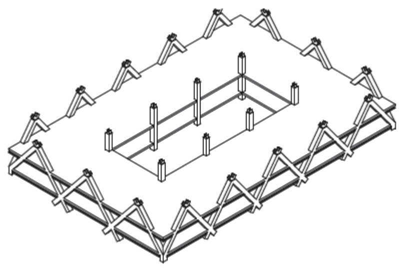
	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	1,92E+02	6,30E-01	4,10E-01	1,33E+00	1,17E+00	1,72E+00	4,17E+00	-4,68E+01	1,54E+02
ADPF	1,41E+03	8,64E+00	1,83E+01	1,29E+02	1,60E+01	3,19E+01	5,42E+01	-4,80E+02	1,19E+03
AP	5,32E-01	2,52E-03	1,37E-03	5,94E-03	2,59E-03	1,35E-02	2,46E-02	-8,67E-02	4,96E-01
EP	4,86E-02	6,22E-04	1,80E-04	9,68E-04	6,06E-04	2,75E-03	3,33E-03	-6,64E-03	5,04E-02
GWP	1,90E+02	6,25E-01	3,46E-01	8,23E-01	1,16E+00	1,65E+00	4,19E+00	-4,66E+01	1,53E+02
ODP	-1,53E-07	2,10E-13	1,13E-11	3,13E-12	3,90E-13	8,21E-12	4,26E-12	2,20E-07	6,67E-08
POCP	4,64E-02	-9,21E-04	1,51E-04	8,73E-04	-8,20E-04	1,33E-03	1,95E-03	-2,05E-02	2,85E-02

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	7,15E-05	4,55E-07	8,27E-07	6,79E-06	8,45E-07	9,75E-07	8,88E-07	-2,52E-05	5,72E-05
NHWD	2,75E+01	6,63E-04	4,05E-03	9,88E-03	1,23E-03	1,44E-02	2,60E+02	4,20E+00	2,92E+02
RWD	2,37E-02	1,18E-05	6,94E-04	1,76E-04	2,20E-05	4,84E-04	7,67E-04	-7,39E-03	1,85E-02
PENRT	1,48E+03	8,67E+00	2,01E+01	1,29E+02	1,61E+01	3,32E+01	5,62E+01	-4,85E+02	1,25E+03
PERT	1,00E+02	4,35E-01	2,26E+00	6,49E+00	8,08E-01	1,98E+00	6,55E+00	9,81E+00	1,29E+02
FW	2,50E-01	8,05E-04	3,56E-03	1,20E-02	1,50E-03	9,63E-03	1,07E-02	-2,54E-01	3,44E-02
PED	1,58E+03	9,10E+00	2,23E+01	1,36E+02	1,69E+01	3,51E+01	6,27E+01	-4,75E+02	1,38E+03

ii) Contribution of life cycle stages per environmental category



Scenario	Type of structure	
6a	All steel diagrid normal steel	
6b	All steel diagrid HS steel	
6c	Composite diagrid	

C1) Scenario 6a

i) LCA results per functional unit

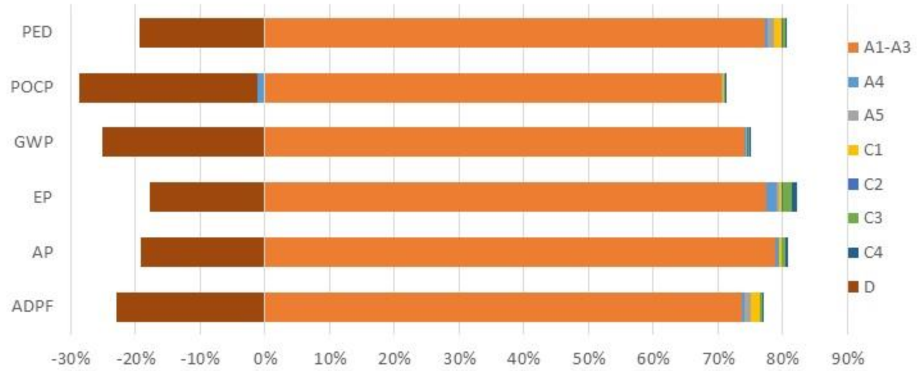
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	3,90E+02	1,66E+00	5,91E-01	7,77E-01	3,86E-01	9,12E-01	9,44E-01	-1,32E+02	2,63E+02
ADPF	4,05E+03	2,28E+01	5,25E+01	7,51E+01	5,29E+00	1,69E+01	1,23E+01	-1,26E+03	2,97E+03
AP	1,05E+00	6,87E-03	2,54E-03	3,46E-03	8,54E-04	7,14E-03	5,57E-03	-2,57E-01	8,23E-01
EP	8,30E-02	1,70E-03	4,04E-04	5,65E-04	1,99E-04	1,46E-03	7,54E-04	-1,91E-02	6,90E-02
GWP	3,87E+02	1,65E+00	3,86E-01	4,80E-01	3,82E-01	8,71E-01	9,48E-01	-1,31E+02	2,61E+02
ODP	-1,19E-06	5,53E-13	3,65E-12	1,83E-12	1,28E-13	4,35E-12	9,64E-13	7,23E-07	-4,64E-07
POCP	1,55E-01	-2,52E-03	3,62E-04	5,10E-04	-2,70E-04	7,04E-04	4,42E-04	-6,03E-02	9,43E-02

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	2,89E-04	1,20E-06	2,74E-06	3,96E-06	2,78E-07	5,16E-07	2,01E-07	-8,46E-05	2,13E-04
NHWD	5,93E+01	1,75E-03	4,61E-03	5,76E-03	4,05E-04	7,61E-03	5,89E+01	1,39E+01	1,32E+02
RWD	4,73E-03	3,11E-05	2,18E-04	1,03E-04	7,23E-06	2,56E-04	1,74E-04	-1,57E-03	3,95E-03
PENRT	4,20E+03	2,28E+01	5,31E+01	7,54E+01	5,30E+00	1,76E+01	1,27E+01	-1,22E+03	3,17E+03
PERT	3,11E+02	1,15E+00	2,94E+00	3,78E+00	2,66E-01	1,05E+00	1,48E+00	7,99E+01	4,02E+02
FW	-3,05E-01	2,12E-03	5,30E-03	7,01E-03	4,93E-04	5,10E-03	2,42E-03	-7,21E-01	-1,00E+00
PED	4,51E+03	2,40E+01	5,60E+01	7,92E+01	5,57E+00	1,86E+01	1,42E+01	-1,14E+03	3,57E+03

ii) Contribution of life cycle stages per environmental category



C2) Scenario 6b

i) LCA results per functional unit

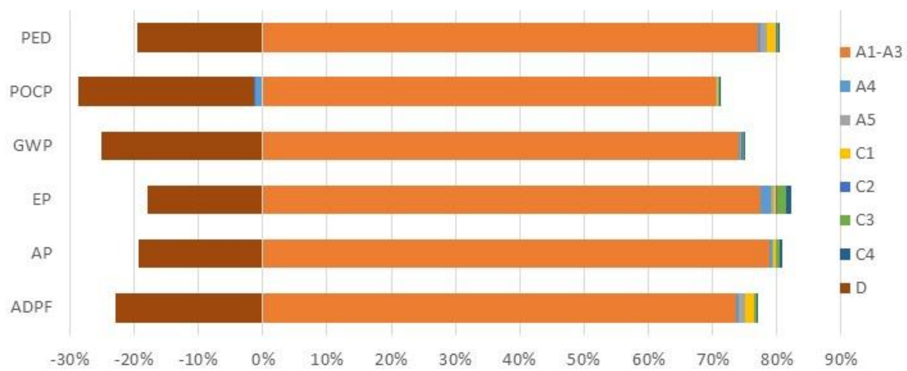
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	3,78E+02	1,61E+00	5,91E-01	7,77E-01	3,81E-01	8,93E-01	9,42E-01	-1,28E+02	2,55E+02
ADPF	3,92E+03	2,20E+01	5,25E+01	7,51E+01	5,22E+00	1,66E+01	1,23E+01	-1,22E+03	2,88E+03
AP	1,02E+00	6,64E-03	2,54E-03	3,46E-03	8,44E-04	6,99E-03	5,56E-03	-2,49E-01	7,98E-01
EP	8,06E-02	1,64E-03	4,04E-04	5,65E-04	1,97E-04	1,43E-03	7,53E-04	-1,86E-02	6,70E-02
GWP	3,75E+02	1,59E+00	3,86E-01	4,80E-01	3,78E-01	8,53E-01	9,47E-01	-1,27E+02	2,53E+02
ODP	-1,15E-06	5,34E-13	3,65E-12	1,83E-12	1,27E-13	4,26E-12	9,63E-13	7,00E-07	-4,48E-07
POCP	1,50E-01	-2,44E-03	3,62E-04	5,10E-04	-2,67E-04	6,89E-04	4,41E-04	-5,85E-02	9,12E-02

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	2,80E-04	1,16E-06	2,74E-06	3,96E-06	2,75E-07	5,06E-07	2,01E-07	-8,19E-05	2,07E-04
NHWD	5,75E+01	1,69E-03	4,61E-03	5,76E-03	4,01E-04	7,46E-03	5,88E+01	1,35E+01	1,30E+02
RWD	4,73E-03	3,01E-05	2,18E-04	1,03E-04	7,15E-06	2,51E-04	1,73E-04	-1,57E-03	3,94E-03
PENRT	4,07E+03	2,21E+01	5,31E+01	7,54E+01	5,24E+00	1,72E+01	1,27E+01	-1,18E+03	3,07E+03
PERT	3,01E+02	1,11E+00	2,94E+00	3,78E+00	2,63E-01	1,02E+00	1,48E+00	7,73E+01	3,89E+02
FW	-2,86E-01	2,05E-03	5,30E-03	7,01E-03	4,87E-04	5,00E-03	2,42E-03	-6,99E-01	-9,62E-01
PED	4,37E+03	2,32E+01	5,60E+01	7,92E+01	5,50E+00	1,82E+01	1,42E+01	-1,10E+03	3,46E+03

ii) Contribution of life cycle stages per environmental category



C3) Scenario 6c

i) LCA results per functional unit

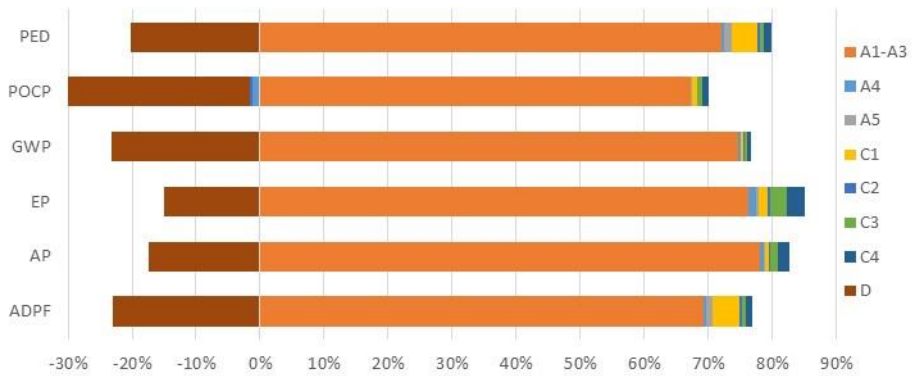
Indicators describing environmental impacts

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
GWP_{exc}	2,25E+02	8,17E-01	4,30E-01	1,28E+00	6,80E-01	1,11E+00	2,28E+00	-6,98E+01	1,62E+02
ADPF	2,05E+03	1,12E+01	3,00E+01	1,23E+02	9,32E+00	2,06E+01	2,97E+01	-6,84E+02	1,59E+03
AP	6,05E-01	3,34E-03	1,67E-03	5,69E-03	1,51E-03	8,70E-03	1,35E-02	-1,34E-01	5,05E-01
EP	5,15E-02	8,23E-04	2,49E-04	9,28E-04	3,52E-04	1,78E-03	1,82E-03	-1,01E-02	4,74E-02
GWP	2,24E+02	8,09E-01	3,17E-01	7,88E-01	6,74E-01	1,06E+00	2,29E+00	-6,95E+01	1,60E+02
ODP	-4,79E-07	2,72E-13	6,65E-12	3,00E-12	2,26E-13	5,30E-12	2,33E-12	3,66E-07	-1,13E-07
POCP	7,49E-02	-1,22E-03	2,18E-04	8,37E-04	-4,76E-04	8,58E-04	1,07E-03	-3,16E-02	4,46E-02

Indicators describing input/output flows

	A1-A3	A4	A5	C1	C2	C3	C4	D	TOTAL
HWD	1,37E-04	5,89E-07	1,51E-06	6,50E-06	4,91E-07	6,29E-07	4,86E-07	-4,26E-05	1,05E-04
NHWD	3,14E+01	8,58E-04	3,74E-03	9,47E-03	7,15E-04	9,28E-03	1,43E+02	7,03E+00	1,81E+02
RWD	1,30E-02	1,53E-05	4,05E-04	1,69E-04	1,28E-05	3,12E-04	4,20E-04	-4,01E-03	1,03E-02
PENRT	2,13E+03	1,12E+01	3,10E+01	1,24E+02	9,35E+00	2,14E+01	3,08E+01	-6,70E+02	1,69E+03
PERT	1,47E+02	5,63E-01	2,24E+00	6,21E+00	4,69E-01	1,28E+00	3,59E+00	3,38E+01	1,95E+02
FW	1,45E-01	1,04E-03	3,81E-03	1,15E-02	8,69E-04	6,22E-03	5,85E-03	-3,81E-01	-2,07E-01
PED	2,28E+03	1,18E+01	3,33E+01	1,30E+02	9,82E+00	2,27E+01	3,43E+01	-6,37E+02	1,89E+03

ii) Contribution of life cycle stages per environmental category



List of abbreviations

ADP_f	Abiotic Resource Depletion Potential of fossil fuels
AP	Acidification potential
BoM	Bill of Materials
C&DW	Construction and Demolition Waste
CF	Characterization factor
EDP	Environmental Product Declaration
EP	Eutrophication potential
FW	Use of net fresh water
GFA	Gross Floor Area
GSA	Global Sensitivity Analysis
GWP	Global Warming Potential
GWP_{exc}	Global Warming Potential excluding biogenic carbon
HWD	Hazardous waste disposed
LCA	Life Cycle Analysis/Assessment
MCS	Monte Carlo Simulation
NHWD	Non-hazardous waste disposed
ODP	Depletion potential of the stratospheric ozone layer
$P_{25\%}$	25th percentile
$P_{75\%}$	75th percentile
PE	Primary Energy
PENRT	Total use of non-renewable primary energy resources
PERT	Total use of renewable primary energy resources
POCP	Formation potential of tropospheric ozone photochemical oxidants
RWD	Radioactive waste disposed
SA	Sensitivity Analysis

List of figures

List of tables

KJ-NA-29324-EN-N

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

Joint Research Centre

EU Science Hub

Publications Office

doi:10.2760/356384

ISBN 978-92-79-92882-6