**Interpreting environmental impacts in building design: Application of a comparative assertion method in the context of the EPD scheme for building products†**

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†Dedicated to the memory of the late Assoc. Prof. Dr. Roman Kunič.

**Abstract**

Due to the profound impact that building sector has on the environment and consequently the sustainability of our society, the evaluation of environmental impacts through life cycle assessment (LCA) should become part of building design. The number of published environmental product declarations (EPDs) is growing, which indicates that they can become valuable tools for building designers to evaluate the environmental performance of construction works. We identified that in the current EPD scheme an important part is missing – the results interpretation. In order to evaluate the environmental performance of buildings or their components and elements, the designer is "forced" to conduct a comparative assertion on a population of alternatives. The paper explores the results interpretation of LCA data in the context of the EPD scheme for building products and presents a comparative assertion method, which could guide designers through the results interpretation step of LCA. The proposed soft comparative assertion method was tested on a sample of external wall assembly alternatives and the results show that it significantly simplifies the LCA results interpretation and enables straightforward decision making. However, the method is not yet a fully functional tool and should be upgraded in order to make the decision process more robust and less subjective. With this paper we wish to encourage further research on the described topic, which is vital in order to add credibility to the EPD scheme as an instrument for lowering the environmental impact of the building sector.

**Keyword:** life cycle assessment (LCA); EPD; building design; building sustainability; results interpretation; soft comparative assertion

**Abbreviations**

| | | | |
|---|---|---|---|
| BSAM | building sustainability assessment method | KVH | finger joint timber |
| LEED | Leadership in Energy and Environmental Design | EPS | expanded polystyrene |
| DGNB | German Sustainable Building Council | SW | stone wool insulation |
| BREEAM | Building Research Establishment Environmental Assessment Method | WF | wood fibre |
| LCA | life cycle assessment | CF | cellulose fibre |
| EPD | environmental product declaration | fGW | flexible glass wool |
| *PS* | percentage share [%] | fWF | flexible wood fibre |
| *IS* | impact score [/] | GWP | global warming potential [kg $CO_2$ eq.] |
| ETICS | external thermal insulation composite system | ODP | ozone depletion potential [kg. R11 eq.] |
| TI | thermal insulation | POCP | photochemical ozone depletion potential [kg $C_2H_4$ eq.] |
| LB | load bearing | AP | acidification potential [kg $SO_2$ eq.] |
| RC | reinforced concrete | EP | eutrophication potential [kg $(PO_4)^{3-}$ eq.] |
| AACB | autoclave aerated concrete block | ADPE | abiotic depletion potential of elements [kg Sb eq.] |
| CLT | cross laminated timber | ADPF | abiotic depletion potential of fossil resources [MJ] |

## 1. Introduction

More than 30 years have passed since the publication of the Our Common Future report [1] by the Brundtland commission, which brought the term and concept of sustainable development into wider awareness [2]. In its essence, sustainable development is described as development that meets the needs of the present, without compromising the ability of future generations to meet their own needs. Following the Brundtland report, on the incentive of the United Nations, a number of international conferences and meetings (e.g. Rio de Janeiro Earth Summit 1992, Millennium Summit 2000, etc.) led to the formulation of 17 sustainable development goals (SDG), which are at the heart of the 2030 Agenda for Sustainable Development [3] proposed by the UN. One of the main goals put forward by the above-mentioned agenda is also the sustainability of natural resources and taking urgent action on climate change. Both issues are integrally linked to the construction sector and the built environment [4], [5].

Buildings as well as other infrastructure define the built environment and thereby have a direct impact on the three pillars of sustainability: economy, society and environment [6]. In the EU, the construction sector generates 9 % of gross domestic product (GDP) and directly provides 18 million jobs [7]. According to some studies people spend approximately 90 % [8] of their time in buildings, which is why their design and functionality crucially affects occupant comfort and health [9], [10]. In addition, built infrastructure provides the foundation for a functional modern society, which affects our overall quality of living. Consequently, the construction sector has an extensive impact on the environment. The built environment shapes the urbanised landscape and affects the ecosphere (e.g. urban heat island, change in precipitation patterns, air quality, soil degradation, water quality, etc.) [11]–[13]. Buildings in the EU are responsible for 40 % of all energy use and emit one third of all anthropogenic greenhouse gases. Furthermore, the EU construction sector is responsible for one third of all generated waste and consumes between 30 and 50 % of all resources [14]. Secher et al. identified that construction material and product manufacturers have a direct impact on 7 of the 17 SDGs set by the 2030 Agenda for Sustainable Development, as well as indirectly on 2 additional goals [15]. From this perspective it becomes clear that the sustainability of buildings and the construction sector as a whole should be considered as a key element in the struggle to achieve the goals set by the UN 2030 Agenda for Sustainable Development. In order to implement the concepts of sustainability in buildings, over the past 25 years a number of building sustainability assessment methods (BSAM), e.g. LEED [16], DGNB [17], BREEAM [18], have been developed throughout the world [19]. These methods vary in their assessment attributes, assessment models and weighting schemes [20]. According to ISO 21929-1 [21], these methods adapt the general sustainability principles to the specifics of buildings and address the economic, social and environmental impacts. Due to the profound impact of the building sector on the environment, the environmental aspect of sustainability is becoming increasingly important and should become part of the building design. With the development of the life cycle assessment (LCA) method, an important step forward has been achieved for assessing the environmental impacts of building products and buildings, throughout their lifetime [22].

In its Communication on Integrated Product Policy [23], the European Commission concluded that LCA provides the best currently available framework for assessing the potential environmental impacts of products. The LCA methodology is standardized in accordance to ISO 14040 [24] and ISO 14044 [25]. In the past decade there has been a steady growth of type III environmental declarations for building products in the form of environmental product declarations (EPDs). As of January 2019, there are over 6000 verified EPDs for construction products registered globally [26]. EPDs are documents, which communicate LCA data in the form of potential environmental impacts, resource use, hazardous substances and waste. Directive EN305/2011, which regulates the European building product market, states that EPDs should be used for assessing the environmental impacts of buildings [27]. The increase in availability of EPDs for building products can be partly linked to the application of BSAMs, as they incorporate the LCA principle in their attributing system for assessing the environmental impacts of buildings [28]. In this way, they stimulate manufacturers of building product to provide EPDs, as buildings projects that incorporate building products with published EPDs are rewarded with extra credits [29]. The principles and rules for creating EPDs are standardized through ISO 14025 [30] and EN 15804 [31], which harmonize the production of these documents by different programme operators (i.e. institutions who provides EPDs). In order to assure better comparability between EPDs of various programme operators, the ECO Platform [32] was founded. At the time of writing, this platform has more than 20 members across Europe and provides access to numerus EPDs for construction products. Standard EN 15978 [33] provides the calculation rules for incorporating EPDs in LCA studies assessing the environmental aspect of building sustainability. In addition, the newly established Level(s) scheme, provided by the European Commission, associates the evaluation of environmental impacts of buildings with the relevant standards for EPDs (EN 15804 and EN 15978) [34].

The above-mentioned facts speak in favour of using the LCA method and EPDs for environmental assessment of buildings. Nonetheless, the comprehensive evaluation of environmental impacts of buildings through their life cycle is still a few steps from being a mandatory element of the building design procedure. Through the implementation of Directive 2018/ 844 of the European Parliament and Council [35] and its predecessor [36], buildings are becoming ever more energy efficient, which is a crucial step in reducing the environmental impact of the operational phase. As shown in the study by Blengini et al. [37], the enhanced energy efficiency of contemporary residential buildings has led to an increased environmental importance of other life cycle phases. They concluded that the embodied environmental impact of building products, or the cradle-to-gate life cycle phase, is becoming increasingly important. This indicates that decisions in the design stage regarding the incorporated building products are becoming ever more crucial for the overall environmental impact of buildings, especially the residential ones.

### 1.1 Objective of the study

Over the past two decades a number of LCA studies regarding the environmental impacts of building products [38]–[43], elements [44]–[49] and buildings as a whole [37], [50], [51] have been conducted. Also many review studies on the subject of LCA in buildings and the construction sector have been published [22], [52]–[54]. Due to the specific nature of each LCA study it is hard to compare the results from various executed studies [54]. Although standards ISO 14040 [24] and ISO 14044 [25] define the basic principles of conducting LCA, there can be important differences between specific studies, which inherently hinder their comparison. There are many reasons for this. For conducting LCA there are various generic life cycle inventory (LCI) databases (e.g. Ecoinvent [55], Gabi [56]), which lead to diverse numerical outcomes [57]. Different life cycle impact assessment (LCIA) methodologies can be used that differ in the study approach (i.e. midpoint or endpoint) and the adopted characterisation methods [58]. Also the considered life cycle stages can vary from study to study [54]. The geographical scope of the analysis is important as well, as some environmental categories (e.g. acidification) have regional and not global characteristics, as is the case for global warming and ozone layer depletion [59], [60]. The above is additionally complicated by the fact that each building is in essence a prototype, with myriad of variables that must be considered during the design phase. This indicates that general recommendations regarding the environmental impacts of buildings have their limits. In order to properly understand their environmental impacts over their service life and to design the most preferable building from the environmental point of view, building designers need to include LCA in their workflow. Therefore, a straightforward methodological principle applicable during the building design process is needed and we consider that the EPD scheme, although not perfect, is the most suitable for providing building designers with relevant environmental data.

During the past years the literature on the topic of EPDs for building products has grown. Some studies discus the harmonisation issues and quality of environmental data [61], [62], others the integration of LCA in building information modelling (BIM), where EPDs could be used [63]–[65]. However, there are only few studies trying to assess the environmental impacts of buildings through LCA data obtained from EPDs [66]–[69]. Although the above stated studies provide valuable information, an important issue regarding the use of EPDs for the evaluation of building's environmental performance is missing in the literature – the results interpretation.

In the above-outlined context, our paper focuses on the use of EPDs for objective environmental decisions during building design. The attention will be mostly on the formulation of a method for interpreting environmental results obtained from EPDs, which enables building designer to choose the preferred design alternative from the environmental point of view. Therefore, a simple method, easy understood by non-LCA experts will be presented. The reasoning behind this is that LCA results in EPDs are used by stakeholders, who do not possess the specialized LCA knowledge, as their expertise lies in the field of building design (e.g. architects, civil engineers, façade designers, etc.). The design of the method is adapted for; (i) the specific nature of buildings (buildings complex systems with a myriad of components), (ii) modern building design (increasing digitalization) and (iii) the concept behind BSAM (evaluating specific criteria, providing credits). This means that (i) it enables to evaluate many design options, (ii) it can be easily used in software to supplement the LCA results, and (iii) it can be incorporated in building sustainability assessment methods. Due to the framework and specifics of the method we named it: soft comparative assertion method.

## 2. Context: Interpreting LCA results obtained from EPDs in building design

In their essence, EPDs are documents for communicating LCA results [70] and do not provide information regarding the environmental superiority or inferiority of a product. Consequently, when evaluating the environmental performance of a building or specific building components with LCA data from EPDs, the obtained results for a single entity do not provide any meaningful conclusions regarding its environmental performance. From a building designer's perspective, such information holds too little practical value. This is in contradiction to other building performance topics like structural stability, energy performance, daylighting etc., where the obtained results can be compared to legislative benchmarks and/or requirements in order to establish how well a specific design solution performs. However, when optimising the design of a building, evaluating various design alternatives is common, especially in the modern digitalised building design. In case of evaluating the environmental performance of various building alternatives the difference is that there are no benchmarks (at least not at present). Therefore, to evaluate how a design solution performs in regards to its potential environmental impact, one needs to compare the results across the environmental midpoint topics defined in EPDs with other design alternatives. Consequently, building designers are "forced" to conduct a comparative assertion. ISO 14044 [25] describes comparative assertion as: "*environmental claim regarding the superiority or equivalence of one product versus a competing product that performs* *the same function*". As it is shown in section 5.1, this comparison can be very complex and without methodological guidance cannot provide the building designer with enough information to make objective decision regarding the environmental performance. The results of the observed entities can vary substantially from one impact category to another, thus making conclusions extremely difficult. Standard EN 15978 [33], which defines the calculation rules and requirements needed to conduct an evaluation of the environmental performance of buildings or construction works, does not address the interpretation phase, nor does it provide guidelines for comparative assertions in the context of building design. This is a major shortcoming in the present EPD scheme. Without addressing this important step in the relevant standards, the decision makers (building designers) are not provided with sufficient guidance, which can lead to confusion and subjectivity in the decision process. Considering the complexity of the LCA method, not addressing the results interpretation in the context of building design diminishes the relative importance, credibility and usefulness of EPDs for lowering the environmental impacts of buildings.

## 2.1 The structure of results interpretation when using EPDs

The results interpretation of LCA data obtained from EPDs can be split in two branches – informational and decisional (Figure 1). The first refers to the individual object studied and provides information regarding the environmental impact contribution of life cycle stages, the most important processes and substances (materials), the most important components (building products) and the dominant building parts when the object of observation is a whole building. On the building product level, this information is part of the EPD document. However, it should be stated that the details and scope of LCA results interpretation vary from one EPD document to another. With the informational results interpretation the environmental hotspots for an individual object are identified. Additionally, the building designer can use this information for the conception of design alternatives. The second, decisional results interpretation, is applied when the aim is to conduct a comparative assertion of various design alternatives. The aim is to identify how they associate from the environmental point of view. This part of results interpretation enables to choose the preferred design alternative from many

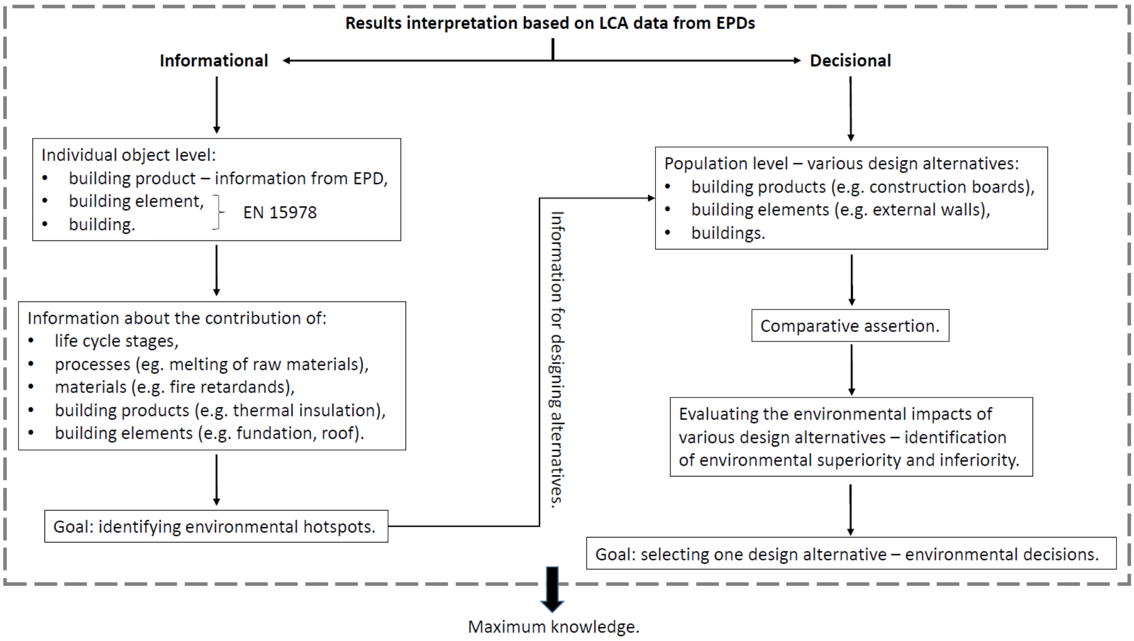


*Figure 1: The structure of results interpretation when using LCA data from EPDs for building design.*

and enables environmental decisions in building design. Information from both interpretation branches provides the maximum knowledge about the environmental performance of a studied object (e.g. whole building, building element), both on the individual level and the level of various design alternatives.

As stated in the previous section, the decisional results interpretation is not sufficiently covered in literature and the relevant standards. Therefore, this paper focuses on a method for decisional results interpretation when using EPDs in environmental building design.

## 2.2 Results interpretation: normalisation and weighting

In 2016 the Joint Research Centre (JRC) of the European Commission published a study on the subject of results interpretation in LCA, in which they stated that: "*further guidance needs to be developed to support interpretation of LCA studies both for LCA practitioners and LCA users (e.g. decision makers*)" [71]. Two important points with respect to the results interpretation are covered in this report: normalisation and weighting. They are optional steps of the LCIA phase of LCA and can be used to conduct comparison across impact topics [72], thus providing more understandable results. As in EPDs, the potential environmental impacts are presented through multiple environmental categories, their application in results interpretation could significantly simplify the decisional results interpretation. ISO 14044 defines normalisation as: "*the calculation of the magnitude of the category indicator results relative to some reference information"* and weighting as: *" the process of converting indicator results of different impact categories by using numerical factors based on value-choices"* [25]. However, normalisation and weighting are controversial topics in the LCA community due to the potential biases and value choices associated with them [73]. For normalisation, the main criticism is that it is biased due to the choice of normalisation references, which can influence the conclusions drawn from the LCIA phase [74]. The criticism of weighting, on the other hand, is even starker [73], as ISO 14044 describes weighting as not being scientifically based but rather as a value-choice process, and therefore should not be used in comparative assertions disclosed to the public. Nevertheless, despite the criticism, normalisation and weighting are often applied in practice for various reasons, such as identifying important impact categories or understanding the meaning of results by comparing with more familiar references [73], [75].

Several approaches and methods for normalisation, weighting and the overall results interpretation have been proposed and developed. As a detailed description of these methods is beyond the scope of this paper, we direct the reader to studies published by other authors in order to acquire more knowledge on this complex subject in LCA ([71], [73], [75]–[77]).

Based on the above stated references, one seems to sense that the LCA community has focused on providing a universal method for interpreting the LCA results, regardless of the industrial sector in which the method is applied. Considering that the LCA approach is universal (standards ISO 14040 and ISO 14044), this is logical. Nevertheless, the design of buildings has its specifics, so it is useful that the method for interpreting the LCA results is adapted for the building design process. In our paper, we present a general framework of a comparative assertion method, which supplements the EPD scheme for building products. At this stage we would like to emphasize that the aim of this paper is not to develop a fully functioning tool, but to present a general principle of a framework, which could guide building designers when making decision regarding environmental impacts of buildings or building elements. The proposed soft comparative assertion method presented in this study adopts normalisation and weighting for interpreting results regarding potential environmental impacts obtained from EPDs. Due to the specifics of using EPDs for evaluating environmental performance, the adopted normalisation and weighing methods should not be considered as part of LCIA, but rather part of the results interpretation step in LCA. The presented method is thoroughly explained in the next section.

## 3. Methodology – soft comparative assertion method

The described method for interpreting the LCA results of potential environmental impacts consists of three steps: normalisation, weighting and categorisation. Figure 2 shows its structure and presents the objective as well as input and output for each step.

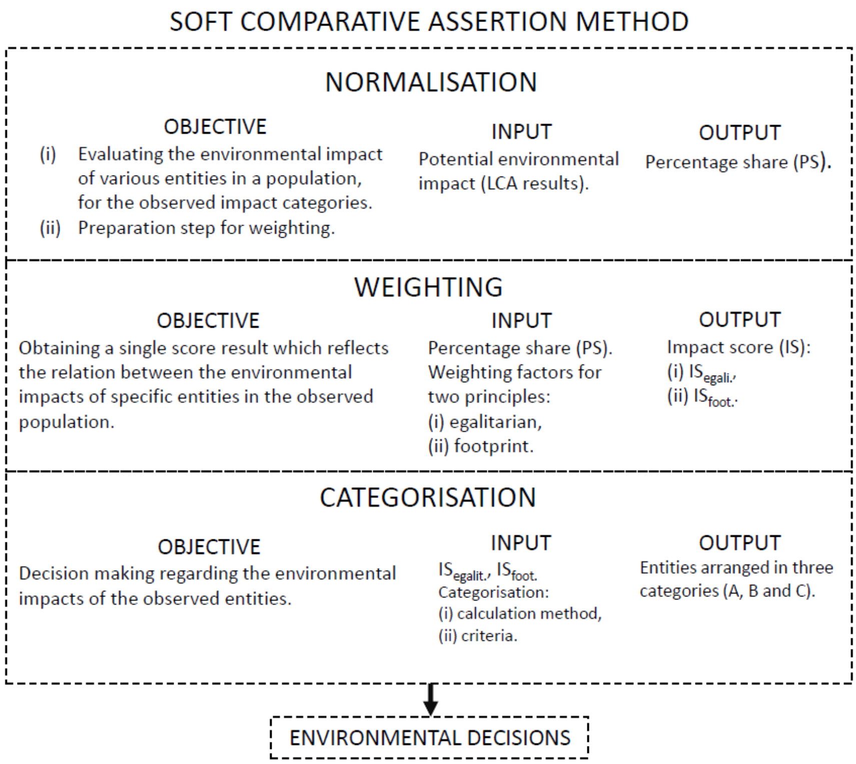


*Figure 2: Structure of the soft comparative assertion method.*

We are aware that general consensus regarding normalisation and weighting is hard to achieve, but for our specific purpose, using EPDs for evaluating the environmental aspects of buildings, we identified these two steps as extremely useful. For normalisation, we applied the internal normalisation principle with the division by sum method, as described by Pizzol et al. [73] and Laurent et al. [74]. Regarding the weighting step we can conclude, based on the reviewed literature, that there is no universal weighting principle that different stakeholders would agree with. For this reason we adopted two different sets of weighting factors. This is in line with the recommendations of ISO 14044 [25], which recommends the adoption of several different weighting factors and methods before making conclusions regarding the LCA results. The last step, categorisation, provides criteria for evaluating the relation between the environmental performances of design alternatives and in modest way accounts for the uncertainties associated within LCA and the EPD scheme for building products.

In this section we will use mathematical terms, population (i.e. all the design alternatives) and entities (i.e. individual members of the population), to describe the underlying principle of the method.

## 3.1 Normalisation

Since the units in each of the environmental categories are different and their numerical values can be dispersed (for the wall population used in this study they ranged from $10^{-9}$ to $10^{3}$, see Table 3), a normalisation is needed in order to better evaluate the relationship of environmental impacts among the observed entities in the population. An internal normalisation with the division by sum in each environmental category is performed. The normalisation base is the summation of absolute values of all of the entities in a specific environmental category. The ratio of the environmental impact of an entity and of the whole population is then multiplied by 100 and the percentage share (*PS*) is obtained (equation 1).

$$PS_i^x = \frac{EI_i^x}{\sum_i |EI_i^x|} \cdot 100\ [\%] \tag{1}$$

*PS* – percentage share [%]

*EI* –the environmental impact of an entity

x – environmental impact category ( *x* = GWP, ODP, …, ADPF )

i – specific entity in a population (e.g. for the studied wall assemblies: *i* = *RC*+EPS, RC+SW, …, KVH: fWF+WF )

*PS* simplifies the interpretation of the results, because the values are in the range of 0 to 100 %. Therefore, each individual *PS* of an entity represents its relative impact in the specific environmental category proportionally to the impact of other entities in the population. The summation of the absolute *PS* values of all entities in an impact category obtains a value of 100 %. Besides the results interpretation across the spectrum of impact categories, the *PS* is the input for the weighting process.

## 3.2 Weighting

Through the weighting step a single score indicator in relation to the potential environmental impacts of the midpoint categories is obtained, for each entity separately. Because the literature review on weighting showed that there is no “right” way to account for the environmental importance of different environmental categories, we adopted two different weighting principles for the proposed comparative assertion method. We named the principles egalitarian and footprint. The egalitarian principle adopts an equal weighting factor (i.e. $w_{egali.}$ = 1) for all environmental categories, meaning that all have the same environmental importance. The reasoning behind the inclusion of the egalitarian principle lies in the understanding that the societal and economic relevance of specific impact categories changes spatially and temporally. For example, global warming can be of far greater concern for coastal regions which are in risk of flooding due to see level rise, than for regions not at risk [78]. Also time is a factor, as 30 years ago ozone depletion was considered a greater environmental concern than today [79], which indicates that it would receive a larger relative weighting factor than at present times. Therefore, the inclusion of the egalitarian weighting principle accounts (to some degree) for such spatial and temporal specifics, while also to some extent reduces the negative consequences of environmental burden shifting. For the second principle, we performed a literature search on different weighting factors for impact categories on the midpoint level ([76], [80]). We decided to use the ones presented in the JRC technical report, in which a weighting set for the 16 defined environmental impact categories for the life cycle based environmental footprint (EF) scheme was presented [76]. These weighting factors are obtained with a combination of different approaches and include a robustness factor for each environmental category. The applied weighting factors for the footprint principle in our study were acquired from the recommended weighting factors excluding toxicity-related impacts (Table 32 in [76]). As the EPD framework adopts 7 environmental categories (according to EN 15804:2012), we derived the weighting factors for the JRC principle by adjusting the weighting values of the relevant environmental categories using normalisation, so that the relation between the 7 environmental categories is maintained. The weighting set for the footprint principle is presented in Table 1.

*Table 1: Weighting factors for the observed environmental categories adopted from the JRC technichal report on weighting.*

| | GWP | ODP | POCP | AP | EP | ADPE | ADPF |
|---|---|---|---|---|---|---|---|
| $w_{foot.}$ | 0.328 | 0.100 | 0.075 | 0.098 | 0.148 | 0.119 | 0.132 |

GWP – global warming potential, ODP – ozone depletion potential, POCP – photochemical ozone creation potential, AP – acidification potential, EP – eutrophication potential, ADPE – abiotic depletion potential of elements, ADPF – abiotic depletion potential of fossil resources

In the proposed method, the PS values serve as the numerical input, while the numerical output of weighting, named impact score, is derived according to equation 2.

$$IS_{i,j} = \sum_{x} \left(PS_i^x \cdot w_j^x\right) [/] \quad (2)$$

*IS* –impact score [/]

*w* – impact category weighting factor [/]

*PS* – percentage share [%]

x – environmental impact category (*x* = GWP, ODP, …, ADPF)

i – specific entity in a population (e.g. for the studied wall assemblies: *i* = *RC*+EPS, RC+SW, …, KVH: fWF+WF )

j – weighting principle (i.e. egalitarian or footprint)

As the result is based on the PS values, for which the normalisation base is the aggregated impact of all the entities in a specific impact category, the IS incorporates the relative differences between the environmental impacts of the entities in different midpoint categories. The IS value cannot be applied to a single object with LCA data, it only works when comparing more than one entity that contains LCA data with identical functional unit, system boundaries and environmental categories. One should not interpret the IS value as an environmental score, like in specific endpoint methods (e.g. Eco Indicator 99 [81], LIME [82]), as it merely represents the relation between the observed entities in a population across the spectrum of environmental categories. The impact score is obtained for each weighting principle separately ($IS_{egali.}$, $IS_{foot.}$).

### 3.3 Categorisation

The last step of the proposed method contributes the adjective "soft" before the expression "comparative assertion". As reasonably stated by the authors of the LCA software Athena Impact Estimator for Buildings [83], when working with the LCA data one needs to keep in mind that, "although LCA is a rigorous science, its precision should not be overestimated" [84]. In LCA, there are many types of uncertainties [85]–[87]. Therefore, when interpreting the LCA results extracted from EPDs, one needs to be aware of the possible imprecisions, especially when conducting comparative assertions.

The categorisation consist of two separate steps, which lead to the final results. These results enable simple evaluation of the observed entities and straightforward decision making.

### 3.3.1 Calculation method

The first step of categorisation consists of mathematical formulations, which split the entities in the observed population into three categories (A, B and C), for each weighting principle. This categorisation is based on three mathematical expressions: range, range quarter and upper bound. The visualisation of this step is presented in Figure 3 and mathematical derivations in equations 3 to 6.

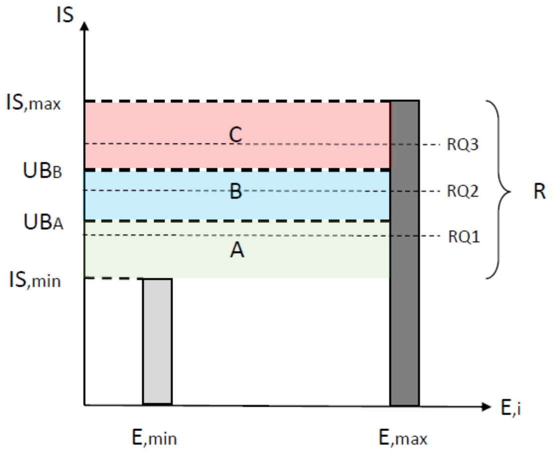


*Figure 3: Schematical representation of the range (R), range quarter (RQ) and upper bound limits ($UB_A$, $UB_B$) in a population of entities ($E_{,i}$).*

With this approach we wish to avoid making decisions based solely on the calculated *IS*. The obtained results qualify the entities in three categories, which are based on the *IS* range of the population. Entities in each category can be perceived as having a comparable potential environmental impact. We used the range quarter as the main parameter for the division into categories. With factor *F*, accounting for uncertainties, we wish to include the entities with the *IS* near the specific quarter limit (*RQ1* and *RQ2*). This is done due to the assumptions and uncertainties inherent to any LCA. In the user manual and transparency document for the Athena Impact Estimator for Buildings LCA tool, the authors state that the results in the tool should be viewed within a 15 % margin of error perspective [88]. Therefore, we decided to use a value of 1.10 for the uncertainty factors. Furthermore, factor F is important when evaluating a smaller number of design alternatives (i.e. 2 to 4 design alternatives), as without the implemented factor, one assembly would always be positioned in category C, even if the range value is small (see section 5.4).

$$R_j = IS_{max,j} - IS_{min,j} \tag{3}$$

$$RQ_j = R_j/4 \tag{4}$$

$$UB_{A,j} = \left(IS_{min,j} + RQ_j\right) \cdot F \tag{5}$$

$$UB_{B,j} = \left(IS_{min,j} + 2 \cdot RQ_j\right) \cdot F \tag{6}$$

*R* – range

*RQ* – range quarter

$IS$ – impact score

$UB_A$ – upper bound for category A

$UB_B$ – upper bound for category B

$F$ – factor accounting for uncertainties in the results (for our study: $F$ = 1.10)

i – specific entity in a population (e.g. for the studied wall assemblies: $i$ = *RC*+EPS, RC+SW, …, KVH: fWF+WF )

j – weighting principle (i.e. egalitarian or footprint)

The mathematical expressions for fitting the entities in categories are presented in equations 7 to 9.

$$Category\ A_j = \{E_{i,j}^{A};\ IS_{i,j} < \left(IS_{min,j} + QR_j\right) \cdot F\} \tag{7}$$

$$Category\ B_j = \{E_{i,j}^{B};\ (IS_{min,j} + QR) \cdot F \leq IS_{i,j} \leq \left(IS_{min,j} + 2 \cdot QR\right) \cdot F\} \tag{8}$$

$$Category\ C_j = \{E_{i,j}^{C};\ IS_{i,j} > \left(IS_{min,j} + 2 \cdot QR\right) \cdot F\} \tag{9}$$

$E$ - entity

### 3.3.2 Criteria for final categorisation

The last step of the categorisation is based on criteria for uniting the entities in a single categorisation framework, as now the results are separate for the egalitarian and footprint principle. The criteria for the final categorisation are shown in equations 10 to 12.

$$Category\ A\text{: } if\ E_i = \begin{cases} E_{i,egali.}^{A}\ AND\ E_{i,foot.}^{A} \\ E_{i,egali.}^{A}\ AND\ E_{i,foot.}^{B} \\ E_{i,egali.}^{B}\ AND\ E_{i,foot.}^{A} \end{cases} \xrightarrow{yields} E_i^{A} \tag{10}$$

$$Category\ B\text{: } if\ E_i = \begin{cases} E_{i,egali.}^{B}\ AND\ E_{i,foot.}^{B} \\ E_{i,egali.}^{A}\ AND\ E_{i,foot.}^{C} \\ E_{i,egali.}^{C}\ AND\ E_{i,foot.}^{A} \end{cases} \xrightarrow{yields} E_i^{B} \tag{11}$$

$$Category\ C\text{: } if\ E_i = \begin{cases} E_{i,egali.}^{C}\ AND\ E_{i,foot.}^{C} \\ E_{i,egali.}^{B}\ AND\ E_{i,foot.}^{C} \\ E_{i,egali.}^{C}\ AND\ E_{i,foot.}^{B} \end{cases} \xrightarrow{yields} E_i^{C} \tag{12}$$

Through the final categorisation, which exerts the results of the soft comparative assertion method, the building designer can choose the preferable design alternative from the whole population. Entities in category A show superior environmental qualities for the defined boundary conditions of the analysis (i.e. life cycle stages, functional unit) and entities in category C show the least preferable potential environmental impact. The entities positioned in the same category can be considered as having a comparable potential environmental impact. In this way the presented framework enables straightforward decision making. The application of the soft comparative assertion method on a sample of 18 external wall assemblies is demonstrated in section 5.

## 4. Test population and its environmental data

The implementation of the soft comparative assertion method will be demonstrated on a set of external wall assemblies, characteristic for energy efficient residential buildings in European heating driven climates (e.g. Central and Northern Europe). All of the observed entities have an equal thermal transmittance value of 0.2 W/(m$^2$K), which roughly corresponds to the most demanding energy efficiency codes in European countries [89]. Furthermore, all of the wall assemblies have the same façade design – an external thermal insulation composite system (ETICS). The wall population consists of 18 entities assembled using different building materials. Half of the wall assemblies employ solid load bearing construction system, while the other half uses filigree construction systems. Regarding the wall components, we can subdivide them into load bearing (LB) and thermal insulating that define the overall number of the external wall alternatives and other components, which complete the wall assemblies to the point of functional integrity (Figure 4).

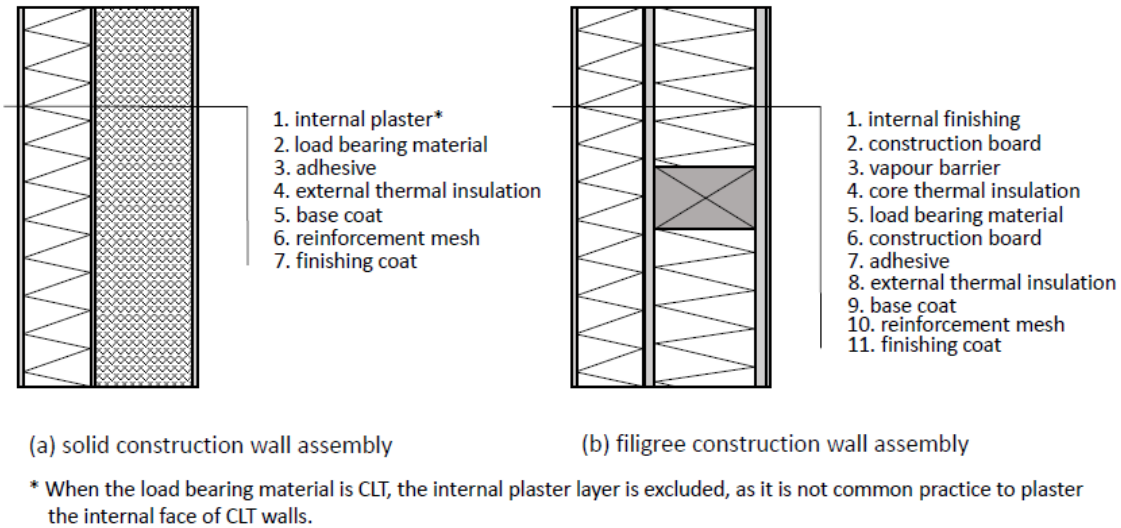


*Figure 4: Generic geometric model of external wall assemblies used in the study.*

For the assemblies with solid LB construction system, three different load bearing products are used: reinforced concrete (RC), autoclaved aerated concrete blocks (AACB) and cross laminated timber (CLT). Each of these load bearing elements is combined with three external thermal insulation (TI) boards, which are part of the ETICS system. The materials of the TI boards are: expanded polystyrene foam (EPS), stone wool (SW) and wood fibres (WF). The filigree LB construction system consists of a wooden frame executed as KVH (finger jointed solid wood) as the main load bearing material. The presumed distance between the 80 mm thick vertical studs is 850 mm. In a typical lightweight timber framed wall, the cavity between the vertical studs is filled with thermal insulation. For this study, three different cavity thermal insulations were used: cellulose fibres (CF), flexible wood fibre board (fWF) and flexible glass wool board (fGW). For clarity purposes the wall assemblies are affiliated into groups using colour coding. Each colour represents a different load bearing construction material in the case of solid construction systems and a different cavity thermal insulation material in the case of the filigree structure entities (Table 2).

*Table 2: Colour label affiliation and abbreviations of the external wall design alternatives of the test population.*

| Colour labels | Wall assemblies |
|---|---|
| | Reinforced concrete (RC) solid load bearing construction system; RC+EPS, RC+SW, RC+WF. |
| | Aerated concrete blocks (AACB) solid load bearing construction system; AACB+EPS, AACB+SW, AACB+WF. |
| | Cross laminated timber (CLT) solid load bearing construction system; CLT+EPS, CLT+SW. CLT+WF. |
| | Filigree loadbearing construction system with cellulose fibres (CF) cavity thermal insulation; KVH:CF+EPS, KVH:CF+SW, KVH:CF+WF. |

| | |
|---|---|
| | Filigree loadbearing construction system with flexible wood fibre board (fWF) cavity thermal insulation; KVH:fWF+EPS, KVH:fWF+SW, KVH:fWF+WF. |
| | Filigree loadbearing construction system with flexible glass wool board (fGW) cavity thermal insulation; KVH:fGW+EPS, KVH:fGW+SW, KVH:fGW+WF. |

The environmental data of the building products are based on EPDs from two programme operators, members of the ECO Platform; Institut Bauen und Umwelt [90] and BAU-EPD [91]. Because no EPDs for vapour barrier could be sourced from the mentioned programme operators, we used the data from the German database Oekobaudat [92]. As the purpose of this study is not to comment on the environmental impact of various design alternatives, but to present the soft comparative assertion method on an example, the details regarding the environmental impacts of the wall assemblies are not presented and commented.

### 4.1 Environmental characteristic: functional unit, system boundaries and environmental categories

The functional unit for the wall population is 1 $m^2$ of the wall assembly with the U-value of 0.2 $W/(m^2K)$. The LCA results for the wall components were gathered for the product stage information modules A1, A2 and A3, as defined in the standard EN 15804, also referred to as cradle-to-gate stage.

Environmental impacts of the wall assemblies are presented in EPDs through seven midpoint characterization factors (environmental categories). In accordance with EN 15804 [31] these are the following: Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Photochemical Ozone Creation Potential (POCP), Acidification Potential (AP), Eutrophication Potential (EP), Abiotic Depletion Potential of Elements (ADPE) and Abiotic Depletion Potential of Fossil resources (ADPF). The environmental impact of the observed wall assemblies is calculated in accordance with the matrix calculation principle defined in EN 15978 [33].

## 5. Method application demonstration

For the studied population of 18 external wall assemblies, the potential environmental impacts obtained through the matrix calculations are presented in Table 3. The results are presented separately for the normalisation step and the soft comparative assertion method. Besides being a preparation step for weighting, the internal normalisation with the division by sum method also has its value for evaluating results across the impact categories. In the example presented in section 5.1 we wish to underline the complexity of evaluating the potential environmental impacts of various design alternatives. In the sections that follow, the results of the soft comparative assertion method are going to be presented for three different populations sizes (i.e. Group № 1, 2 and 3).

*Table 3: The potential environmental impacts of the observed wall assembly population.*

| Entity | GWP [kg $CO_2$ eq.] | ODP [kg R11 eq.] | POCP [kg $C_2H_4$ eq.] | AP [kg $SO_2$ eq.] | EP [kg $(PO_4)^{3-}$ eq.] | ADPE [kg Sb eq.] | ADPF [MJ] |
|---|---|---|---|---|---|---|---|
| RC+EPS | 69.44 | 1.69E-07 | 8.78E-02 | 1.81E-01 | 1.67E-02 | 3.14E-04 | 797.61 |
| RC+SW | 73.26 | 6.25E-07 | 1.95E-02 | 2.62E-01 | 2.87E-02 | 3.13E-04 | 682.43 |
| RC+WF | 31.67 | 1.12E-07 | 1.87E-02 | 1.92E-01 | 2.00E-02 | 3.29E-04 | 854.23 |
| AACB+EPS | 88.82 | 1.12E-07 | 5.87E-02 | 1.78E-01 | 1.63E-02 | 2.99E-04 | 971.14 |
| AACB+SW | 91.14 | 3.89E-07 | 1.72E-02 | 2.27E-01 | 2.35E-02 | 2.99E-04 | 901.07 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| AACB+WF | 65.85 | 7.77E-08 | 1.67E-02 | 1.85E-01 | 1.83E-02 | 3.09E-04 | 1005.59 |
| CLT+EPS | -71.32 | 9.26E-07 | 7.36E-02 | 1.61E-01 | 1.54E-02 | 7.33E-05 | 688.54 |
| CLT+SW | -68.1749 | 1.30E-06 | 1.73E-02 | 2.27E-01 | 2.52E-02 | 7.32E-05 | 593.6725 |
| CLT+WF | -102.427 | 8.79E-07 | 1.67E-02 | 1.70E-01 | 1.81E-02 | 8.61E-05 | 735.1782 |
| KVH:CF+EPS | -1.05 | 6.06E-08 | 3.81E-02 | 1.36E-01 | 1.20E-02 | 9.61E-04 | 524.44 |
| KVH:CF+SW | 0.39 | 2.32E-07 | 1.24E-02 | 1.66E-01 | 1.65E-02 | 9.61E-04 | 481.16 |
| KVH:CF+WF | -15.24 | 3.94E-08 | 1.21E-02 | 1.40E-01 | 1.33E-02 | 9.66E-04 | 545.71 |
| KVH:fWF+EPS | 9.77 | 2.43E-08 | 3.50E-02 | 1.61E-01 | 1.35E-02 | 5.15E-04 | 696.42 |
| KVH:fWF+SW | 10.93 | 1.62E-07 | 1.43E-02 | 1.85E-01 | 1.71E-02 | 5.15E-04 | 661.57 |
| KVH:fWF+WF | -1.65 | 7.30E-09 | 1.41E-02 | 1.64E-01 | 1.45E-02 | 5.20E-04 | 713.55 |
| KVH:fGW+EPS | 14.32 | 2.23E-08 | 3.14E-02 | 2.38E-01 | 3.39E-02 | 7.13E-04 | 565.69 |
| KVH:fGW+SW | 15.37 | 1.48E-07 | 1.27E-02 | 2.60E-01 | 3.71E-02 | 7.13E-04 | 534.06 |
| KVH:fGW+WF | 3.95 | 6.90E-09 | 1.24E-02 | 2.41E-01 | 3.48E-02 | 7.17E-04 | 581.23 |

## 5.1 Normalisation

As can be seen from Table 3, the results across the various environmental categories can be difficult to interpret for such a large population. One needs to present the data in more informative form, for example through hierarchically ordered bar charts. The respective *PS* can then help to identify the differences between the observed entities (Figure 5). The *PS* value represents the contribution of a single entity to the overall environmental impact of the population. As an example, in the POCP category, the AACB+EPS assembly contributes a share of 11.5 % to the overall populations impact. Also, by dividing the *PS* values of entities in a specific category, one can calculate the relative difference between the environmental impacts. As an example, in the AP category CLT+EPS exerts a *PS* value of 4.6 % and the CLT+SW assembly a value of 6.5 %, meaning that using SW boards instead of EPS ones in the ETICS façade of CLT walls results in a 41 % larger acidification potential (for the specific products and system boundaries). The relation between the environmental impacts of the observed entities changes from one impact category to another. The GWP category is special, as the GWP value can be negative. This is due to the characterisation method defined in the standard EN 15804 [31] for evaluating the potential environmental impact, as it accounts for $CO_2$ sequestration in materials. For this reason, wall assemblies consisting of wooden products can exert a negative GWP value, when the system boundaries are set to the cradle-to-gate life cycle phase. The $PS^{GWP}$ value of CLT+WF is -13.9 %, meaning that this assembly lowers the GWP of the whole population by a share of 13.9 %. The $PS^{GWP}$ values for the entities range from -13.9 % to 12.4 %. In the other categories the values are always positive, which makes it easier to compare the relative differences between specific entities in one category. The *PS* values for the studied population of 18 external wall assemblies in other environmental categories are as follows: between 0.1 – 24.6 % in the ODP category, 2.4 – 17.3 % in the POCP category, 3.9 – 7.5 % in the AP category, 3.2 – 9.9 % in the EP category, 0.8 – 11.1 % in the ADPE and 3.8 – 8.0 % in the ADPF environmental category. These differences in ranges illustrate that the distribution of environmental impacts between the entities varies from one impact category to another. This becomes obvious when observing the population standard deviations (σ) between the entities in each category (Table 4).

*Table 4: Population standard deviation (σ) of the observed PS values in the impact categories.*

| | GWP | ODP | POCP | AP | EP | ADPE | ADPF |
|---|---|---|---|---|---|---|---|
| σ | 7.2 | 7.0 | 4.3 | 1.1 | 2.0 | 3.4 | 1.2 |

The differences of potential environmental impacts between the entities are the largest in the GWP and ODP categories and the smallest in the AP category. The ratio between the wall assembly with the largest and the smallest impact is 246 in the ODP and 3 in the AP category. This indicates large differences between the potential environmental impacts of the observed entities from one impact category to another. Besides these differences, which reflect changes in the various impact categories among the observed population, also the relations between the entities change importantly. Focusing only on the categories with the largest standard deviations, GWP and ODP, we can notice that in the first category the CLT assemblies perform best, lowering the populations overall environmental impact by nearly one third (i.e. 32.9 %). However in the second category, the CLT assemblies exert the largest *PS* values, totalling at 58.7 %. Focusing on the filigree assemblies, we can notice that they show a nearly neutral impact in the GWP category, a relatively minor contribution for ODP, a wide dispersion of *PS* values for POCP (from 1$^{st}$ to 15$^{th}$ position), AP (1$^{st}$ to 17$^{th}$ position) and EP (form 1$^{st}$ to 18$^{th}$ position). As in the case of the CLT assemblies, we can notice that some filigree assemblies can exhibit small environmental contribution to the population's impact in one category and one of the largest in another. The RC and AACB entities show the most significant contributions to the population's environmental impact in the GWP and ADPF categories and the smallest in the ADPE one (positions from 4$^{th}$ to 9$^{th}$). In the other categories they are dispersed throughout the bottom half positions of the population.

Thus, the question is which wall assembly should we use in our new energy efficient residential house, for which we want to reduce the environmental impact of the incorporated materials? Based on the *PS* results, we can probably say that the RC and AACB assemblies show the largest potential environmental impact, as they exert the biggest $PS^{GWP}$ and $PS^{ADPF}$ values and are never positioned among the top three places in other environmental categories. The KVH:CF assemblies show a fairly good *PS* value in GWP and ODP, the largest impact in the ADPE and low *PS* values in other categories. KVH:CF+WF would probably be the most appropriate option, as the EPS and SW ones can exert important contributions in some of the environmental categories. Should we use the CLT+WF assembly, which shows the lowest impact in the GWP and one of the smallest in ADPE, a major ODP contribution, and is never positioned better than 7$^{th}$ position in the remaining four categories? Additionally, the question of the impact category importance arises. Which midpoint category is more important from an environmental perspective? Based on the calculated results in accordance with the matrix principle defined in EN 15987 and without methodological guidance, building designers can make decisions solely by professional judgement and personal criteria. Their judgement can also be influenced by other factors (e.g. seismic resistance, fire safety, costs etc.), which are important for the functionality and rationalization of the building. These factors also influence the sustainability of the building in accordance with the criteria in BSAM.


*Figure 5: The potential environmental impacts of the external wall design alternatives presented through the PS value.*

## 5.2 Soft comparative assertion – entire population (Group №1)

For the egalitarian principle, the *IS* values are larger than for the footprint weighting principle. This is an expected consequence of using weighting values between 0 and 1 in case of the footprint method. Table 5 clearly shows the differences between the two weighting principles in the obtained values for the relevant metrics of the interpretation method. Interesting to note is that $IS_{min, foot.}$ is negative. This is due to the negative $PS^{GWP}$ values and the combination of the largest weighting factor and the most pronounced standard deviation for the GWP category (see section 3.2 and 5.1).

*Table 5: Comparison of the minimum and maximum IS value, range, range quarter and upper bounds of the weighting principles for Group №1.*

| Egalitarian principle | | Footprint principle | |
|---|---|---|---|
| $IS_{min, egali.}$ | 22.5 | $IS_{min, foot.}$ | -0.56 |
| $IS_{max, egali.}$ | 49.9 | $IS_{max, foot.}$ | 8.01 |
| $R_{egali.}$ | 27.3 | $R_{foot.}$ | 8.6 |
| $RQ_{egali.}$ | 6.83 | $RQ_{foot.}$ | 2.14 |
| $UB_{A, egali.}$ | 32.30 | $UB_{A, foot.}$ | 1.74 |
| $UB_{B, egali.}$ | 39.82 | $UB_{B, foot.}$ | 4.10 |

The *IS* results for each weighting principle are presented in Figures 6 and 7. For $IS_{egali.}$, four assemblies fit the criteria for category C and 8 entities qualify in the instance of the footprint weighting principle. Category B hosts 5 entities in the egalitarian and 8 in the footprint based weighting principles. Out of these, only one assembly qualifies into category B in both principles, CLT+SW. Category A is the most numerous one for the egalitarian principle, as it hosts 9 assemblies. Contrary, for the footprint principle only the CLT+WF and CLT+EPS assemblies qualify for this category. The presented differences demonstrate something that was previously exposed in many literature references (e.g. [73], [76], [93]), namely that the weighting principle (or different set of weighting factors) can importantly affect the results interpretation. The assemblies positioned in the same categories, regardless of the adopted weighting principle, are: (i) category A – CLT+WF, (ii) category B – CLT+SW and (iii) category C – AACB+EPS, AACB+SW, RC+EPS and RC+SW. Similarities in the category qualifications also arise for the KVH:CF and KVH:fWF filigree assemblies and the KVH:fGW+WF assembly, as all are positioned in category A for the egalitarian and in category B for the footprint weighting principle.

Table 6 presents the final categorization based on the criteria presented in section 3.3.2. Category A hosts 9 assemblies: CLT+WF, CLT+EPS and all the filigree assemblies exempt the KVH:fGW assemblies combined with EPS and SW boards. These are positioned in category B, together with the remaining CLT assembly and RC+WF. All the AACB assemblies, RC+EPS and RC+SW qualify for category C. It is interesting to note that also the KVH:fWF+SW assembly qualified for category A, even though it is never positioned higher than 6th place, but also never lower than 11th place based on the PS values.

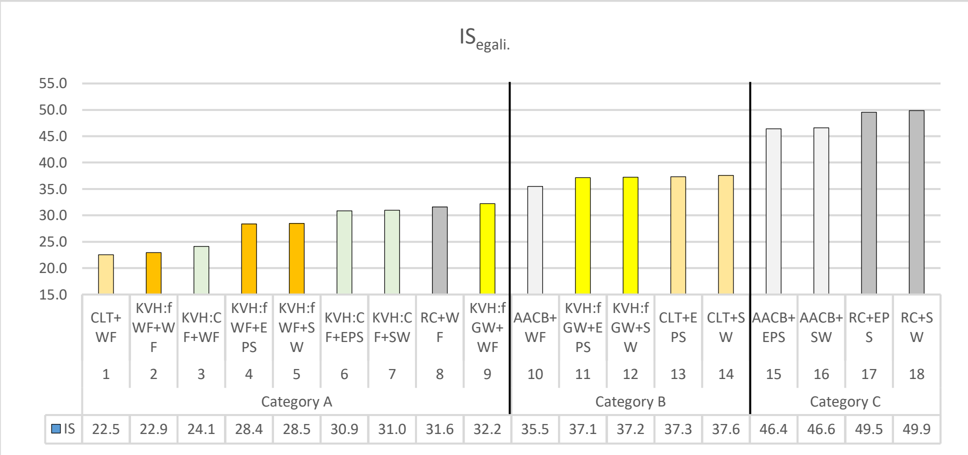


*Figure 6: Categorisation of the design alternatives in the entire population for the egalitarian weighting principle.*

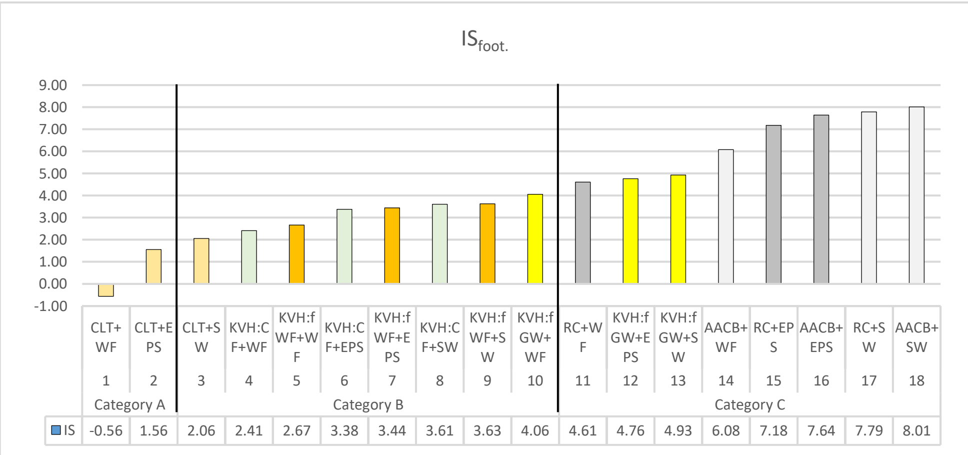


*Figure 7: Categorisation of the design alternatives in the entire population for the footprint weighting principle.*

*Table 6: Results of the soft comparative assertion method for the population group №1.*

| Category | Entity | | | |
|---|---|---|---|---|
| A | CLT+WF | KVH:fWF+WF | KVH:CF+WF | KVH:fWF+EPS |
| | KVH:fWF+SW | KVH:CF+EPS | KVH:CF+SW | KVH:fGW+WF |
| | CLT+EPS | | | |
| B | CLT+SW | RC+WF | KVH:fGW+SW | KVH:fGW+EPS |
| C | AACB+WF | AACB+EPS | AACB+SW | RC+EPS |
| | RC+SW | | | |

Based on the results of the soft comparative method presented in Table 6, the building designer can choose the preferable design alternative. Compared to the results presented in the previous section, the decision process regarding the potential environmental impacts of the design alternatives is simplified. From the *PS* values alone, it was hard to identify which assembly shows superior environmental qualities (e.g. CLT+WF, see section 5.1) and practically impossible to deduce which assemblies show comparable environmental performance. When observing many design alternatives, it is of great practical value to determine which alternatives display equivalent environmental characteristics, as this enables the building designer to choose the one that is more suitable from the standpoint of other building performance topics. The results depend solely on the observed design alternatives. Choosing a wall assembly from category A means using an entity with a lower potential environmental impact, compared to the assemblies positioned in categories B and C. As building designers have to consider many performance aspects, from this categorisation they can consciously choose an assembly from category B or C, if other design parameters are preferable. In this way, the building designers can be aware that they have sacrificed environmental aspects, in order to satisfy other building performance issues. This is in line with the philosophy behind BSAMs, as besides the environmental aspect, credits are given also to economic (e.g. life cycle costs) and social aspects (e.g. thermal, visual and acoustic comfort).

### 5.3 Soft comparative assertion – selected Group №2

In this section we demonstrate the implementation of the soft comparison assertion method on a selected group of assemblies from the entire population and evaluate how the selection of entities and the population size affect the final categorisation results. The selected assemblies are the filigree assemblies that showed similarities regarding their positioning in categories based on the weighting principles for Group №1. The resulting Group №2 contains all of the KVH:CT and KVH:fWF assemblies and the KVH:fGW+WF assembly.

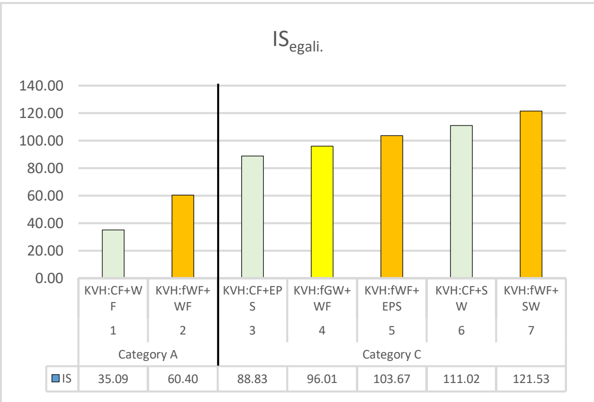


*Figure 8: Categorisation of $IS_{egali.}$ values for Group №2.*

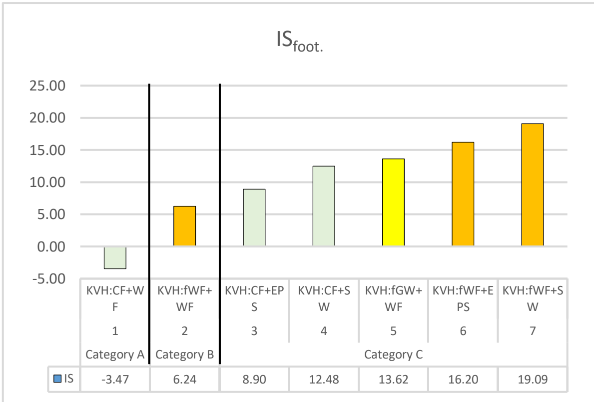


*Figure 9: Categorisation of $IS_{foot.}$ values for Group №2.*

As can be observed in Figures 8 and 9, again as in the instance of the whole population, the adopted weighting principle changes the relation between the entities and the categorisation, but not as drastically as in the case of Group №1. For $IS_{egali.}$ the entities qualify for category A and category C. As for the categorisation based in $IS_{foot.}$, the entities qualify for all three categories.

*Table 7: Results of the soft comparative assertion method for the population Group № 2.*

| Category | Entity | | | |
|---|---|---|---|---|
| A | KVH:CF+WF | KVH:fWF+WF | | |
| B | / | | | |
| C | KVH:CF+EPS | KVH:fWF+EPS | KVH:CF+SW | KVH:fWF+SW |
| | KVH:fGW+WF | | | |

The final results of the soft comparative assertion method for the Group №2 are presented in Table 7. Two of the assemblies are positioned in category A and the remaining in category C. No entities qualify for category B. The results are somewhat surprising, as based on the results of the soft comparative assertion on the initial larger population (i.e. Group №1) the observed entities qualify in the same categories, both on the *IS* level and in the final categorisation. This indicates that the selection of the population size and the entities can importantly impact the outcome of the soft comparative assertion method.

## 5.4 Soft comparative assertion – selected Group № 3

In this section, the soft comparative assertion method is presented for those entities from the whole population, which were positioned in category C for both weighting principles. These assemblies are the RC and AACB ones combined with the EPS and SW insulation boards. As in the case of Group №2, the aim is to demonstrate the soft comparative assertion method on a smaller population size and to compare the results with those for the entire population.

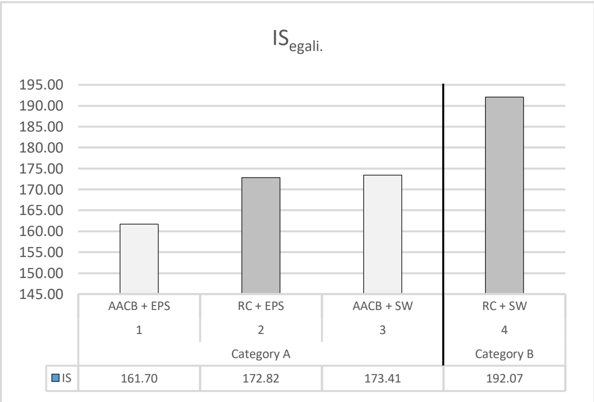


*Figure 10: Categorisation of $IS_{egali.}$ values for Group №3.*

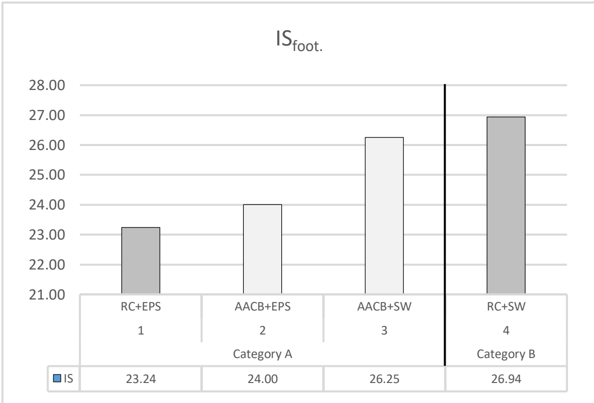


*Figure 11: Categorisation of $IS_{foot.}$ values for Group №3.*

For this population we can observe (Figures 10 and 11) a slight variation in the positions and the same qualification results for both weighting principles. The RC+SW assembly qualifies for category B for both weighting principles, whereas all the remaining assemblies are positioned in category A. Based on the criteria for the final categorisation, three entities qualify for category A and one for category B (Table 8). Thus, again, as observed for Group №2, even though the observed assemblies qualify for the same category in Group №1, when reducing the population size, they show differences in relation to their potential environmental impact.

*Table 8: Results of the soft comparative assertion method for the population Group No3.*

| Category | Entity | | |
|---|---|---|---|
| A | AACB+EPS | RC+EPS | AACB+SW |
| B | RC+SW | | |
| C | / | | |

Another aspect of the soft comparative assertion can be commented here. In the observed population, the factor accounting for uncertainties plays an important role, as none of the assemblies are positioned in category C. The *IS* range is small for both weighting principles, which consequentially causes that none of the assemblies are placed in category C, as the upper bound for category B ($UB_{B,\,j}$) is larger than $IS_{max,\,j}$. Additionally, we should mention that a situation is possible in which all the design alternatives are positioned in category A, if the upper bound for category A ($UB_{A,\,j}$) is larger than $IS_{max}$. However, this would not indicate, that all the design alternatives display superior environmental performance, but that all have comparable environmental impacts.

## 6. Discussion

Because buildings are complex systems consisting of a myriad of different components, and because modern building design is getting increasingly digitalised (e.g. the implementation of BIM), a great number of alternatives can be compared during the design process. The presented soft comparative assertion method enables the evaluation of many different design alternatives and allows the building designer to make robust and conscious decisions regarding the exerted potential environmental impacts (LCA results). This is of great significance, as EPDs are documents which communicate LCA data and do not obtain knowledge about the environmental superiority or inferiority of a product. As discussed in section 5.1, without additional guidance, the decision process is based solely on the building designer's professional judgement and personal criteria. Considering that the functionality (e.g. fire safety, seismic resistance, daylighting, etc.) and economic optimisation (project costs) of a building also play an important role in the selection of design alternatives by building designers, their decisions regarding the environmental performance are prone to subjectivity. The soft comparative assertion method can be integrated into software tools (e.g. One Click LCA [94]) to supplement the results interpretation phase. In the final results of the method, the observed entities from a population of design alternatives are arranged in three categories (A, B and C), according to the relations between their environmental impacts. The alternatives in A show superior environmental qualities compared to those positioned in B and C, whereas alternatives in category C show inferior environmental qualities compared to other alternatives in the observed population. Entities grouped in the same category can be perceived as having comparable environmental characteristics. This categorisation enables simplified decision making. Choosing an entity from category A assures the building designer that this alternative shows superior environmental qualities compared to those positioned in categories B and C. If for other reasons the designer prefers to choose an alternative from category B or even C (e.g. when designing a hospital seismic resistance, fire safety and indoor comfort are priority), the decision maker knowingly sacrificed the environmental performance in order to satisfy other building performance issues. This is in line with the sustainable design principle present in modern BSAM, as sustainability depends on the environmental, economic and social aspects of buildings and credits are given for a variety of performance topics. The above stated underlines the purpose for which the soft comparative assertion method was designed: (i) specific nature of buildings, (ii) modern building design and (iii) the concept behind BSAM.

The method adopts normalisation, weighting and categorisation, as explained in the methodology section of the paper (section 3). The aim was not to present a fully functional tool but to present a general principle of a framework, which could guide building designers when making decisions regarding environmental impacts of buildings or building elements. This is evident through the decision to build this approach on normalisation and weighting, which are controversial topics in the LCA community, and to use the range quarter and the uncertainty factor of 1.10 as criteria for splitting the population in categories. For the presented soft comparative method to become a fully functional tool applicable in building design, it needs to be substantiated through statistical studies (i.e. analysing uncertainties in LCI databases and LCIA methods, sensitivity analysis) on a large number of test populations and evaluated by various stakeholders (e.g. LCA experts, building designers, policy makers).

A minimum of two alternatives need to be compared in order for the soft comparative assertion method to work. In sections 5.3 and 5.4 it was demonstrated that the results of the presented method strongly depend on the selection of design alternatives and the population size. This can be an important shortcoming as one could choose the design alternatives with the intention to exert preferable results. This problem could be solved by integrating LCA data of a "control" design alternative in the observed population, which are based on average (or median) LCA results of products for each product category. In this way the final results of the soft comparative method would provide additional information on how the design alternative performs in regards to an alternative with average environmental performance. Another shortcoming of the presented method is that when observing a large population, many design alternatives could be positioned in one category (see section 5.2, where based on the final categorisation half of the population's entities are positioned in category A). Thus, for large populations, it could be practical to use more than three categories. This decision should again be substantiated through statistical studies that would encompass the uncertainties inherent in the EPD scheme for building products and also uncertainties inherent in the LCA method.

Considering the complexity of the LCA methods and the vast efforts that were needed to make the EPD scheme for building products work, we consider it an important shortcoming that EN 15978 [33] does not provide a method for interpreting results from EPDs. This becomes even more evident, as due to the nature of information in EPDs, in order to evaluate the environmental performance and make environmental decisions, building designers are "forced" to conduct comparative assertions. In future, LCA should become part of the building design and building designers will need guidance when working with EPDs and LCA data, as they are rarely LCA experts and the results interpretation phase is complex. With no guidance at this important step of environmental evaluation, the danger is that the results can be improperly evaluated or disregarded. Additionally, when considering the complexity of the LCA method, not addressing the results interpretation in the context of building design diminishes the relative importance, credibility and usefulness of EPDs for lowering the environmental impacts of the building sector.

## 7. Conclusion

Due to the profound impact that the construction sector has on the environment and consequently the sustainability of our society, the evaluation of environmental impacts through LCA should become an integral part of building design. Current standards and literature fail to provide sufficient guidance for conducting comparative assertions of building products, building elements and buildings as a whole, when using environmental product declarations (EPDs). In this context we presented a method for interpreting potential environmental impacts of various design alternatives in order to enable decision making for building designers.

The results demonstrated that the soft comparative assertion method significantly simplifies the decision making process. It enables evaluation of multiple design options, can be integrated into software tools to supplement the LCA results and is suitable for the building design approach in accordance with the sustainability principle inherent to building sustainability assessment methods. The method is not a fully functional tool and can be improved in order to make the decision making process more robust and less prone to subjectivity of the decision maker. Therefore, our intention was to encourage more research on the topic of interpreting LCA results in the context of building design, because this topic is still developing, while at the same time it is extremely important for lowering the environmental impact of the built environment.

**Acknowledgements**

This work was partially supported by the Slovenian Research Agency (Programme P2 – 0158) and European Union: European Regional Development Found, Research and development programmes

(TRL 3-6), Sustainable and innovative construction of smart buildings (Smart buildings and home, including wood chain: TIGR4smart, Programme C3330-16-529003).

Special thanks go also to Mitja Lakner and Marjeta Kramar Fijavž for their constructive comments regarding the mathematical formulation of the presented method.

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