BUILDING RESEARCH & INFORMATION
2024, VOL. 52, NOS. 1–2, 129–147
https://doi.org/10.1080/09613218.2023.2236254

RESEARCH ARTICLE

Making sense of LCA results when evaluating multiple building designs – comparison of interpretation concepts

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ABSTRACT

Identifying environmental hotspots and comparing design options are the most common goals in building life cycle assessment (LCA). Our paper focuses on the latter by identifying and evaluating various concepts for interpreting LCA results that can be applied when comparing multiple design options. The term LCA interpretation concept is introduced. Eight approaches were analysed and classified into three groups; (i) raw LCA data, (ii) benchmarking and (iii) single score indicator interpretation concepts. Features and attributes for making sense of LCA data were defined and used to evaluate how the investigated LCA interpretation concepts support decision-making. Finally, the results were compared and evaluated whether the applied LCA interpretation concepts could influence the designer's perception of environmental superiority. The outcomes show substantial differences in the ability of LCA interpretation concepts to support the decision-making process. Benchmarking, weighting and normalization are essential to making environmental decisions when comparing multiple design options coupled with multiple environmental indicators. Otherwise, the risk of decision-making dilemmas due to data overflow is high. Our case study with 21 design options showed that the perception of environmental superiority and inferiority may be conditioned by the selection of the LCA interpretation concept.

ARTICLE HISTORY
Received 10 May 2023
Accepted 5 July 2023

KEYWORDS
Life cycle assessment; LCA results interpretation; Building sustainability; Building design; Environmental assessment; LCA interpretation concept

Introduction

With the implementation of Directive 2018/844 of the European Parliament and Council (2018) and its predecessor (Directive, 2010/31/EU, 2010), buildings across Europe are becoming ever more energy efficient. As shown in the study by Blengini and Di Carlo, the enhanced energy efficiency of contemporary residential buildings has led to the increased environmental importance of other life cycle phases (Blengini & Di Carlo, 2010). The study concluded that the embodied environmental impact of building products, or the cradle-to-gate life cycle phase, is becoming increasingly important in residential buildings. Several other studies also addressed this phenomenon, analysing single-family (Stephan et al., 2013; Weißenberger, 2016) and multi-apartment buildings (Kovacic et al., 2018; Thormark, 2002). The common conclusion was that the embodied environmental impact of buildings is increasing due to the growing influence of building envelope materials and HVAC systems. This means that design decisions about the selection of incorporated building products are becoming ever more crucial for reducing the overall environmental impact of buildings. Therefore, a life cycle approach must be adopted as a design decision tool to reduce the environmental impact of buildings. In this context, the life cycle assessment (LCA) method is particularly suitable, as it enables the analysis of the environmental burden of products at all stages of their life cycle (Guinée, 2002).

Standards EN 15978 (2011) and ISO 21931–1 (2010) provide guidance and rules for using/ calculating LCA data and thereby provide a general framework for applying LCA in building projects. They define that when a building-level LCA analysis is performed, the already calculated LCA data for building products and processes can be used. A quality source for LCA data is environmental product declarations (EPDs), documents that communicate LCA data in the form of potential environmental impacts, resource use, hazardous substances and waste. The principles and rules for creating EPDs are standardized through ISO 14025 (2006) and EN 15804 (2019, 2013). As of March 2023, there were over 16,000 verified EPDs registered for construction products under these standards (Anderson,

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/09613218.2023.2236254.

2023). In addition to EPDs, there are also databases in accordance with EN 15804 (e.g. Ökobaudat (2022)) that provide further LCA data sources for building products and services. This indicates that data for building LCA is becoming increasingly available. Additionally, building stakeholders have shown increasing interest in adopting environmental life cycle assessment as a decision support tool. At the same time, an ever-growing number of green building rating schemes (GBRSs) include LCA as part of their evaluation framework (Sartori et al., 2021), and LCA is also being implemented into national building codes (Construction carbon regulation, 2022) (e.g. The Netherlands (Quelle-Dreuning, 2017), Sweden (Boverket, 2021) and France (Arrêté Du 4 Août, 2021)). Furthermore, Level(s), an EU-wide framework for building sustainability evaluation, incorporates LCA (Dodd et al., 2021). The above underlines that it is a realistic assumption that LCA will soon be a widely used design tool for evaluating the environmental performance of buildings.

Several LCA software tools are available to building designers (Hollberg et al., 2021; Karunaratne & Dharmarathna, 2022). With the ever-increasing digitalization of the building design process through BIM, the inclusion of LCA data and analysis in the design process is becoming simplified (Hollberg et al., 2020; Obrecht et al., 2020). An essential contribution of BIM to building design is that numerous design alternatives can be generated relatively quickly. Therefore, the environmental impacts of these alternative designs can be compared, as demonstrated by Eleftheriadis et al. (2018). The BIM-LCA integration will therefore enable to compare the environmental impact of design alternatives in a time-efficient manner. The stated is significant as the most common goals of building LCA are identifying environmental hotspots and comparing design alternatives (Hollberg et al., 2021).

In the context of the stated characteristics of the LCA framework, our study will focus on the LCA results interpretation step. Specifically, the focus will be on interpreting LCA results when comparing multiple design alternatives. The results interpretation phase of LCA is crucial and is considered complex, especially when comparing multiple entities (Zampori et al., 2016; Zanghelini et al., 2018). As a genuinely sustainable building must also consider social and economic aspects, designers must balance them to achieve specific goals of a project. There is a risk that the LCA analysis will not affect the actual design decision, as the designer cannot intuitively match the results with the architectural design (Lotte Bjerregaard & Negendahl, 2018). Therefore, it is important to ask ourselves if the current LCA framework provides sufficient guidance and if various approaches for comparing LCA results of multiple design alternatives exist.

The present study identifies and evaluates different approaches that building designers can use for environmental decision-making when comparing multiple design options. To our knowledge, this is the first attempt to systematically evaluate the LCA results interpretation step when comparing various building design alternatives. Consequently, the study is built upon an extended introduction and specific methodological approach. In the study, we (i) introduce the term LCA interpretation concept (LCA-IC), (ii) identify and analyse selected interpretation concepts, (iii) define a methodological framework for evaluating different LCA-ICs and (iv) evaluate how the selected LCA-ICs empower and condition environmental decisions. The study results are descriptive evaluations of identified LCA-ICs from a building design perspective. At its core, the study attempts to answer the question of how the selection of the LCA-IC affects environmental evaluation and supports/impedes design decisions. The explored subject is vital for decision-makers involved in implementing LCA and building stakeholders that use LCA as a design tool for reducing the environmental impact of buildings.

Problem clarification

Interpretation of LCA results in the context of building design – introducing the term LCA interpretation concept

Building LCA standards provides building designers with rules and guidance for obtaining the LCA results for a single entity (e.g. following EN 15978 and ISO 21931-1), but no guidance for interpreting the LCA results. As demonstrated in the study by Hollberg et al. (2021), no harmonized way of presenting LCA results when designing buildings exists. The authors performed a detailed presentation and systematisation of visualization types in the context of building design, which is of great value for understanding the potential of visualization in building LCA. Apart from visualization techniques, various concepts that differ in complexity can be used to interpret and compare the LCA results of multiple design options.

By the LCA interpretation concept (LCA-IC), we refer to the underlying framework (goal and scope requirements, calculation methods, guidelines) and data format, which enables the designer to make environmental decisions when comparing design

Table 1. Goal and scope requirements and characteristics of the evaluated LCA interpretation concepts (LCA-IC).

	LCA interpretation concept and concept acronym		Goal and scope requirements					Environmental indicator (number)	Characteristics						
			LIFE CAYCLE STAGES	LEVEL OF DETAIL	BUILDING TYPE	CALCULATION PERIOD	FUNCTIONAL UNIT		UNDERLYING INTERPRTATION METHOD	BENCHMARKING	NORMALISATION	WEIGHTING	SINGLE SCORE INDICATOR CALCULATION	INTENDED USE/ AUDIENCE*	source
Raw LCA data-based	Single environmental indicator	GWP	/	/	/	/	/	GWP (1)	NO	NO	NO	NO	NO	general	EN 15978 (EN 15978, 2011)
	Two environmental indicators	E&C	/	/	/	/	/	GWP, PENRT (2)	NO	NO	NO	NO	NO	general	
	Multiple environmental indicators	MEI	/	/	/	/	/	GWP, AP, EP, ODP, POCP, ADPE and ADPF (7)	NO	NO	NO	NO	NO	general	
Benchmarking	Top-down GWP	B_GWP	A1-A3, B4, B6 C3, C4	/	residential	60 years	kg CO_2-e/ (c*a)	GWP (1)	PARTIAL	YES	NO	NO	NO	research	(Hollberg et al., 2019)
	Reference LEED	B_LEED	Cradle to grave	Structure and enclosure	multiple	at least 60 years	/	GWP, ODP, AP, EP, POCP, ADPF (6)	PARTIAL	YES	NO	NO	NO	certification	(LEED v4.1, 2022)
Single score indicator	OI3	OI3	A1 – A3, B4	Multiple options	/	100 years (may vary)	Level of detail depended (e.g. m^2 construction, m^2 conditioned area, …)	GWP, AP, PENRT (3)	YES	YES	YES	YES	YES	general	(OI3, 2018)
	Soft comparative assertion method	sCA	/	/	/	/	/	GWP, ODP, AP, EP, POCP, ADPE, ADPF (7)	YES	NO	YES	YES	YES	research	(Božiček et al., 2021)
	DGNB	DGNB	A1-A3, B4, B6, C3, C4, D	Structure and enclosure	multiple	50 years	m^2NFA a	GWP, ODP, POCP, AP, EP, PENRT and PET (7)	YES	YES	YES	YES	YES	certification	(ENV1.1, 2020)

Notes: * general = various building stakeholders, research = published in scientific literature, certification = part of a specific building sustainability rating scheme; /, not declared or optional; c, capita; a, annual; NFA, net floor area.

options. Although the LCA-IC is crucial for the LCA results interpretation, it can condition the LCA study scope (see Table 1). As in the case of visualization, there is no harmonization for LCA-ICs.

Various LCA-ICs can be identified. For example, performing building LCA according to relevant standards (e.g. EN 15978) leaves designers without guidelines for interpreting LCA results. The standard defines calculation rules and requirements needed to evaluate the environmental performance; however, it does not address the interpretation phase, nor does it provide guidelines for comparative assertions in the context of building design. On the other hand, when performing LCA according to some GBRSs (e.g. DGNB (ENV1.1, 2020), LEED (LEED v4.1, 2022)), additional interpretation rules and methods complement the calculated LCA results. These provide guidance when comparing LCA results of multiple design alternatives.

The exposed issue underlines a discrepancy between building designers' decision-making abilities conditioned by the applied LCA-ICs. In the first case, the designer can rely solely on visualization techniques and cognitive input to interpret the LCA data calculated following EN 15978. As observed by Božiček et al. (2021), this can lead to a situation where the results are too complex to interpret, specifically if the LCA results comprise multiple environmental indicators. In the second case, she or he is equipped with additional interpretation criteria, benchmarks, and calculation methods (normalization, weighting), which transform the LCA results into a different data format and simplify environmental decisions. It is, therefore, of particular interest to examine different types of LCA-ICs and how they contribute to the designer's ability to make conscious and robust environmental decisions.

Study objectives and limitations

In the scope of the described problems and open questions regarding the LCA results interpretation, our study will focus on identifying different LCA-ICs and investigating their implication for the building designer's decision-making process.

The research will focus on the decisional part of the building LCA analysis, where building designers evaluate multiple design options. Therefore, the study objectives are:

(1) Identify representative building LCA-IC and systematically present and evaluate their structure and characteristics.
(2) Evaluate how the identified LCA result interpretation concepts support the building design decision process.
(3) Evaluate if the applied LCA-IC can condition the perception of environmental superiority or inferiority.

It is also important to underline what is not the intent of the study. Firstly, the scientific robustness of the presented LCA-ICs will not be evaluated and questioned. This means that we will focus on the implications for the building design decision-making process and not question the underlying calculation principles. A population of single-family buildings will be used to execute the 2nd and 3rd study objectives. The goal is not to analyse and assert the environmental performance (i.e. environmental superiority or inferiority) of the studied building design alternatives. Therefore, we will use acronyms for specific design alternatives, while detailed data from the LCA analysis will be presented in the supplementary document.

LCA interpretation concepts

As introduced above, the term LCA interpretation concept (LCA-IC) stands for the underlying framework (level of detail, life cycle stages, environmental indicators, calculation methods, guidelines) and data format, which provides the context and information based on which environmental decision-making is possible. Our study explores LCA-ICs for comparing multiple building design alternatives. The selected and presented LCA-ICs do not represent a fully exhaustive list. They should be considered as a variation of representative possibilities for interpreting building LCA results of multiple design options.

Generally, three approaches can be identified among the surveyed LCA-ICs. The first group (Raw LCA data-based interpretation concepts) consists of direct LCA results from single or multiple environmental indicators. Normalization and weighting are not used to modify the LCA results, and there are no benchmarks to which the data can be compared. The second group (Benchmarking interpretation concepts) applies a benchmark approach in which the environmental impacts of specific design alternatives are compared to a benchmark design or benchmark values. The third group (Single score indicator interpretation concepts) is characterized by using a methodology that transforms the LCA results presented with multiple environmental indicators into a single score value. This is achieved by applying normalization and weighting. The subsequent sections will present the LCA-IC for all three groups and an overview of their characteristics.

Raw LCA data-based interpretation concepts

Single environmental indicator (GWP) – description

The use of a single environmental indicator represents the most basic situation for evaluating LCA results. Evaluating the environmental performance of buildings based on global warming potential (GWP [kg CO_2 eq.]) is one of the most common approaches found in the literature (Dong et al., 2021; Röck et al., 2021). Therefore, we chose GWP as a parameter to illustrate the specifics of interpreting results based on this concept. GWP describes the radiative forcing impact of one mass-based unit of a given greenhouse gas relative to that of carbon dioxide over 100 years (EN, 15804, 2013; Stocker & Qin, 2013). The GWP indicator can be divided into three subcategories indicating the origin of greenhouse gas emissions; fossil, biogenic and land-use change (EN, 15804, 2019). The approach of accounting for biogenic carbon can greatly affect the results, which is something to consider when interpreting the LCA results (Hoxha et al., 2020; Ouellet-Plamondon et al., 2023). For the purpose of our study, we will not distinguish between emission origins and will use the total GWP indicator and consider biogenic carbon according to the −1/+1 approach.

Two environmental indicators (E&C) – description

We will use GWP as defined above and the resource use indicator for total primary non-renewable energy (PENRT [MJ]) to present the specifics of evaluating the LCA results based on two indicators. This is a common approach identified in the literature and is often referred to as ‘embodied energy and carbon (E&C)’, although the analysis may also include the building operation and end-of-life stages (Cabeza et al., 2021; Dong et al., 2021).

Multiple environmental indicators (MEI) – description

The last of the raw LCA data-based LCA-ICs implement the use of multiple environmental indicators. For this study, seven environmental indicators from EN 15804: 2013 will be used. These are GWP, ozone depletion potential (ODP [kg. R11 eq.]), photochemical ozone depletion potential (POCP [kg C_2H_4]), acidification potential (AP [kg SO_2 eq.]), eutrophication potential (EP [kg $(PO_4)^{3-}$ eq.]), abiotic depletion potential of elements (ADPE [kg Sb eq.]) and abiotic depletion potential of fossil fuels (ADPF [MJ]) The MEI approach is in line with the Levels(s) indicator 1.2, which states that in addition to GWP, the building LCA practitioners can also include other environmental indicators defined in EN 15978 for assessing environmental impacts (Dodd et al., 2021). Therefore, considering multiple indicators is a realistic proposition for building LCA practitioners.

Benchmarking interpretation concepts

Environmental benchmarks can be used as a possible solution for improving communication in LCA (Galindro et al., 2019), and countries are starting to implement limit values for construction carbon footprints (Šijanec-Zavrl & Gjerkeš, 2021). Various types of benchmarks for evaluating the environmental performance of buildings can be found in the literature (e.g. limit, reference, best practice, target, top-down, bottom-up) (Dong et al., 2021; Trigaux et al., 2021). Including all benchmarking types as a separate benchmarking LCA-IC in our study would be unpractical for the scope and purpose of the study. Therefore, we included two distinct benchmarking principles: the top-down GWP and the reference LEED approach. The first presents a variation of a single indicator target value benchmark, while the second takes a reference multiple indicator approach built upon a predefined set of evaluation criteria. Additionally, the OI3 and DGNB single-score LCA-ICs include benchmark approaches that supplement the diversity of benchmarking types covered in the study.

Top-down GWP (B_GWP) – description

The top-down GWP approach is based on target GWP values provided by Hollberg et al. (2019). The target values are defined according to SIA 2040 (SIA 2040, 2017), the Swiss roadmap to a 2000-watt society, and adapted to meet the global target of 1 t CO2-e per capita per year. The respective benchmarks for embodied, operational and total GWP impacts per building occupant are 270, 90 and 360 kgCO_2 eq. per capita per year.

Reference LEED (B_LEED) – description

The second concept is adopted in the LEED (Leadership in Energy and Environmental Design) GBRS, developed by the United States Green Building Council (USGBC, 2022). Conducting a whole building LCA to reduce environmental impact is rewarded with credits according to the LEED criteria. We will adopt the LEED v4.1 MR Path 3 method based on a 10% environmental impact reduction in at least 3 out of 6 impact categories compared to a baseline building (LEED v4.1, 2022). In addition, the impact in the remaining categories should not increase by more than 5%. The impact categories used are GWP, ODP, AP, EP, POCP and ADPF. The baseline building should be of comparable size, function, orientation and operating energy performance. For the purpose of our study, a randomly selected design alternatives will serve as the baseline building.

Single score indicator interpretation concepts

These interpretation concepts are the most complex, built around LCA goal and scope requirements and a methodological framework that transforms raw LCA data into a different data format. They are designed to assist the decision maker in environmental assertions, when comparing multiple design alternatives. The LCA data consist of multiple environmental indicators and is transformed into single score indicators by an underlying calculation methodology. This is done through normalization and weighting. Some concepts also apply benchmarking.

OI3 indicator (OI3) – description

The OI3 indicator is an environmental indicator developed by the Austrian Institute for Healthy and Ecological buildings (IBO, 2022). It is a single score indicator that combines GWP, AP and PENRT. The OI3 indicator can be calculated for different scenarios, ranging from building assemblies (e.g. external wall) to entire buildings with varying levels of detail. A detailed description of the concept and the rules for calculating the indicators can be found in the IBO guidelines (OI3, 2018).

When applying the scope defined in the IBO guidelines (i.e. 100 years, A1-A3 + B4 stages), an OI3 value below 350 indicates excellent environmental performance and a value above 800 inferior environmental performance. These values represent the best and worst practice benchmarks and supplement the results interpretation process. For clarity, the two values will be referred to as OI3 min and OI3max, respectively.

Soft comparative assertion (sCA) – description

The sCA method developed by Božiček et al. (2021) is an LCA-IC developed to guide the building designer at the results interpretation phase when evaluating multiple design options coupled with 7 midpoint environmental indicators (per EN 15804 (2013)). The method was developed with the awareness that LCA is not an exact science and that many uncertainties exist. The underlying interpretation method adopts internal normalization by sum and two weighting principles with diverse weighting factors (i.e. egalitarian and footprint). In this way, two single score results (IS_{egal}, $IS_{foot.}$) are calculated. The analysed entities are classified into three environmental categories (A, B and C) by applying mathematical formulations, considering the relative difference between calculated single score indicators and a factor accounting for uncertainties. Entities in category A show superior environmental qualities for the defined boundary conditions of the analysis, while entities in category C show the least preferable potential environmental impact. In this manner, large populations of design options can be compared, and the decision-making process is simplified for the building designer.

DGNB method (DGNB) – description

DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen) is a GBRS developed by the German Sustainable Building Council (DGNB, 2022). LCA is included in the ENV 1.1 Building life cycle assessment criteria, which is one of the six criteria for ensuring the environmental quality of buildings (DGNB System, 2022). To compare the environmental performance of multiple design options, DGNB provides a 'DGNB life cycle assessment method', which is part of the ENV 1.1 Indicator 3: Life cycle assessment comparison calculation. The method defines the LCA goal and scope, evaluating GWP, ODP, POCP, AP, EP, PENRT and the total use of primary energy (PET [MJ]) by environmental categories. The interpretation method includes two benchmarking principles (bottom-up for construction and reference for operation), normalization, which transforms the LCA results into sub-points (SP) for each environmental indicator, and weighting. A final single-score environmental indicator (SP_{TOT}) is calculated by applying weighting factors and summation of the SPs. The maximum available SP_{TOT} value is 90, and the minimum is 0. The sub-points are awarded in discreet steps of 0, 20, 40, 80 or 90. A SP_{TOT} value of 40 indicates a 'standard' performing building in accordance with national regulation or data provided in appendix 5 of the ENV 1.1 criteria description (ENV1.1, 2020). The present study used a reference energy consumption to compare the operational energy consumption. The data can be found in the supplementary materials document. A detailed description of the DGNB construction benchmarking concept can be found in Schlegl et al. (2019).

LCA goal and scope requirements and characteristics

Table 1 presents and compares the LCA-ICs included in the study with their specific goal and scope requirements and characteristics. The background and context of the presented LCA-ICs differ. As some have specific goal and scope requirements, it can be stated that besides LCA results, also the LCA study's general structure can be conditioned by the chosen LCA-IC. The B_GWP, B_LEED, OI3 and DGNB have the most detailed goal and scope requirements, whereas the raw LCA data-based approaches and the sCA method define only the number of environmental indicators. This can be linked to benchmarking, as without it you do not need to align the goal and scope to a specific context (e.g. level of detail, life cycle stages). The 'environmental indicator number' should be considered both as a LCA goal and scope requirement and LCA-IC characteristics.

The characteristics of the presented LCA-ICs determine their complexity. The three raw LCA data-based concepts have no specific characteristics. However, the number of environmental indicators varies, which significantly impacts the data format based on which the designer evaluates the results. The single-score interpretation concepts are the most complex, as all have an underlying interpretation method that defines the guidelines and calculation rules. All of them calculate a single score environmental indicator by applying normalization and weighting, which transforms the raw LCA data, calculated discretely for each environmental indicator, into single score values. The OI3 and DGNB methods also apply benchmarking, while the sCA method does not include this feature. The benchmarking approaches, B_GWP and B_LEED, can be considered to have partial underlying interpretation methods, as the guidelines and calculation rules are not at the same level of complexity as in the case of single score concepts.

Methodology

LCA goal and scope

The primary purpose of the performed LCA calculations is to evaluate the selected LCA-ICs and underline their informational value for the building designer. For this reason, we do not need to be as rigorous in the goal and scope as we would be if we wanted to meet specific LCA requirements (e.g. for DGNB criteria). A simplified building model is going to be used in order to reduce the level of complexity. The LCA results will be calculated for a single system boundary option and calculation period. As presented in Table 1, the goal and scope requirements differ. Care was taken to choose such LCA scenario that does not generate faulty requirements and that LCA results are valid for all the evaluated interpretation concepts. The stated simplifications will enable the comparison of results across different LCA-ICs.

Table 2. LCA goal and scope information.

System boundary (per EN 15978)	A1-A3, A4, B1-B5, B6, C1-C4
Background data	Gabi (Ecoinvnent when Gabi not applicable)
Environmental Indicators	GWP, AP, EP, ODP, POCP, ADPE, ADPE, PERT, PENRT, PET
Calculation period	50 years
LCA software	One Click LCA

System boundary, data and tools

Table 2 presents the basic LCA information concerning the performed calculations. The One Click LCA (One Click LCA, 2021) software was used to calculate the LCA results of each design alternative. The building geometries and envelope material compositions were initially modelled in Revit (Autodesk, 2021). Using the One Click LCA plugin in Revit, the bill of materials was exported and mapped with the corresponding LCA data. The selected system boundary and calculation period are defined to meet the DGNB requirements as much as possible, as it has the most thoroughly defined LCA requirements and one of the most complex calculation methods.

Building design: Purpose and scenario, level of detail

A population of single-family residential building variants will be used to evaluate the presented interpretation concepts. The population size and composition were chosen to represent a situation at the start of the design process, where many envelope compositions and load-bearing constructions can be considered. The building geometry is fixed and corresponds to the average dimensions of single-family buildings for which the Slovenian Environmental Public Fund (Eco Fund) (Eco Fund, 2021) provided grants in 2019 and 2020. Only the opaque external thermal envelope will be considered in the LCA analysis. The building has a rectangular floor plan of 9 by 12 m and a symmetrical double-pitched roof. The height of the building is 4.7 m at the eves and 8.1 m at the ridge. The visualization of the building design, a block diagram representing the generation of design alternatives and more detailed assembly characteristics are presented in the supplementary materials document.

For the LCA study, we also need data about operational energy demand (B6). In line with the simplifications, the assumed operational energy use for heating, cooling and lighting corresponds to average values sourced from the Eco Fund data. A conditioned area of 150 m^2 is assumed. The calculation procedure, with other building-related data, is presented in the supplementary materials document.

Framework for evaluating how LCA interpretation concepts influence decision-making

LCA-ICs will be evaluated based on their capacity to guide the decision-maker (i.e. designer) to make environmental decisions during the building design process. The population of 21 design alternatives will be used to demonstrate the positive and negative attributes of relevant LCA-IC features. These features determine the informational value of the data format and support or impede the ability to incorporate environmental decisions into the design process. In short, they enable the designer to make sense of the LCA results when comparing design options. The identified features are: (i) environmental classification expressed by ranking, and (ii) designer empowerment evaluated through the assertion of environmental superiority/inferiority and the risk of decision-making dilemmas (Table 3).

Environmental classification is the first part of results interpretation, in which the decision maker identifies the environmental impact relation in the observed population. The data format must enable ranking of design options (discrete or in groups) based on their environmental performance, to positively affect design decisions. Ranking should not be affected by the population size or the relation between entities (impact of population characteristics). If this is the case, ranking is population dependent or, in the worst case, impossible (ranking disabled).

The environmental superiority/inferiority assertion feature provides the decision maker with information about the successfulness of her/his design decisions. It is split into an internal and an external part. The internal assertion refers to the distinction of environmental impacts between the design options. It is closely linked, but not limited to, ranking, as ranking does not automatically enable qualitative assessment of environmental impact relations between the entities. There is no linear correlation between ranking and environmental impact by default. To illustrate, a design option may be ranked second but have slightly better environmental performance than the last ranked entity in a population of 10 entities, while showing considerably worse performance than the first ranked option. On the other hand, external assertion provides an environmental reference (e.g. benchmark), which is not tied to the studied population, but provides external verification of the successfulness of environmental decisions.

The last feature is of crucial importance in supporting the building design process. If the risk of decision-making dilemmas is high, then the LCA-IC can create confusion in the design process. Ideally, the designer should have a clear overview of the LCA results and should be able to relate them to other performance criteria (e.g. costs, fire safety, etc.). The decision-making risk was assessed on a five-point scale from no risk, low risk, modest risk, high risk to very high risk, with reasoning for each score. If equipped with positive attributes, the LCA-IC empowers the building designer. In this case, the environmental performance data is not an isolated data group with low utilization value but can be perceived as vital information for the building design process. However, if there is a very high risk for decision-making dilemmas, then negative attributes dominate and the designer is unable to make sense of the LCA results. Consequentially, including them into the building design process becomes difficult.

Ultimately, the LCA results will be compared among the evaluated LCA-ICs. This comparison will investigate to what degree the selection of a specific LCA-IC can influence the environmental performance perception of design options.

Methodological limitations and specifics

The methodological limitations are related to the studied population of building design alternatives and the framework for evaluating the identified LCA-ICs.

Table 3. Features and attributes for making sense of LCA data when comparing multiple building design options.

Feature			Attribute: Positive	Attribute: Negative
Environmental classification	Ranking		Enabled (discrete or grouping)	Enabled (population dependent) or Disabled
Designer Empowerment	Environmental Superiority/inferiority Assertion	Internal	Enabled (straightforward)	Enabled (complex) or Disabled
		External	Enabled	Disabled
	Risk of decision-making dilemmas		No risk, low risk	Moderate risk, high risk, very high risk

When executing a comparison between design alternatives, the structure and number of compared alternatives are important. A small population could be too monotonous and, therefore, not substantiate the implications of specific LCA-IC for environmental decision-making. On the other hand, a large population would overburden the data presentation and is also not realistic for real-world projects. Therefore, our goal was to amass a diverse population which is simultaneously built-upon realistic building design predispositions. However, unrelated to the studied population, the results for the applied LCA-ICs show one situation, although various outcomes are possible. These possibilities were also discussed and evaluated in accordance with the framework presented in Table 3.

The study results are presented descriptively in accordance with the evaluation framework of Table 3. Care has been taken to describe the results in a condensed manner. The risk of decision-making dilemmas is the most important feature, strongly related to ranking and environmental superiority/inferiority assertion attributes. It provides evaluations of the studied LCA-ICs on a five-point scale (no risk to very high risk). However, these scores are not absolute and should be viewed as orientational judgements.

Results and discussion

Making sense of LCA results – evaluating how LCA interpretation concepts support or inhibit building design decisions

Single environmental indicator (GWP) – results

Using GWP for evaluating the environmental impact of multiple design options enables straightforward ranking based on the calculated GWP value. One can easily apply simple and effective visualization techniques, such as vertical or normalized bar charts (Figure 1). The ranking is discrete and enables the ranking from best to the worst performing entity. However, the LCA data does not include any external reference (e.g. GWP benchmark), which would indicate how successful the designs are. The absence of such data poses the risk for decision dilemmas.

Two environmental indicators (E&C) – results

In the case of E&C, the PENRT environmental indicator is added to GWP, enabling the evaluation of a broader environmental profile compared to only GWP. Straightforward and discrete ranking is enabled for each indicator, respectively. However, there is no option to quickly and directly rank design alternatives simultaneously according to both environmental indicators. This inherently means that population size influences

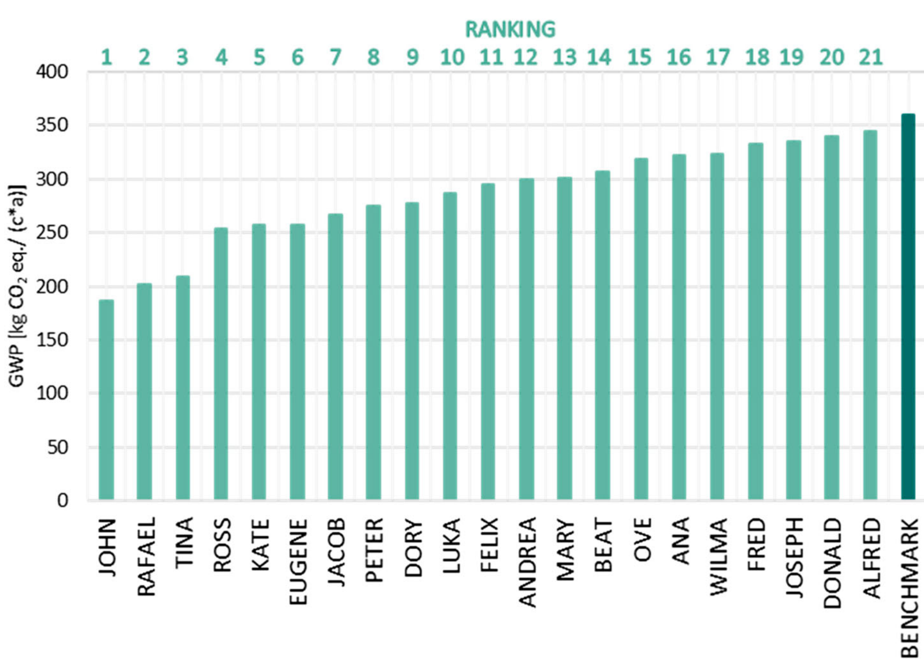

Figure 1. GWP values and ranking (from smallest to largest) for the compared design options coupled with the GWP benchmark for B_GWP. Remark: the benchmark value is added to not duplicate the figure for B_GWP and is ignored when evaluating the GWP concept.

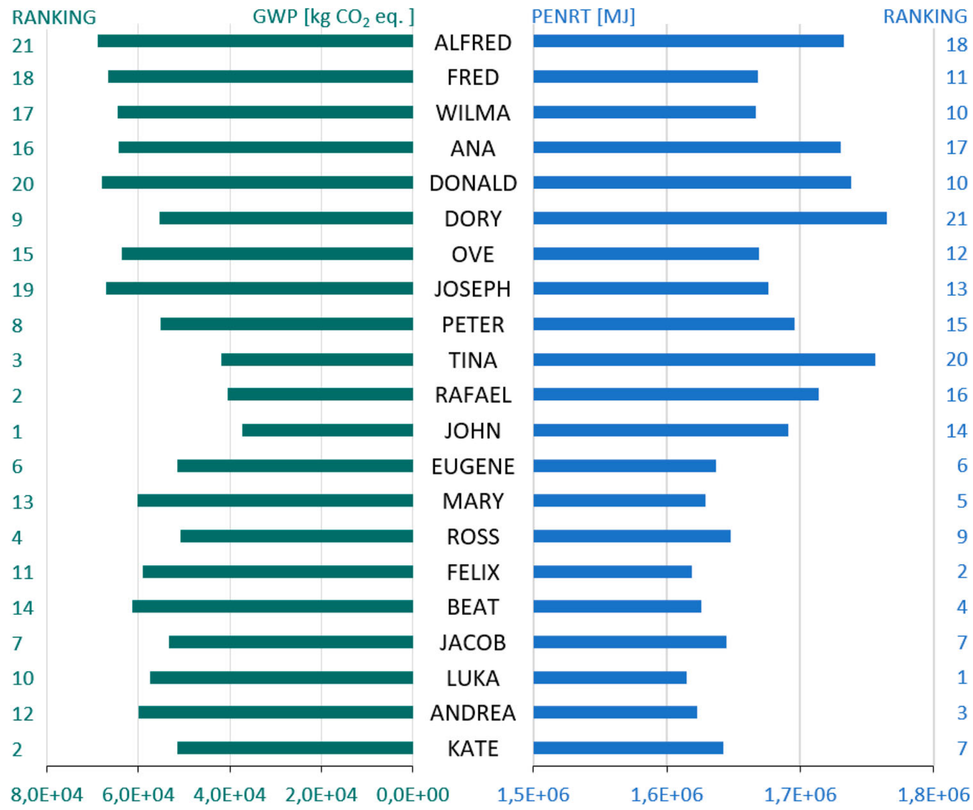

Figure 2. GWP and PENRT values and rankings for the observed population.

the complexity of environmental decisions. In other words, the larger the population size and the more significant the difference between the GWP and PENRT ranking orders, the harder it is to identify the most optimal design alternative. This issue is clearly illustrated in the case of our population (Figure 2), from which it is evident that there are substantial variations in the ranking of individual alternatives according to the GWP and PENRT indicators. Therefore, determining environmental superiority or inferiority is not straightforward and requires additional cognitive effort.

Multiple environmental indicators (MEI) – results

Evaluating multiple environmental indicators enables designers to make decisions based on a broad environmental profile. However, determining environmental superiority is challenging due to numerous environmental categories. Additional cognitive effort is

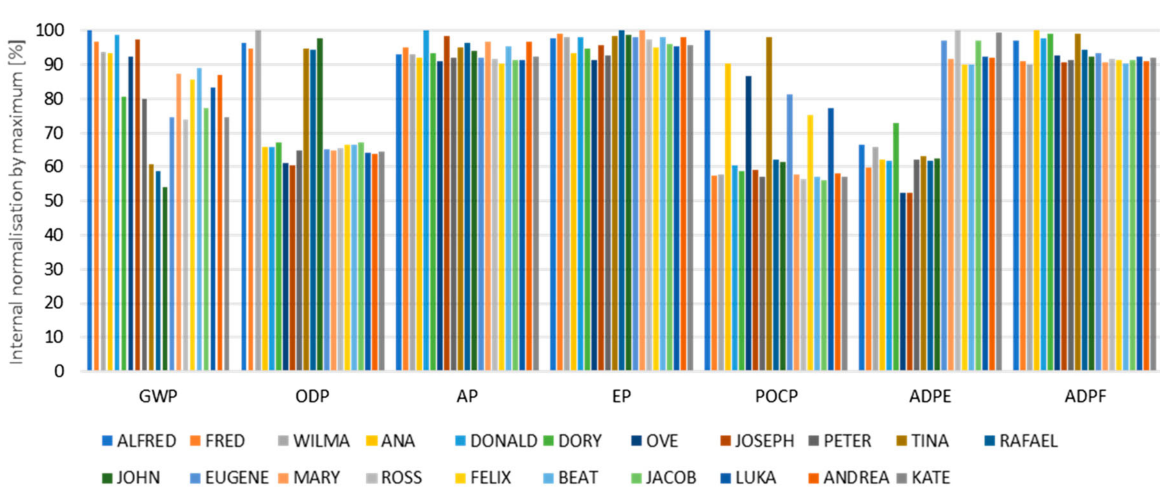

Figure 3. Comparrison of environmental impact for the MEI concept with bar charts, representing internaly normalised values (by maximum).

necessary, and without appropriate visualization techniques, comparison between design alternatives may be impossible even for small population sizes. In the case of our design population, we can observe that the relation between the entities changes from one category to another (Figure 3). In some environmental categories (e.g. AP, EP, ADPF), the relative difference between alternatives is small (i.e. below 10%). In contrast, GWP, ODP, POCP and ADPE categories exert substantial performance differences (i.e. above 40%).

Based on the above-exposed issue, it can be concluded that applying MEI as a design decision tool can be challenging, if not impossible. There is a risk that the LCA analysis will not affect the actual design decision, as the designer cannot intuitively match the results with the architectural design (Lotte Bjerregaard & Negendahl, 2018). A study by Božiček et al. (Božiček et al., 2021) provides an in-depth detailed explanation of the difficulties and challenges of evaluating the environmental impact of many design alternatives with multiple design options.

Top-down GWP (B_GWP) – results

The B_GWP approach enables identical ranking as the GWP approach, but with an important difference. In addition to a straightforward and discrete ranking of design alternatives according to the calculated GWP values, a top-down benchmark value is added. The benchmark provides external verification and informs the designer how successful the designed decisions are outside the scope of the analysed population.

In the case of our population, all of them perform better than the benchmark (Figure 1). This allows for greater flexibility in coupling the LCA results with other performance topics. Conversely, a situation where all design alternatives would be above the benchmark. In the latter case, the designer receives information that the design has to be improved. Finally, the benchmark can split the population into two groups, which narrows down the number of design options that comply with the defined limit. From a design perspective, a smaller number of options can simplify decision-making.

Reference LEED (B_LEED) – results

In the B_LEED approach, the baseline building was chosen randomly from the population of 21 options. The remaining design alternatives are then compared to the baseline and evaluated using simple 'YES-NO' filtering, based on the LEED criteria.

As with the B_GWP approach, three outcomes are possible, two extremes where all or none perform better than the benchmark and the third where the population is split into two groups. The latter situation occurred in our test population of 21 design alternatives, as 9 design options did not fulfil the criteria and 11 did (Table S4 in supplementary materials and Figure 6). However, a significant difference compared to the B_GWP concept is that a much broader environmental profile is evaluated, but no discrete ranking is enabled. Therefore, environmental superiority or inferiority assertion is not as straightforward as in B_GWP. In order to identify the environmental impact relationships between the various design options (internal assertion of environmental superiority), additional cognitive effort and visualization techniques are needed. By doing this, a complex situation occurs (described for the MEI concept), as the LCA results comprise six environmental categories. This increases the risk for decision dilemmas. The full results for the B_LEED concept are presented in the supplementary materials document.

OI3 indicator (OI3) – results

The OI3 indicator enables the discrete ranking of alternatives based on the calculated indicator values. The smaller the OI3 value, the better the environmental performance. Furthermore, the OI3 indicator also includes an upper ($OI3_{max}$) and lower ($OI3_{min}$) boundaries indicating environmental successfulness (upper and lower benchmark limits). As the goal and scope for calculating the LCA results differ from the IBO guidelines, we used hypothetical benchmark values of 600 ($OI3_{min}$) and 1500 ($OI3_{max}$).

Compared to B_GWP and B_LEED, adding an upper external reference improves informational value. This approach enables more effortless decision-making when coupling the design's environmental and other performance aspects. The issue can be illustrated by the example of our population (Figure 4), where it becomes apparent that the environmental impact of the studied design options is close to the lower benchmark value. This information could signal to the designer that other building performance topics may be more detrimental to the overall building performance. Due to the above-stated features, the risk of decision-making dilemmas is low. However, additional guidelines and cut-off rules for results interpretation would be valuable and make decisions less ambiguous. One such cut-off rule could be a minimal OI3 range, at which the value difference could be perceived as so small that it fits within the data uncertainty range. Such a rule would be beneficial for our situation, where the difference between the population's minimum and maximum is only 8.6 percentage points.

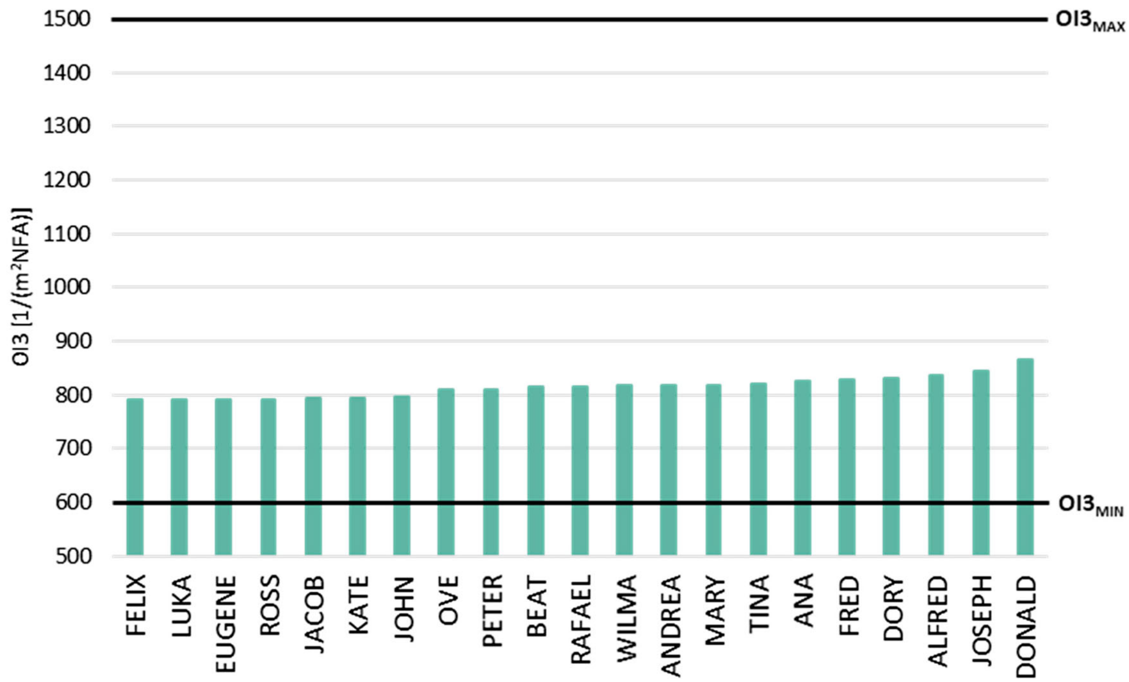

Figure 4. OI3 values (smallest to largest) for the compared design options, coupled with upper and lower benchmark limits.

Table 4. Categorization of design options in three groups, based on the sCA categorization criteria.

A					B	C
FRED	DORY	TINA	MARY	JACOB		ALFRED
WILMA	OVE	RAFAEL	ROSS	LUKA		
ANA	JOSEPH	JOHN	FELIX	ANDREA		
DONALD	PETER	EUGENE	BEAT	KATE		

Soft comparative assertion (sCA) – results

For the 21 design alternatives, the sCA methods underlying mathematical formulations and categorization criteria result in only one design option being ranked in category C (i.e. worst performing). In contrast, all others are ranked in category A (i.e. best performing), while category B is empty (Table 4). Such results convey to the designer that entities in category A have comparable environmental performance and that the entity in category C is environmentally inferior. Based on the results, the designer may conclude that other performance topics, not environmental ones, may be more detrimental to the selection of design alternatives. The full results, including a short comment on challenges due to ranking in categories, are presented in the supplementary materials document.

Other outcomes are possible, such as that all design options are classified in group A or split among the three categories. The categorization of multiple design options in groups, implemented by the sCA approach, can benefit the design process. It simplifies the interpretation of the results and enables straightforward assertion of environmental superiority. As the underlying interpretation method is designed to provide final results, no additional cognitive effort is needed to evaluate the results (e.g. as in the case of the OI3 indicator). However, this cannot be stated for the external assertion of environmental successfulness, as the sCA method considers only the relation between the environmental impacts of the design options in the population. No environmental benchmarks are included in the method. Therefore, the designer receives no information about whether designs in category A can be perceived as environmentally successful outside the scope of the studied population. This creates a risk of decision-making dilemmas.

DGNB method (DGNB) – results

The DGNB method with its calculated SP_{TOT} values enables straightforward and discrete ranking of compared design alternatives. Contrary to the OI3 indicator, a higher SP_{TOT} value indicates superior environmental performance. For our study population, the entities are split into 5 groups with identical SP_{TOT} values (Figure 5). The calculated values are: 76 (6 entities), 72 (3 entities), 70 (6 entities), 66 (5 entities) and 62 (1 entity). From a designer's perspective, the aggregation into groups can be beneficial as it allows more freedom in selecting the final design from a group with the same environmental performance. Similar to OI3, the designer has external references to evaluate the environmental successfulness. In addition to the upper and

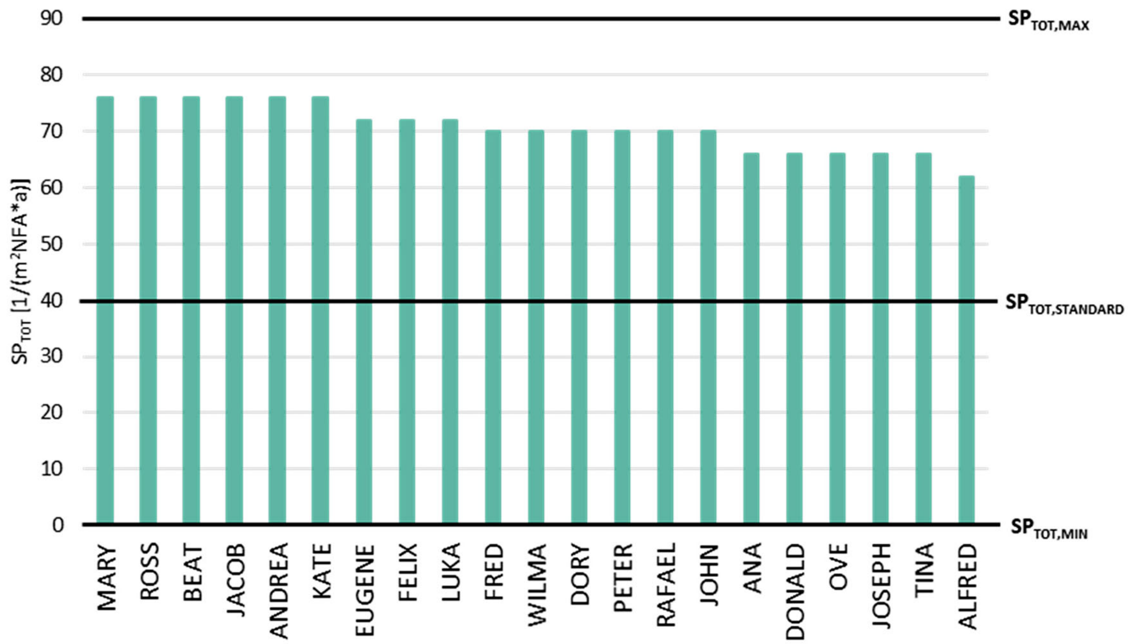

Figure 5. SP_{TOT} values (largest to smallest) for the compared design options, coupled with external reference values.

lower limits ($SP_{TOT,MAX}$ and $SP_{TOT,MIN}$) a value of 40 ($SP_{TOT,STANDARD}$) indicates environmental performance in accordance with standard building practice. Therefore, values above 40 signal environmental superiority compared to standard building design.

The above stated confirms that the DGNB method consists predominantly of positive attributes, as it enables ranking and internal/external environmental superiority assertion. Therefore, the risk of decision dilemmas is low. However, as in the case of OI3, additional guidelines and cut-off rules for results interpretation would be valuable for unambiguous decision-making. For example, in the scope of our case study, it would be beneficial to know whether the difference of 2 SP points between the third and second groups of alternatives is significant or whether it is inside the margin of data uncertainty.

Comparison of design supporting features of LCA interpretation concepts

Table 5 presents the main attributes of the investigated LCA–ICs that determine the ability to make sense of the LCA data when analysing multiple design options. It is built upon the definition of positive and negative attributes of the features presented in Table 3 and also proposes the characteristics of a hypothetical ideal LCA-IC. The main findings can be condensed into the following bullet points:

- Results show that ranking can be challenging even for the E&C concept, where only two environmental indicators are used. If multiple environmental indicators compose the LCA results, they need to be transformed into a single score indicator to enable ranking. OI3, sCA, and DGNB concepts do this by applying normalization and weighting (see Table 1).
- The internal environmental superiority assertion is straightforward for all LCA-ICs that enable ranking. The B_LEED benchmark concept is unique in that it does not enable ranking, but the internal environmental assertion can be considered straightforward.
- Benchmarks enable external assertion of environmental superiority. Therefore, all LCA–ICs with benchmarks have positive attributes for this feature (B_GWP, B_LEED, OI3 and DGNB). Benchmarking is vital for empowering designers, as it provides an external reference for the calculated results.
- Besides the inclusion of benchmarks, it is also essential to determine how many and what types are included in the LCA–IC structure. The results showed that more than one benchmark (see OI3 and DGNB results) provides better decision-making abilities than using a single benchmark reference.
- LCA-ICs with negative attributes for ranking and/or environmental superiority assertion features show a modest to very high risk of decision-making dilemmas.

When assessing the risk of decision-making dilemmas, all LCA-ICs in the raw LCA data-based group and B_LEED were assessed as having modest to very high risk. Such assessment is based on the negative attributes of these LCA-ICs concerning environmental classification and superiority/inferiority assertion (see

Table 5. Evaluation of LCA interpretation concepts (LCA-IC) for comparing multiple building design options.

		Environmental classification		Designer empowerment			
				Environmental superiority/ Inferiority assertion		Risk of decision-making dilemmas	
LCA-IC group	LCA-IC	Population impact	Ranking	Internal	External	Assessment	Rationale (+/−)
Raw LCA data-based	GWP	No	Enabled, discrete	Straightforward	Disabled	Modest risk	+ Ranking enabled, enabled straightforward internal assertion. − External assertion of environmental superiority disabled.
	E & C	Yes	Population dependent	Complex	Disabled	High risk	− Complex internal and disabled external assertion of environmental superiority.
	MEI	Yes	Population dependent/ disabled	Disabled	Disabled	Very high risk	− The results structure disables decision-making as they are to complex, disabled internal and external assertion (only negative attributes).
Benchmarking	B_GWP	No	Enabled, discrete	Straightforward	Enabled	Low risk	+ Ranking enabled, enabled straightforward internal and external assertion. − Additional benchmarks (e.g. upper limit) and cut-off rules would benefit the decision-making process.
	B_LEED	Yes	Disabled	Straightforward/ complex	Enabled	Modest to high risk	+ External assertion enabled. − Ranking disabled, internal assertion straightforward only in comparison to the baseline building. More detailed internal assertion is very complex.
Single score indicator	OI3	No	Enabled, discrete	Straightforward	Enabled	Low risk	+ Ranking enabled, enabled straightforward internal and external assertion (two benchmarks). − Additional cut-off rules would benefit the decision-making process.
	sCA	No	Enabled, grouping	Straightforward	Disabled	Low to modest risk	+ Ranking enabled, enabled straightforward internal assertion. − External assertion of environmental superiority disabled.
	DGNB	No	Enabled, discrete (grouping)	Straightforward	Enabled	Low risk	+ Ranking enabled, enabled straightforward internal and external assertion (three benchmarks). − Additional cut-off rules would benefit the decision-making process.
	IDEAL CONCEPT	No	Enabled (discrete or by grouping)	Straightforward	Enabled	No risk	The interpretation concept is designed to eliminate the possibilities for decision-making dilemmas.

the rationale in Table 5). The OI3, B_GWP and DGNB concepts were assessed as having the lowest risk of decision-making dilemmas. The OI3 benchmarks define limits for both environmental superiority ($OI3_{min}$) and inferiority ($OI3_{max}$), while DGNB adds a third benchmark that represents the environmental performance of a standard practice building. Nevertheless, additional cut-off rules would benefit the decision-making process of the OI3 and DGNB concepts and eliminate the risk of dilemmas. For example, the question remains if a difference of 8.6 percentage points between the population's minimum and maximum in OI3 values or a difference in 2 SP_{TOT} is small enough to be in the margin of data uncertainty and, therefore, insignificant. Finally, the risk of decision-making dilemmas in sCA and GWP was assessed as modest because both enable ranking and internal environmental assertion but lack external benchmarks. However, sCA is the only LCA-IC that provides a data format, eliminating the need for additional cognitive effort when identifying the environmental hierarchy in the population of design options. This is done by ranking in groups that communicate environmental performance. As LCA is subject to many uncertainties (Finnveden et al., 2009; Igos et al., 2019), merging design options in groups may be more suitable for presenting LCA results than discrete ranking.

An ideal LCA interpretation concept would eliminate the risk of decision-making dilemmas and support the building design process. The evaluated LCA-ICs showed various options for interpreting LCA data. Combining positive attributes of different LCA-ICs could be a good foundation for designing a no-risk LCA-IC. In the case of GWP, results showed that more than one benchmark coupled with guidelines and cut-off rules for results interpretation would improve the decision-making process and eliminate the risk of decision-making dilemmas. However, selecting a benchmark is not trivial, as there are multiple benchmarking approaches with different benchmark values (Dong et al., 2021; Trigaux et al., 2021). Also, as displayed in Table 1, using benchmarks for LCA results leads to predefined LCA goal and scope requirements. In this way, the LCA-IC also conditions the general LCA structure.

If LCA results comprise more than one environmental indicator, only single score indicator concepts are suitable for efficient results interpretation. In our study, these had the lowest risk of decision-making dilemmas and were best suited for interpreting LCA results of multiple design options. However, as they apply normalization and weighting, how this is performed is not trivial. Normalization and weighting are controversial topics in the LCA community due to their potential biases and value choices (Pizzol et al., 2017). Additionally, they can influence the perception of environmental superiority and the interpretation of LCA results (Anderson, 2023). This issue can also be observed in intermediate sCA results presented in the supplementary materials document (Figures S6 and S7).

Comparing the perception of environmental superiority or inferiority

Figure 6 presents a parallel coordinates chart for the B_GWP, OI3, DGNB, sCA and B_LEED interpretation concepts. The comparison aims to evaluate whether different LCA-ICs provide a matching perception of environmental superiority or inferiority of the analysed design options.

Comparing the B_GWP indicator to others demonstrates that some designs with a high rank (i.e. superior environmental quality) according to GWP are not best performing according to other LCA-ICs. For instance, the best-performing entity according to GWP (JOHN) is positioned 7th according to OI3 and in the third group according to DGNB. Another interesting observation can be made when focusing on the baseline design option (ALFRED) for the B_LEED concept. According to the sCA, DGNB and GWP concepts, this design option shows the worst environmental performance. Nevertheless, 9 design options are classified as having inferior environmental performance according to B_LEED criteria. Among them are also the best-performing ones according to GWP (e.g. JOHN).

The abovementioned issues highlight that selecting an LCA-IC can affect the perception of environmental superiority and consequentially environmental decisions. Although alignment in the results can be observed, particularly between the single score concepts and when benchmarks are considered, the differences between LCA-ICs can be substantial. Interesting are the differences between the B_GWP concept and other LCA-ICs. This may be a coincidence resulting from the characteristics of the analysed population but should be further investigated, as GWP is the most often used LCA metric for evaluating the environmental performance of buildings (Dong et al., 2021; Röck et al., 2021). Previous studies have identified limitations when using carbon footprint for evaluating environmental sustainability because of the risk of shifting environmental burdens (Laurent et al., 2012). The influence of biogenic carbon accounting has also been underlined in previous studies, as it can importantly influence the results (Hoxha et al., 2020; Ouellet-Plamondon et al., 2023).

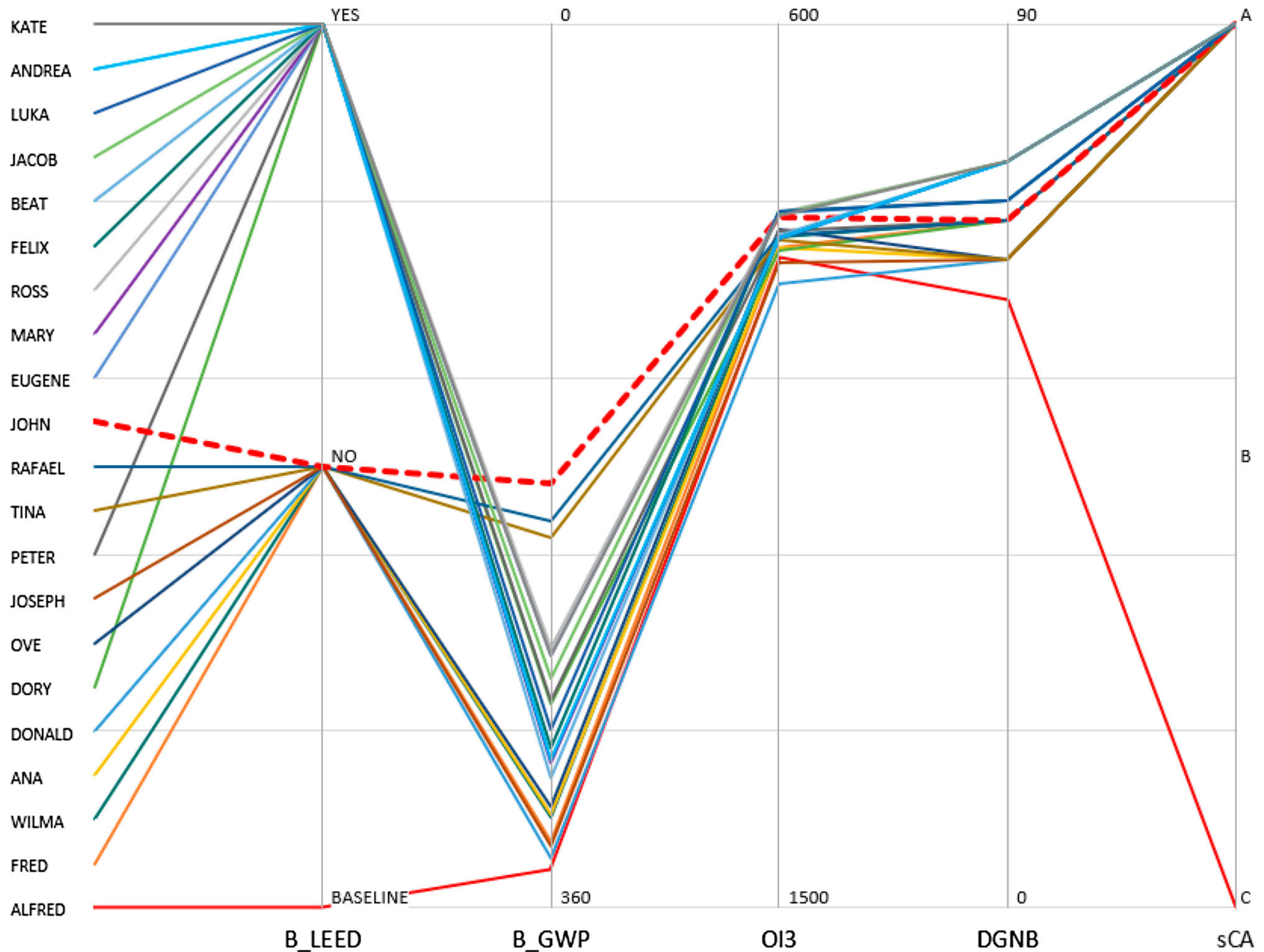

Figure 6. Parallel coordinate chart comparing the results of LEED, GWP, OI3, DGNB and sCA interpretation concepts. Red lines indicate the highest (JOHN – dashed) and lowest (ALFRED – solid) ranked design options according to GWP. The results for B_GWP, OI3 and DGNB are plotted in relation to benchmark limits.

Conclusions

As the building industry strives for greater sustainability of the built environment, LCA is becoming a central tool for achieving this objective. Therefore, building stakeholders need a robust and consistent approach to incorporate LCA into the design process. The executed study can be of value in this respect, as it presents the complexity of interpreting LCA results of multiple building design options and highlights the pros and cons of different interpretation concepts. The primary study findings are:

- When comparing design options, there is a high risk of decision-making dilemmas due to data overflow if LCA results are comprised of multiple environmental indicators.
- Generally, it could be concluded that a single environmental indicator supported with appropriate benchmarks presents the most suitable data format for design decision-making. The results for the single score indicators (DGNB, OI3, sCA) and the benchmark supported global warming (B_GWP) revealed that additional interpretation guidelines (i.e. cut of rules) would benefit the decision process and further reduce the risk of decision-making dilemmas.
- Multiple benchmarks are beneficial as they provide a broader context for the environmental successfulness of evaluated designs.
- Instead of discrete ranking, ranking design options in groups/categories representing equivalent environmental performance (e.g. the sCA approach) could benefit the decision-making process, as it can reduce the need for cognitive input and simplify the matching of environmental results with other building performance topics
- The LCA-IC can condition the perception of the environmental superiority of compared design options.

Implementing LCA should add value to the building design process, not confusion. It is vital that LCA results complement the design process when evaluating multiple design alternatives. Otherwise, a risk exists that the LCA analysis will not affect the actual design decision, as the designer cannot match the results with the design and other building performance topics. Although our study managed to identify the characteristics of the evaluated LCA interpretation concepts and, based on these, indicate what an ideal one should provide to the decision maker. It is still unclear what concept is best suited for the building design process, as many questions remain open (e.g. the number of environmental indicators, benchmarking, normalization approach and weighting factors). Currently, the LCA results interpretation phase is not sufficiently covered in relevant building LCA standards (e.g. EN 15978). The exposed issues need to be resolved to facilitate unambiguous decision-making when evaluating the environmental performance of building design alternatives in practice.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This paper was supported by the Slovenian Research and Innovation Agency as part of the bilateral research project (No. N2 – 0258) between the Czech Republic and the Republic of Slovenia. The last author further acknowledges the financial support from the Slovenian Research and Innovation Agency (research core funding No. P2 – 0158).

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