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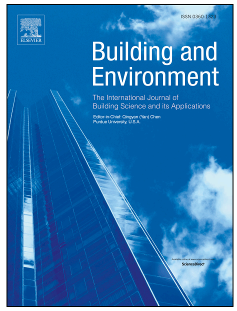

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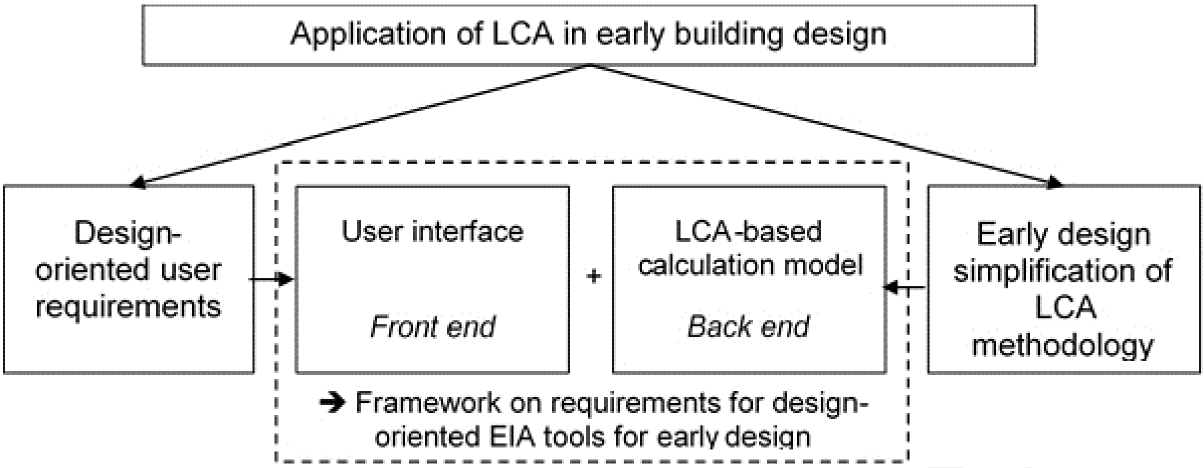

Application of LCA in early building design
Design-oriented user requirements
User interface
Front end
+
LCA-based calculation model
Back end
Early design simplification of LCA methodology
➔ Framework on requirements for design-oriented EIA tools for early design

REQUIREMENTS FOR APPLYING LCA-BASED ENVIRONMENTAL IMPACT ASSESSMENT TOOLS IN THE EARLY STAGES OF BUILDING DESIGN

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Abstract

Life Cycle Assessment (LCA) is considered as the most suitable way to assess the environmental impact of buildings. Due to its extensiveness and complexity, but also due to a lack of knowledge amongst architects, the LCA methodology is currently most often applied as a post-design evaluation and not used to support or optimize design decisions during early design stages. Therefore, this paper looks at possible solutions to apply LCA, including operational energy demand simulation, in early design from two different perspectives: design-oriented user requirements, derived from literature, a survey, interviews and a focus group with architects, and LCA simplification strategies based on a literature review. Both perspectives are discussed and merged into an evaluation framework that can be used to check the suitability of LCA-based environmental impact assessment (EIA) tools for use by architects during early design stages, but also to develop new design-supportive LCA-based EIA tools. In turn, this can contribute to an increased uptake of these tools in building practice.

Keywords: architect; BIM; LCA; computational tools; design support; user-friendliness

1 LCA in the building sector

1.1 Context

The building sector is very resource-intensive; approximately 50% of Europe's processed raw materials are used for construction and about 30% of the waste is generated during construction and demolition [1]. Additionally, buildings account for more than 40% of the world's primary energy demand and one third of greenhouse gas emissions [2]. Since the 1980s, the focus of many national regulations and incentives was on lowering the operational energy demand of buildings in order to achieve more energy efficient buildings. These regulations have been increasingly tightened, leading to 'nearly zero energy buildings' (NZEB), amongst others, as stipulated by the European Energy Performance of Buildings Directive (EPBD) [3]. According to Passer, Kreiner, and Maydl [4], energy optimization measures for the use phase in low-energy buildings have reached the limit of what can be achieved.

Therefore, the focus of sustainable construction is broadening by considering not only the operational phase of a building, but also the energy demand, resources, emissions and waste from construction, maintenance and the end-of-life stage of buildings as well. In research, the assessment of the environmental impact of buildings over the entire life cycle is already common practice, but there is a growing share of initiatives that aim to stimulate the implementation of environmental impact assessment (EIA) into everyday design and construction practice (e.g. Roadmap to resource efficient Europe [5]).

There are various types of EIA tools for quantifying environmental sustainability [6]. Out of these tools, Life Cycle Assessment (LCA) is the only internationally standardized method and widely employed. LCA is considered as the most suitable and objective assessment method to quantify the energy and resource consumption, emission and waste generation and the environmental impacts of a building over its whole life cycle [7]. In addition, more and more countries are developing EIA tools using LCA. Therefore, the focus of the paper is on LCA-based EIA tools.

1.2 Challenges of implementing LCA in building practice

1.2.1 Application of the LCA methodology on a building level

In comparison to the LCA of consumer products, there are a number of challenges for LCA on a building level [8–11]. Firstly, the long life span of buildings, which can last over one hundred years, introduces a high degree of uncertainty, especially regarding the use phase (due to refurbishments, occupant behaviour, consumption patterns, etc.) and the end-of-life (EOL) treatment of the building. Secondly, buildings are usually unique designs which makes standardization difficult and causes the need for an LCA of each individual building [10]. Over the past years, the standards EN 15804:2012 on Environmental Product Declarations or EPDs [12] and EN 15978:2011 on the assessment of the environmental performance of buildings [13] were initiated to create a framework for standardization of life cycle assessments of building products and buildings as a whole. However, different interpretations of and additions to these standards can still be made by individual EU member states. In addition, for now, environmental data are not yet available for all materials. Each year, the number of environmental product declarations (EPDs) increases and national databases such as ökobau.dat [14] are established and extended. However, the declared life cycle modules often vary from one EPD to the other; databases of different countries apply different assumptions and scenarios in the background and often employ different environmental indicators. To facilitate the application in building practice, further harmonization of EPDs on a European level is needed [15,16].

1.2.2 Usability of the LCA methodology in building practice: EIA tools and their application

Various Environmental Impact Assessment (EIA) software tools already exist or are under development to facilitate the LCA of buildings (e.g. eLCA tool in Germany [17]; LCAbyd in Denmark [18]; eco2soft/baubook in Austria [19]; MRPI-MPG Freetool [20] in the Netherlands; novaEQUER [21] in France; MMG tool [22] in Belgium). Reviews and comparisons of LCA-based EIA tools can be found in literature [23–26]. In most tools, the focus is on embodied impact of the materials. However, a few tools integrate the calculation of the operational energy demand (often in a simplified way) to provide a full LCA. With the right functional unit, additional important aspects such as compactness, size and durability are also considered in LCA.

Since most tools have been developed for a post-construction evaluation of the building by engineers or LCA experts, many of these tools are mainly applied in scientific research [27,28] and the uptake of these tools in design practice is still very limited. Reasons for this lack of application of LCA-based EIA tools in design practice were already explored in literature (e.g. [28–31]) and can be classified into two main categories: 1) user-related problems which are inherent to the conventional application of the LCA methodology and 2) the lack of external triggers to perform an LCA-based EIA.

User-related problems (for non-LCA experts such as architects) are for instance the complexity of the assessment, the detailed information on building materials and systems that is necessary to perform the assessment, the time and labour intensity of the assessment and the fact that often an extensive knowledge on the methodology is needed to correctly perform an LCA [28,29], which architects do not have [30]. For instance, buildings usually consist of many different building materials, which makes the establishment of a very detailed bill of quantities (BOQ), needed for conventional LCA applications, a laborious task. In addition, the results of an LCA consist of a complex set of numerical values for the environmental impact indicators and a report with all assumptions etc. made during the assessment, which makes interpretation of the results by non-experts difficult, especially if no reference or benchmark for comparison is available.

Additionally, external triggers such as clients' demand, government incentives or a regulatory obligation are often still lacking [32]. Within some voluntary building certification schemes, such as DGNB [33], BNB [34], BNK [35] or MinergieEco [36], an LCA-based impact assessment is already mandatory, while others, such as LEED [37] or BREEAM [38], award additional credits for performing an LCA. Since 2011, all buildings commissioned by the German Federal Government have to be certified with BNB which includes an assessment by means of a simplified LCA [39]. The Chamber of Architects of Baden-Württemberg (Germany) and the German Sustainable Building Council also want to integrate an LCA-based assessment in the national regulatory framework [40,41]. In the Netherlands, an LCA-based impact assessment is required since 2013 upon building permit application of small-scale projects such as dwellings and offices. From 2018 on, these calculations also have to meet a certain benchmark [42].

1.3 Need for application of LCA-based EIA in early design

As an LCA-based EIA might become part of the building permit request in the near future, it will likely be added to the architects' task package. Since most architects work in small-scale offices in many European countries (e.g. Belgium [43], Germany [44], and the Netherlands [45]), they largely rely on their own knowledge and expertise to make design decisions prior to the building permit request, in interplay with the client [46,47]. This in contrast to large-scale architectural offices, who have the ability to work in a construction team together with structural engineers, energy and environmental specialists, etc. from early design on.

In the earliest stage of building design (pre-design and concept design phase), different design solutions are often compared and influential decisions are made [48,49]. As, by designing, architects define (mostly implicitly and unknowingly) the environmental impact of a building over its whole life cycle to a great extent, it is expected that for EIA, this need for (early) design feedback will be similar to that with regard to the energy performance. Therefore, an EIA can provide valuable decision supportive information to architects during these early stages. However, in early design, the availability of information, both on the buildings' geometry and materials, is often still limited. In addition, all afore mentioned thresholds regarding the application of the LCA methodology itself (e.g. labour and time intensiveness, extra effort and costs, complexity, etc.) must also be overcome to allow architects to perform an LCA-based EIA in early design, since their knowledge level on and familiarity with such tools is limited.

In an attempt to solve these issues regarding the need for the application of an LCA-based EIA in early design, the following research questions are explored in this paper:

1) What are the user requirements to make an LCA-based EIA tool suited for application by architects in early design stages?
2) How can the LCA methodology be simplified and the calculation be parametrized to become more usable by architects in early design stages?
3) Are these user requirements and LCA simplifications compatible, so that they can serve as a starting point for the development of simplified LCA-based EIA tools for architects in early design?

2 Methods

In this paper, a framework with requirements for LCA-based EIA application in early design is developed from two different perspectives (Figure 1): 1) user requirements for 'architect-friendly' LCA-based EIA tools (i.e. usable by architects during the early stages of the design process); 2) criteria for simplifying the LCA methodology and parametrizing the calculation method in order to make it more applicable in an EIA software tool during the early stages of the design process. This framework can be used to evaluate (future) LCA-based EIA tools on their suitability for application by architects in the early design stages and to develop new, design-integrated, LCA-based EIA tools.

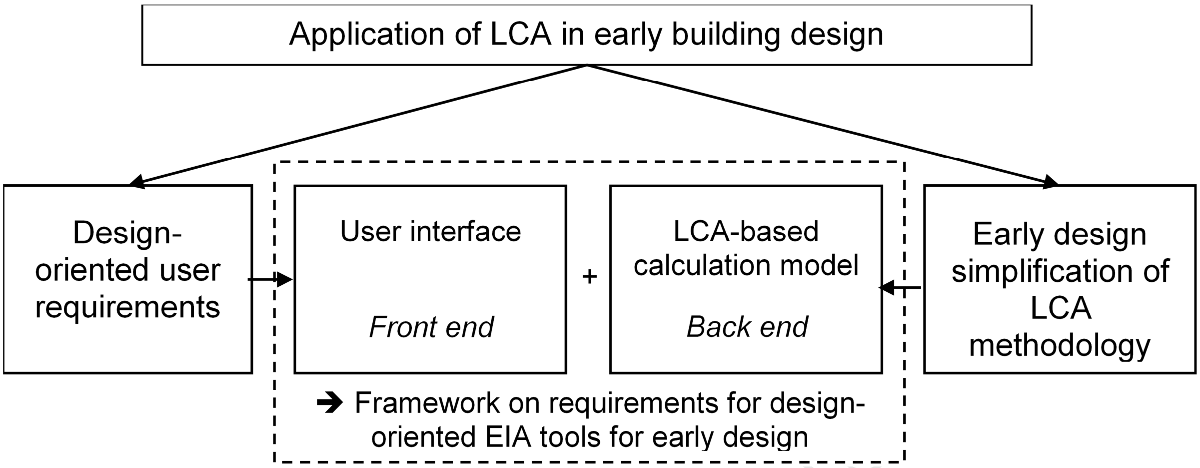

Figure 1: Methodological approach for the framework development (Black and white, 2 columns)

2.1 Design-oriented user requirements

Since numerous studies have already investigated user requirements of architects for energy performance simulation tools [46,50–55], an existing framework with requirements for architect-friendly energy performance tools by Weytjens and Verbeeck [46] is used as a starting point for the establishment of user requirements. Some of these requirements are directly applicable in the context of EIA, e.g. the need for default values to replace unknown design data in early design stages. However, due to the specific nature of EIA, a revision and adaptation of user-related criteria to the context of building EIA is needed, especially with regard to the input and output data and calculation methodology of an LCA-based impact assessment. Based on a large-scale survey (N=364), semi-structured interviews (N=5) and a focus group with architects (N=12), 43 criteria on architect-friendliness of EIA tools for early design are established and used here in the evaluation framework. A detailed description of the subsequent steps of the framework development can be found in [56].

2.2 Early design simplification of the LCA methodology

The methodological LCA simplifications are based on a literature review of the state of the art regarding simplifications of LCA. Most methodological simplifications are derived from the

EeBGuide [57], with some diversions where necessary. Three increasing levels of detail are defined: screening, simplified and complete LCA. Screening LCA is intended for application for the pre-design and concept design phase. Simplified LCA aligns with the requirements in building certifications, such as DGNB [33], BNK [35] and BNB [34] and can be employed in the developed or detailed design phase and the building permit phase. The level of detail of these LCA types follows the level of detail and information available in the design process, see Figure 2, especially with regard to the specification of the material-related information (from rudimentary material category information in the earliest design stages to more detailed product information by the developed design stage [58]).

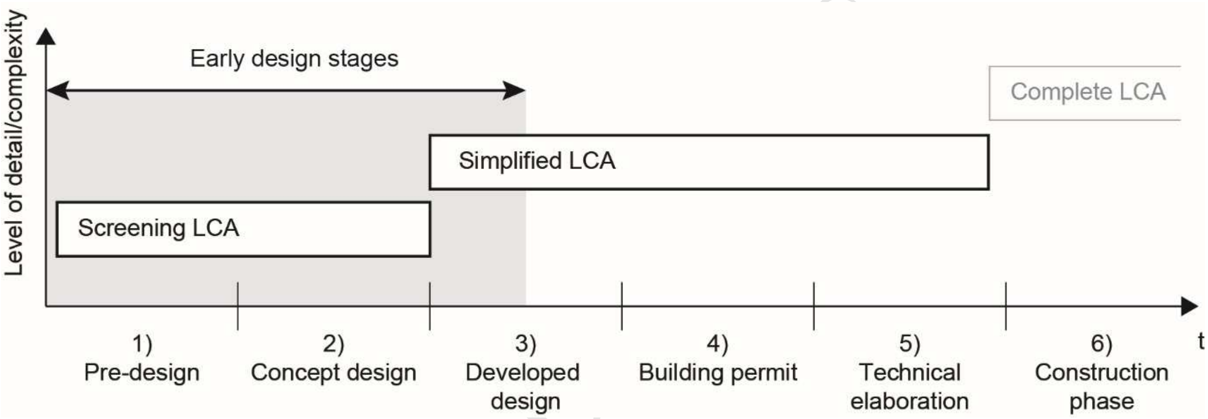

Figure 2: Relation between design stages and simplifications in LCA (Black and white, 1 column)

The EeBGuide focusses mainly on the calculation of the LCA and the input of data, although it also includes some aspects concerning the output and communication of results. These simplification criteria are implemented in the evaluation framework.

2.3 Framework with requirements for design-oriented EIA tools for early design

Both perspectives are combined into a framework with requirements for design-oriented EIA tools for early design. Additional requirements to improve the functionality of an EIA software application, both regarding the front end (user interface) and the back end (calculation/simulation model) are added to the framework. The final evaluation framework is 1) oriented to architects' needs regarding the application of EIA tools in early design and 2) includes minimum methodological and calculation requirements which should be met by a simplified LCA-based application in order to be usable for the assessment of the environmental impact of buildings. In the next section, the framework themes and criteria are discussed in detail and requirements for LCA-based EIA tools in early design are derived.

3 Results and discussion

Table 1 shows the framework with requirements for applying LCA-based EIA tools by architects in early design. This framework is subdivided into four themes: 1) Data-input, 2) Calculation, 3) Output and 4) Usability in the design process.

The left column represents all user requirements (‘what they want’). The right column addresses all criteria related to the simplification of the LCA methodology. The middle column represents suggestions of how these criteria could be met and merged into an EIA software tool, both regarding the user interface and the background calculation model. In the next paragraphs, all framework themes and their corresponding criteria are discussed.

3.1 Data-input

From the user’s perspective, the input data should be limited and consistent with the design phase. This can be achieved by implementing a clearly structured and extensive library with standard materials or building components (e.g. national averages based on common practice) and by providing default values and settings that can be used to substitute missing data on materials in buildings. Also from the methodological point of view, the EeBGuide gives some recommendations to simplify the data input in early design, both for the building geometry and the building materials.

For the geometry, guidelines on which building components to include in the assessment in (early) building design are provided in the EeBGuide. For screening LCA, the EeBGuide proposes to include at least the building envelope, including exterior walls, windows, roof and floor slab, and the primary load-bearing structure. These components are cumulatively responsible for approximately 76% of the embodied impact on average [25]. For the simplified LCA of the EeBGuide, foundations, interior walls, building services, and surface finishes, should be added to the assessment. Staircases, cables, door handles, etc. can be neglected according to German certification systems [33].

Structure		User	EIA tool		LCA methodology	
Theme	**Subtheme**	**User requirements**	**Front end (user interface)**	**Back end (calculation model)**	**Screening LCA**	**Simplified LCA**
INPUT	-	Limited data-input, consistent with the design phase: both for building geometry and material specification	Clearly structured, extensive material library with standard materials, building components (e.g. based on national averages)	Consistent model that allows use of default settings / values but can also be filled/extended with detailed data with access to different material libraries	Use of generic environmental data	Specific environmental data if available, if not average or generic
			Default values and/or settings for assessment of 'incomplete' buildings		At least include: Exterior walls, windows, roofs, ceilings, slabs, interior walls, columns, foundations, finishing, building services + default values for other data	
		Quick data-input via a simple and intuitive procedure	Link to common design tools to be easy to learn and avoid additional effort (e.g. Sketch-Up)	Automatic take-off of material / element quantities from the 3D model	-	
CALCULATION	**Methodological and calculation choices**	Transparency of methodological and modelling choices, not adaptable but clearly communicated	Provide detailed manual / description of predefined calculation settings and assumptions + a clear help function or discussion platform for Q&A and support	Predefined calculation settings per building type and design stage, such as the reference study period, impact indicators, etc.	Report at least the indicators PENRT and GWP and a single-score indicator (endpoint) if possible	Report the indicators GWP, EP, AP, ODP, POCP, ADP, PET, PENRT and a single-score indicator (endpoint) if possible
					Life cycle stages: A1-A3, B4, B6, B7, C3, C4, (D)	
		Objective, correct information and data (regional, verified, independent)		Database with verified and independent data, representative for the assessment context	Assure representativeness of data (time, regional) and data quality	
	Scope of the assessment	Holistic approach: integrate energy performance, link to economic costs, health, … to enable well-balanced decision making	Provide combined calculation and presentation of outcome for energy performance and environmental assessment	Combined calculation of operational energy demand and environmental impact assessment	Operational energy calculation based on performance targets (statistical data)	Operational energy calculation based on quasi-steady state energy calculation
	Time investment	Minimal interruption of the design process / implementation in workflow of architect	Interoperability with other design or analysis tools	Import / export features to other tools	-	
		Quick application, minimal time required to operate tool	Real-time calculation, in tune with design process	Computation time <1s		

Table 1: evaluation framework with requirements for early design application of LCA-based EIA tools by architects (user requirements based on Weytjens and Verbeeck [46] *and Meex et. al.* [56]*; LCA simplifications based on the EeBGuide* [57] *and Hollberg* [7] *(continues on next page)*

OUTPUT	-	Simple but supportive information for design decisions, adapted to design stage	Aggregated score + more detailed scores (per element, per life cycle stage), combined with design-supportive feedback	Calculate aggregated single score and individual indicators	Optional aggregation into single score	
				Optional: calculation of points in sustainable building certification systems		
		Easy to interpret, clear and limited output, which is communicative towards the client	Visual output (e.g. graphs, grading scale) instead of extensive report	Aggregation of results on different levels of detail (per building, per element, per life cycle stage)	-	Reporting templates for LCA practitioners
			Visualization of output relative to benchmarks/average values/regulatory targets	Provide European or national average/target values for individual building components and whole buildings	Normalization using national targets or benchmarks for buildings	
			Visualization of possible deviation of results (sensitivity / uncertainty)	Calculation of uncertainty based on information in environmental data and level of detail of geometry model	-	Information on uncertainty using statistical methods
USABILITY IN THE DESIGN PROCESS	Adaptability & flexibility	Adaptable to / in tune with design stages	One software tool for different types of projects, which evolves with the design progress	Flexible / parametric calculation model with different levels of detail	-	
		Easy data review / change	Parametric control, e.g. number slider, for input of material thicknesses, etc.			
		No loss of data	Automatic save function, redo/undo function	Provide sufficient memory capacity / provide space in the cloud		
		Quickly and easily create and test alternatives (parallel)	Copy-paste function / duplicate instead of start from scratch	Database to store variants		
	Comparison & feedback loops	Comparing a number of different design alternatives in detail (parallel)	Visualization of changes (improvements) between variants	Enable opening multiple variants and comparing them in parallel	-	
		Real time feedback on design changes				
		Clear indication of problem areas	Visualization of problem areas in 3D model	Comparison of environmental impact per building component e.g. with average values and indications for large deviations		
		Generate suggestions / alternatives for improvement	Indicate optimization potential and generate suggestions / alternatives	Provide the possibility to use optimization algorithms to propose solutions		

Table 1: continuation

However, adding components during later stages of the design process causes an increase in environmental impact: the environmental performance becomes “worse” in the point of view of the designers and their clients. Furthermore, the results from screening and simplified LCA cannot be compared due to different system boundaries. Therefore, ideally, the same system boundaries should be chosen and as many components as possible should be included from early design on. Clearly, this requires more modelling effort. Therefore, a list of components as a minimum requirement is included in the framework in Table 1. This list refers to the simplified method of the DGNB system [33]. Since, in early design, the focus is mainly on the development of the building shape and plan functionality, detailed information on all building components will not (yet) be available. To limit the modelling effort for the screening LCA, default values can be employed. For interior walls, for example, average values on the amount of m² of interior wall surface / net floor area can be used (e.g. as provided by Minergie Eco Guidelines [7,36]).

As previously mentioned, default values or assumptions can be used to substitute the missing or unknown data in early design. This is also the case for the building material types. In general, there are two approaches for improving the impact of a building concerning materialization: A) Changing the type of construction and its materialization (e.g. a concrete or a timber construction, which can be done based on generic environmental data) and B) Choosing a product from a specific producer with the best environmental performance within one type of material (e.g. choosing a concrete with low environmental impact based on an EPD).

Since in early design the availability of material data is generally limited (e.g. only a material category or construction type [47,58]) and the focus is mainly on the design development, approach A of comparing different material types based on generic data is recommended. This approach already allows a first impact assessment of the design and its corresponding generic materials (complemented with assumptions based on common practice) in early design, even though no producer-specific choices have been made. The importance of the design quality and main construction materials in achieving a low environmental impact was also found in [59].

The material specification by choosing a specific producer and product (cfr. approach B, e.g. with EPDs) to replace the generic data can be applied later on. Generally, these specifications to a product-specific level already take place by the detailed design stages, but usually no producer-specific choices have been made at that point. This usually occurs during tendering, although some architects have developed a pattern of habits over time, based on which they already assume a specific producer earlier on.

When using predefined environmental data in the form of EPDs or generic data, the most time-consuming aspect of EIA is the manual input of a detailed bill of material quantities. For the architects in the empirical research, the input of data should be quick, via a simple and intuitive input procedure. They prefer data input on the building geometry and materials through a software program, which they already frequently use in the design process. This way, the assessment would be integrated in the design process and the additional effort and time-investment for learning and applying an EIA can be kept to a minimum. Using a 3D CAD (Computer Aided Design) model could be a solution. A number of existing tools already use a Building Information Modelling (BIM) environment, e.g. Tally [60] or Optimi360 [61]. In the detailed design stages and for big projects with many collaborators, a BIM generally provides many advantages. However, for the early design stages and for smaller residential projects, mostly carried out by small architectural offices, tools such as SketchUp are preferred by the architects in the focus group due to its simplicity, accessibility and widespread use. Therefore, EIA tools should be able to work on the basis of simple 3D models such as SketchUp. Many SketchUp plugins for energy simulation exist and, recently, a plugin for an LCA tool called CAALA [62] has been developed.

3.2 Calculation

The calculation requirements in the framework are subdivided into three subthemes:

Methodological and calculation choices, Scope of the assessment and Time investment. All requirements are discussed per subtheme in the following paragraphs.

3.2.1 Methodological and calculation choices

From the perspective of LCA practitioners, the assumptions and methodological choices made for the calculation are very important. In contrast, architects do not need to be able to adjust these methodological/calculation choices (due to their limited knowledge level and expertise [30]), but they wish for transparency and clear communication of all assumptions, in order to trace the origin of a certain outcome if necessary. In addition, a help feature or discussion platform for questions and answers should be available in case additional support is needed. In brief, all methodological decisions should already be pre-programed by the tool developer (e.g. following the national methodological requirements), ready to be used by the architects. Since in early design not all (environmental) data are always available, the EeBGuide discusses possible simplifications of the LCA methodology for early design by reducing the set of 1) life cycle modules and 2) environmental indicators for screening and simplified LCA. Furthermore, also the data quality should be assured. These three simplification requirements are discussed below.

3.2.1.1 Selection of life cycle modules

According to the EeBGuide, a screening LCA requires a declaration of the impacts in life cycle modules A1-A3, B6 and B7. Typically, the product stage (modules A1-A3) of a material has the largest share of the embodied impact, and must therefore be included. Combined with the operational energy use (module B6), they typically account for 70-90% of the environmental impact of residential buildings [25,63,64]. Furthermore, data for these modules are declared with a high accuracy in almost all EPDs and all databases for building materials. As such, they can be included without difficulties and define the minimum life cycle modules for screening LCA.

For simplified LCA, the life cycle modules A1-A3, B4, B6, B7, C3, C4, and optionally D should be included to provide a more holistic picture. This is necessary to account for shifting environmental impacts from one phase to another. The modelling of benefits outside the system boundary for module D introduces some methodological difficulties [65], but especially for bio-based products module D has a high influence on the overall results [59] and should therefore be considered.

As mentioned above, it is important to use the same system boundaries throughout the design process to allow correct interpretation and comparison over the different design stages. Therefore, in contrast to the EeBGuide, the framework proposed here recommends to use all life cycle modules of the simplified LCA in the screening LCA as well.

Modules B6 (operational energy use) and B7 (operational water use) are only relevant on the level of the whole building. Even though operational energy use partially depends on the user-related energy use, architects still have a direct influence on the building-related energy use (e.g. space heating and cooling). Therefore, it is found that module B6 is an important part of the assessment by architects (will be discussed in more detail in paragraph 3.2.2). The relevance of module B7 can be questioned, since architects seem to have little influence on the operational water use (heavily depending on user behaviour) and (early) material choices do not really affect this module. Therefore, it could be suggested to leave module B7 out of both screening and simplified LCA, but this should always be a reversible choice, so that the assessment is expandable to a complete LCA again.

3.2.1.2 Selection of environmental indicators

The EeBGuide is vague about the number of indicators to be used for screening LCA. It is stated: 'A screening study might focus on one single indicator or several, and most studies should include PENRT (primary energy non-renewable, total) and if relevant the GWP (global warming potential) and PERT (primary energy renewable, total)' [57]. Using only one indicator may be adequate for a specific study, but for holistic assessment of building designs, this is impractical as it might lead to suboptimal solutions and burden shifting. For instance, some wood-based products have a negative GWP which could lead to the conclusion that the more wood is used, the better the environmental performance, which might not be the case when taking other indicators into account as well.

Currently, the European CEN standards EN 15804 and EN 15978 provide several indicators that can be considered in an environmental impact assessment of building products and buildings. However, national regulations may still differ from each other. The Swiss standard for embodied energy SIA 2032 only demands the declaration of PENRT and recommends the assessment of GWP optionally [66]. In Austria, three indicators, namely PENRT, GWP, and AP (acidification potential), are aggregated into one OI3 index (Ökoindex 3) [67]. Based on the EeBGuide, it is recommended to use at least the indicators PENRT and GWP for screening LCA. For simplified LCA, the parameters describing outputs to the environment defined by EN 15978 [13] (GWP, EP (Eutrophication Potential), AP (Acidification Potential), ODP (Ozone Depletion Potential), POCP (Photochemical Ozone Creation Potential), and ADP (Abiotic Depletion Potential)) should be considered. For the input-related parameters, PET (primary energy, total) and PENRT should be included to comply with certification systems. Again, these indicator sets are minimal requirements and should always be expandable to a more complete LCA, compliant with (future) building codes.

3.2.1.3 Environmental data quality

Besides transparency of the methodology, architects expect that all data that are used within the EIA tool are objective and reliable. This availability of objective and independent data that are valid to be used within the tool should be guaranteed by the tool developers. In the methodological requirements, a number of guidelines are specified to ensure this objectivity and reliability. First of all, data should be employed from a single database as much as possible to ensure that environmental data for different components are based on similar assumptions [57,59]. Second, the environmental data provided by the tool should be valid regarding time and location. If regional data is not available, factors to adapt to regional conditions can be employed.

Methods such as NativeLCA [68] can be used.

3.2.2 Scope of the assessment

Since the choice of materials not only influences the environmental impact, but also might affect the operational energy demand, architects prefer a combined assessment of both aspects. By providing this more holistic assessment scope (combination of environmental impact assessment and operational energy demand calculation, optionally also complemented with information on costs, health, etc.), architects are able to make well-balanced design decisions and find the optimal solution taking both energy consumption and environmental impact into account.

A combined calculation in one tool should be pursued, since separate assessments would take too much effort and could lead to suboptimal solutions. Therefore, the EIA software application should allow this combined assessment, by integrating both calculation modules into one assessment. From a methodological point of view, it was already mentioned that the EeBGuide recommends to take module B6 (operational energy use) into account. For screening LCA, energy performance targets can be used instead of an actual operational energy calculation. This way, criteria such as a maximum U-value can be employed to provide the link between operational and embodied impact (based on heat transmission losses associated with that U-value). This is the most time-efficient approach and sufficient for a rough estimation of the environmental impact. For simplified LCA, the EeBGuide recommends national calculation methods, which can be quasi-steady state methods (QSSM) or dynamic building performance simulation (DBPS). DBPS, such as EnergyPlus [69] or TRNSYS [70] deliver detailed results based an hourly or quarter-hourly basis, but are computationally intensive and complex [71]. Simplified QSSM usually calculate the energy demand on a monthly basis and are used for national energy saving regulations, and European energy performance certificates [72]. According to van Dijk et al. [73] the accuracy of the results from QSSM are acceptable for residential buildings in warm, moderate, and cold climates. QSSM are much easier to use and able to generate real-time feedback [71]. Therefore, a QSSM seems to be the most suitable energy calculation for early design phases.

3.2.3 Time-investment

Users require a minimal interruption of the design process and therefore an implementation of the assessment in the workflow of the architect. The time-investment of an assessment should be as low as possible, since in early design the focus is on testing several design solutions and choosing the most appropriate solution and not yet on assessing a completely elaborated design solution. To keep the additional time-investment as low as possible, interoperability with other (design) tools is required, which was also already discussed as a feature to facilitate the data input (link to e.g. SketchUp) and to enable a holistic design assessment (i.e. combination of operational energy use and environmental impacts). In addition, 'real-time calculation' is preferred, which means a response time of the LCA tool that seems instantaneously. According to Nielsen [74] 0.1 second is about the limit for having the user feel that the system is reacting instantaneously, while 1.0 second is about the limit for the user's flow of thought to stay uninterrupted. Even though the user will notice the delay, no special feedback is necessary during delays of less than 1.0 second and can therefore be assumed as a limit to guarantee a high usability.

3.3 Output

For the architects consulted, the output data should foremost be simple but supportive and adapted to the design stage. Not just an environmental impact score is desired, but also meaningful feedback and suggestions for alternatives should be provided. Most architects prefer to have a single aggregated environmental impact score on a building level, complemented with more detailed information on the environmental impact of building components and the different life cycle stages of the building. In the LCA methodology, the weighting step to aggregate all individual environmental scores into a single score is optional. In addition, these weightings are based on value choices rather than on scientific calculation [75]. However, Kägi et. al. [76] report that decision-makers always implicitly or explicitly weight and aggregate LCA results to make a decision on it. Therefore, it might be better to provide a single score for decision-makers instead of letting them make the weighting on their own [76]. Currently, no common European single-score aggregation method is available. In Switzerland, a single score called 'Umweltbelastungspunkte' [77] is used. In Belgium, a single-score using monetary values based on damage and prevention costs has been developed [78]. Also in the Netherlands, all environmental impacts are monetarized and summarized into a single MPG-score, using a 'shadow costing' method [79]. Building certification labels weight the individual indicators when awarding points for LCA-related criteria. These points can be used indirectly as single score and be a useful means of communicating the results to clients [80].

This single score already facilitates the interpretation of the environmental impact of the building. However, comparison to a benchmark or target value to check (future) building code compliance could further ease interpretation. According to the EeBGuide, this benchmark can be obtained by normalizing the outcome. This means that the LCA results are scaled to a regional, national or European reference. There are some individual values provided for France in the EeBGuide, but they do not cover all indicators of EN 15978. The method of ecological scarcity [77] provides national references for Switzerland. There have been initiatives to employ this method for other countries, such as Germany [81]. However, they cannot be used with indicators from EN 15978 or EPDs, but need sophisticated LCA software. In general, normalization factors adapted to the building sector are missing. A different form of providing a reference for the interpretation of LCA results and allowing for comparison is the use of benchmarks, which is also demanded by the consulted architects. The EeBGuide lists the benchmarks for entire buildings based on French HQE [82] and German DGNB [33] certification labels. The Swiss standard SIA 2040 [83] derives limits for the primary energy demand of buildings based on the 2000 Watt society [84]. However, no European benchmarks are currently available. Nevertheless, further development of these benchmarks seems indispensable in order to facilitate the interpretation of the environmental impact assessment outcomes by non-experts and establish national target values for buildings in the future (e.g. in the Netherlands, a national benchmark will be implemented in 2018 [42]).

In addition, the EeBGuide also gives recommendations on how to deal with the numerous uncertainties that come with an LCA and should therefore be communicated to decision makers. Especially if the results in a comparative analysis deviate less than 20%, uncertainty analysis is recommended for simplified LCA [85]. However, uncertainty information is not available in common environmental data for building products, such as EPDs. Furthermore, uncertainty analysis using Monte Carlo simulation or sophisticated statistical methods is far too complex for non-experts. A clear strategy how to treat and communicate uncertainty in building LCA to decision-makers is still missing, even though transparency is demanded by architects.

All results should foremost be presented in a visual, graphical way and not by means of an extensive report. This facilitates communicating the output to clients. In the EeBGuide, guidelines and templates for reporting of the results are also included, but these are more aimed at LCA experts (to ensure transparency and reproducibility of the results). The visualization of analysis results is not covered by the recommendations of the EeBGuide, but often asked for by designers [86,87]. LCA-based EIA tools, such as eLCA [17] or CAALA [62], present the results in different graphs to indicate building components with high environmental impact which potentially can be improved. Another possible way of representing the results is mapping them onto the 3D model [88] using a false colour scheme, which could be a more intuitive means for very early design stages.

3.4 Usability in the design process

To further increase the general usability in the design process, some other requirements are listed here. Since these requirements go beyond the methodological recommendations of the EeBGuide on the LCA methodology, only the requirements of the user, based on the empirical research, and how this could be reflected in an EIA software tool are discussed.

For instance, a tool should be adaptable and flexible to use. This means that all data should be adapted to the design stage, easy to review or change without loss of data and that alternative solutions should be easily created and tested in parallel within the application. To avoid data being re-inputted when moving on to a more detailed design stage, the EIA model should be continuously enhanced with data that are more detailed. This implies that the building model in the EIA software application should evolve with the design project and consist of different levels of detail for the impact calculation. In addition, a parametric approach could facilitate easy data review and changes. According to Davis [89], the real benefit of parametric description comes from the low cost of the design changes. Therefore, a parametrized input of the data for calculation seems a suitable solution for quick evaluation of multiple design alternatives in early design. Ideally, default values are provided in the tool for early design stages, but these can be modified by the user. By using a ‘parametric’ input instead of fixed values, they can always be adapted in later design stages, keeping the model flexible to changes. To create different alternatives in parallel, without having to start from scratch, a copy-paste function or duplication function would be helpful. All variants should be stored in a database or library. In addition, an automatic save function and redo/undo function increases the usability of a software tool (in general).

Regarding the output, it was already mentioned that comparison to a benchmark or target value would be an added value. The performance of the project can be compared to e.g. average performances of buildings within the same category or with national target values. However, the consulted architects also wish to compare multiple variants of their own design project. Opening multiple projects at the same time and seeing the changes or improvements between different variants, next to each other within the software, can help in the final decision making of the project. Furthermore, real time feedback on design changes makes the link between the input and output of the assessment more clear to the user. In addition, problem areas in the design, i.e. with high environmental impact, should be clearly indicated, preferably in a visual way (e.g. by means of green-red colour scales, …) so that users can see which building parts have the largest optimization potential. Architects also prefer to get alternative suggestions, so that they can broaden the horizon instead of sticking to general solutions within their knowledge field. This could be done by not only providing an environmental impact score, but also design supportive feedback on their design choices. Manual optimization can be performed by the architect, or computational optimizers (as described in for instance by Hollberg and Ruth [26]) and can be used to optimize certain parameters, e.g. the thickness of an insulation material. These alternatives and indications of optimization potential can induce a learning process on the environmental performance of building materials and building design among architects.

3.5 Limitations

The user-requirements are mainly derived from the focus group, combined with the survey and interviews, and are therefore based on the context of Flemish architects. Further research is necessary to check if these requirements are also valid in other design contexts with similar conditions (e.g. small-scale architectural offices working on residential projects for individual clients). However, according to the 'Architectural profession in Europe 2016' report [90], the situation in many other European countries is similar: 55% of the architects' work is private housing and 72% of the practices consists of one person. Therefore, these findings are believed to be valid for many European countries.

Regarding the simplification approaches presented by the EeBGuide, one of the main limitations is that they do not specify the accuracy of results (compared to a complete LCA). In the literature, few studies compare the deviation of results between different levels of detail of LCA. A comparison between simplified and complete LCA for a building by Bonnet et al. [91] shows a maximum deviation of 20%. Another LCA study for a building shows a deviation of 30% in GWP between simplified and complete LCA [92]. The framework does not specify the accuracy of results (e.g. compared to a complete LCA) either. Based on values and references from the literature and academic studies, it can be assumed that a maximum deviation of 30% for screening LCA and 20% for simplified LCA can be realized. To verify the accuracy of the results, a large study with complete LCA results of many buildings would be necessary. Currently, these data are not available. Furthermore, the uncertainty of environmental data is not integrated in the framework.

As mentioned above, the EeBGuide does not specify the indicators to be used for the assessment. The parallel use of several indicators is difficult to interpret for non-experts, such as architects. A European indicator describing the 'environmental-friendliness' of a building in a single score is still missing. The availability of such an indicator would make the wide-spread use of LCA-based EIA tools in practice much easier.

4 Conclusions and further recommendations

An LCA-based EIA tool can be very valuable in the decision-making process of architectural design. However, the analysis of the state of the art of conventional building LCA applications showed that there are many gaps that should be overcome to meet the user requirements of architects for EIA tool application in early design. On the one hand, methodological simplifications of building LCA are needed to make it more suitable for application in early design. On the other hand, the usability of LCA-based EIA software tools during the design process should be improved by better following the architects' work method.

In this paper, an evaluation framework for EIA tools is presented that considers both user-requirements and LCA simplifications. It seems that the methodological simplification recommendations from the EeBGuide are already a step in the right direction towards meeting the user-requirements from architects: e.g. the EeBGuide advices to implement operational energy use in the environmental impact assessment, which is also requested by the architects to make well-balanced decisions. In addition, the limitation of the level of detail required for the data-input of a screening/simplified LCA corresponds better to the architects' work method: in early design, no detailed geometrical and material-related information is available and therefore, default values and settings can be used to substitute lacking data.

However, to really enable the use by architects in early design stages, additional requirements for the implementation of the LCA methodology in a calculation model for EIA are necessary. Examples are a link to a (frequently used) 3D CAD software package and the implementation of a parametric, flexible assessment approach so that the assessment can be integrated in the work process of architects as much as possible and the additional time-investment can be limited to a minimum. In addition, default values and settings for the early design stages should be implemented where necessary, since not all information needed for an EIA is available at that point. Both for unknown quantities of materials and unknown material types, such defaults should be provided. Where possible, these should be based on national averages to ensure representativeness of the result, which requires comprehensive studies on national building practices. Furthermore, an aggregated single environmental impact score should be provided, because architects are more interested in a quick scan of a design option than in an elaborated report with detailed environmental scores of all different environmental indicators. In addition, a benchmark is requested to compare alternative design solutions. As numbers alone cannot be interpreted by non-LCA-experts, visualization of the results in graphs or within the design environment is crucial for decision makers.

The evaluation framework with methodological, software and user requirements for early design LCA-based EIA tools can be used to evaluate the compatibility of current tools with these requirements. In addition, these requirements can be considered in the development of new EIA tools, which are specifically oriented to be used by architects in early design stages. This can stimulate the uptake of LCA-based EIA in design and construction practice.

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Highlights:

- The importance of building environmental impact assessment (EIA) is increasing
- Most influential design decisions are made by architects in early design
- Current life cycle based EIA tools are not adapted to the architects' needs
- Architect-oriented user requirements and LCA simplification strategies were derived
- The framework will improve the usability of EIA tools in architectural practice