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Article

Learnings from Developing a Context-Specific LCA Tool for Buildings—The Case of LCAbyg 4

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Abstract: Buildings are a major cause of global resource consumption, greenhouse gas (GHG) emissions and other impacts on the environment, originating from both operational energy and material use. Informed design decisions can help mitigate potential impacts on the environment, by the use of life cycle assessment (LCA) in the early project stages. In order to mitigate building environment impacts throughout the industry, architects and engineers need tools that are integrated in the design workflow and based on the information available. Existing LCA tools for building design professionals are predominantly embedded in a specific context such as a country or a sustainability scheme. This paper provides learnings for the development of context-tailored tools for building-LCA using the case of Denmark, with specific focus on GHG-emissions that are in focus worldwide. Based on stakeholder involvement, four key areas were defined: Default information, flexibility, environmental design feedback and transparent results. Tool functions include a component library and a quantity estimator for bridging incomplete building information. A comparison monitor displays the performance of design solutions selected in the model, while a number of graphs and tables provide analysis of inventory and results. Finally, a customisable model data export, a complete input/output file for revision and custom analysis are among key functions for transparency.



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Keywords: LCA tool; life cycle assessment; integrated design process; design tool; Greenhouse Gas emissions; LCA; environmental impact assessment

1. Introduction

With the Paris agreement, many countries have agreed on committing to limit global warming to 2.0 degrees with an aspiration to 1.5 degrees. The national target for Denmark has been set to a 70% greenhouse gas (GHG) emissions reduction by 2030 compared to 1990 [1]. The building sector, representing almost 40% of GHG emissions [2], is a pivotal area of action in achieving this aim. For several decades, policies on energy efficiency in new [3] and existing buildings [4] have been implemented. Currently, the goal is to achieve buildings with zero operational energy by 2050. As emissions caused by the operational energy use of new buildings have decreased, the share of embodied emissions has grown [5–9]. Therefore, a whole-life perspective of building GHG emissions should be applied.

Benchmarks for building GHG emissions have predominantly existed in procurement programmes and certification schemes [10,11]. National legal emission limits are still uncommon [12], but several countries have issued rules for assessing GHG emissions based on the life cycle assessment (LCA) method, thus creating a foundation for later regulatory frameworks [12–16]. While more environmental impact categories should be considered in order to ensure a holistic environmental perspective, these emerging LCA-based regulation efforts are mainly focussing on GHG emissions, driven by the current political climate action.

In order to mitigate GHG emissions, architects and engineers strongly need LCA tools for making informed design decisions [17], especially during the early design stages, where

major decisions are made [18–20]. However, the complexity of LCA is often perceived a barrier for implementation of LCA in building design [21–24]. LCA tools can potentially make the analysis methods and data handling accessible for building consultants. Hence, a well-considered tool design can deliver reliable and valid results while keeping the extra workload for LCA implementation in the design process to a minimum.

The main concern here is to embed LCA into the specific context of the consultancy processes, in order to avoid time-consuming adjustments at the level of the individual consultancy. To be feasible for the industry, the tool must therefore meet the specific national context, including building regulation, information flow, design method and construction method.

The second major precondition refers to the LCA method itself. European standardisation of building LCA [25] is leaving a considerable definition gap between theory and practice [26,27]. This means that specific national adjustments of the LCA method [14,15,28–30] are needed to close definition gaps, strengthen the use of LCA in the industry, and create momentum for meeting climate mitigation targets. Adjustments include the definitions of system boundaries, scenarios, emission factors, service life of materials, data quality and reporting format.

Existing tools for whole building LCA such as Athena Impact Estimator [31], Baubook eco2soft [32], the plug-in Caala [33], eLCA [34], One Click LCA [35], Anavitor [36] and BM [37] are, therefore, tailored to each of their specified regional contexts, aiming to provide user-friendly integration into the design process. Some examples exist on the practical uptake of LCA in the building sector [23,27] and the requirements for developing LCA-tools for building design [22]. However, there is a knowledge gap in research literature about the context of the LCA tool application, and the influence this context has on the tool design.

This paper exhibits and analyses the development of the Danish building-LCA tool LCAbyg with the aim of providing learnings for the development of context-tailored tools for building-LCA. The novel perspective lies in linking the general LCA methodology with the specific context of the user. Guiding research questions for this paper consist of the following: (1) What types of requirements for building-LCA tools are prevalent in a Danish context? (2) How are the implemented features evaluated by building professionals and which future directions for development does this point to?

2. Materials and Methods

The 2014 building strategy by the Danish government [38] pinpointed the introduction of a voluntary sustainability class in the building regulations as a key goal, and the development of national building-LCA definitions, as well as a tool, as important milestones.

The initial version of the LCAbyg tool was launched in 2015 under the auspices of the Danish building authorities [39,40]. Prior to the development, an advisory council representing a broad range of future users and other interested parties was established. During workshops and dialogue with the advisory council, the Department of the Built Environment (BUILD) developed the first LCAbyg release [41]. The present paper refers to LCAbyg version 4 [42], which was released in 2019.

A range of the LCA methods implemented in the LCAbyg originate from the development of the 2014-version of the LCAbyg tool. A major influence on the tool development has been the implementation of the building certification scheme DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen) in Denmark in 2010 [43]. The DGNB adaptation process included the selection of the life cycle impact assessment (LCIA) database Ökobaudat [44] as a source for national generic environmental data. Using Ökobaudat ensures compliancy of generic environmental product data with the European Standard (EN) 15804:2012 [45] standard for LCA on building products. LCAbyg further complies with the LCA calculation method in the European Standard EN 15978:2012 [25] standard for LCA on whole buildings, albeit including only a selection of life cycle stages and impact categories: LCAbyg supports the product stage and the modules for replacements, energy use, waste processing and disposal (Figure 1). The selection of the life cycle stages and impact categories is the result of sectoral

consultation in the initial DGNB implementation. LCAbyg supports the following ten categories of environmental impacts and resource uses, according to EN 15978/15804:2012:

- Global warming potential total;
- Depletion potential of the stratospheric ozone layer;
- Acidification potential;
- Eutrophication potential freshwater;
- Formation potential of tropospheric ozone;
- Abiotic depletion potential for non-fossil resources;
- Abiotic depletion potential for fossil resources;
- Use of renewable primary energy excluding renewable primary energy resources used as raw materials;
- Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials;
- Use of non-renewable secondary fuels.

Product Stage			Construction Process Stage		Use Stage						End of Life Stage			Benefits and Loads Beyond the System Boundary		
Raw material supply	Transport	Manufacturing	Transport	Construction, installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction, demolition	Transport	Waste processing	Disposal	Reuse-, Recovery-, Recycling potential
A1	A2	A3	A4 ¹	A5 ¹	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D ¹

¹ Modules available in the next tool version

Figure 1. Life cycle according to EN 15978:2011 [25]. Modules included in the tool are highlighted. Reproduced with permission from the Danish Standards Foundation.

The selection of the categories is highly dependent on the data available in Environmental Product Declarations (EPD) for construction materials as well as in the Ökobaudat. The characterization model in use is the CML-IIA characterisation method [46], in accordance with the standard. The LCIA database already includes the characterisation step, and the process is therefore not part of LCAbyg.

The legally mandatory operational energy calculations supplements the approximate whole life approach based on available data. Other methodological definitions include the development of default reference study periods for building types and component service life [47]. Finally, emission factors for energy production in Denmark, based on the national energy planning, were published and included in LCAbyg [48].

From the first release, users could provide feedback on the tool via a permanent support mailbox, used for debugging and collecting user feedback for later tool improvements. Together with feedback from the courses for professionals held regularly by the developing team from BUILD, a constant input of ideas and requests for new features was established, and basic usability principles of the software were established [40,41]. In a 2018 project, the user interface was revised to facilitate LCA screenings at early design stages [49]. Table 1 outlines the extensive user involvement in this project [50,51]. The workshops, consultations and hearings of items 1–6 in Table 1 provided the empirical

background for generating the user requirements for the LCAbyg tool development. The seven training courses of items 7–8 in Table 1 provided the testing and evaluation of the tool features.

Table 1. User involvement in the project prior to the 2018 LCAbyg 4 release.

No.	Activity	Topic	Participant (Main Profile)	Participant (No.)
1	Workshop 1	Preconditions for early design LCA	Architects, civil engineers, drafters	18
2	Workshop 2	tool requirements	Civil engineers	7
3	Workshop 3	Component library development	Delegates from consultancies, contractors, manufacturers	12
4	Industry consultation			
5	Industry hearing	Component library evaluation	Delegates from consultancies, contractors, manufacturers	30
6	Workshop 4			
7	Course 1–5	Training/tool test	Architects, civil engineers, drafters	99
8	Course 6–7	Training/tool test	Drafter students	72
9	Workshop 5	Design guide publication [52], discussion of first draft	Architects, civil engineers, drafters	21

The tool was tested in a series of one-day training courses for building professionals held throughout the country (Table 1). There was a total of 99 participants, of which 37% were architects, 28% engineers, 18% drafters and 7% other building professionals. The objective was to provide LCA training for professionals and, at the same time, test to what degree the tool is able to affect design decisions by providing specific LCA information. The participants were asked to bring one of their projects, preferably in the early design stages, for performing two LCA exercises: First, modelling the as-is state and then reducing GHG emissions through design variations. The only information given beforehand was a beginner-level presentation of the LCA method and the required tool functions. Overall, 79% of participants had never conducted an LCA before; however, 55% had more than 10 years professional experience in the building industry. Participants were asked to respond to two questionnaires, at the beginning (Table A1) and at the end of the course (Table A2). The first questionnaire concerned the profile of the participant, and the place of employment. In the second questionnaire, participants described their specific project: project stage, available documentation, and their opinion on the usability of the tool. From the 99 asked participants, 71 submitted a complete pair of questionnaires, which were used in this study (72% response rate). The questionnaire was conducted using the tool SurveyXact [53].

3. Results and Discussion

3.1. Stakeholder Requirements for Tool

The development of the tool was driven by four objectives, both evolving from stakeholder involvement and framed by a political strategy of increasing the use of LCA in building practice:

- Available default data and settings;
- Versatility;
- Environmental feedback for informing design;
- Transparent results.

The user requirements identified through the development process are presented in Table 2.

Table 2. User requirements and tool features.

User Requirement	Tool Feature
Available default data and settings	<ul style="list-style-type: none"> Curated translation and implementation of the LCIA database Ökobaudat; Standard component service life; Emission factors for delivered energy; Modular building element structure for design optimisation; Component library encompassing common building types, scales and material choice; Inventory estimation guide for common building types and scales.
Versatility	<ul style="list-style-type: none"> Model data exchange; Exportable graphs and tables; Optional data input, i.e., for Building Information Modelling (BIM) integration (requires user script); LCA method applicable for new buildings, renovations or demolitions; Different complexity levels from screening/sketch design to as-built LCA.
Environmental feedback for informing design	<ul style="list-style-type: none"> LCA results available in real-time; Component library displaying environmental impact; Quick performance comparison during modelling; Analysis graphs and tables including hotspot.
Transparent results	<ul style="list-style-type: none"> EN 15978:2012 compliancy; Report generator (pdf); Transparency on method and user-defined preconditions; Input model analysis tables; Complete result and model export for revision; Project comparison.

3.2. Tool Overview

The LCA tool LCAbyg version 4 was released as a beta in January 2019. An overview on the main tool elements is given in Figure 2. At the core, the LCA model represents the inventory of a given project. In order to enhance usability, different kinds of default data are integrated in the tool as well. It includes product and component libraries, service life, and assumptions on quantity estimation. Depending on the stage of the building project or the goal and scope of the LCA, inputs can vary from detailed and specific to using mostly, or only, default data. However, user input must at least include information on floor area and operational energy. Further, default components have to be selected from the library and their quantities specified. These quantities can also be estimated by the tool. This requires the user to add basic building properties usually available in the design stage. The amount of default data in the project can be adjusted at all times. The tool generates a result report and input/output data files. Model data can be exchanged in proprietary file formats both ways. Manufacturers have made use of this possibility by publishing their EPD data as provisional LCAbyg material-files. These files can be downloaded and imported into the tool by users.

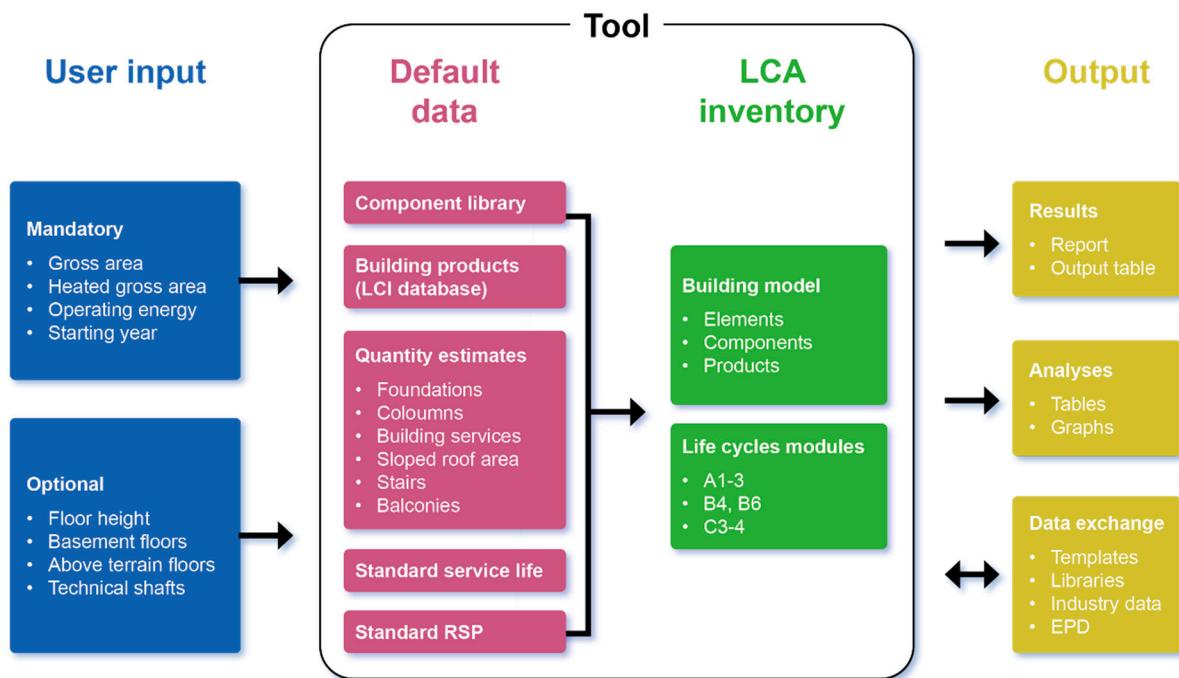


Figure 2. Tool overview.

The subsequent sections are divided into the above-mentioned usability topics and present the responding tool features. Each subsection discusses how the implemented tool features support usability by referring to the user survey results and the literature.

3.3. Tool Features—Available Default Data and Settings

3.3.1. Building Model Structure

Default data help users establish a complete inventory regardless of project stage and LCA level of detail, based on the currently available information. The backbone of the complete inventory is the integrated model structure for the inventory (Figure 3), linking building materials with environmental information. When using a simplified approach, users can focus on optimising building design by modelling only on element and component level. Thereby, interaction with the environmental data can be avoided. The Ökobaudat database delivering environmental information is represented on the levels of products and of life cycle modules.

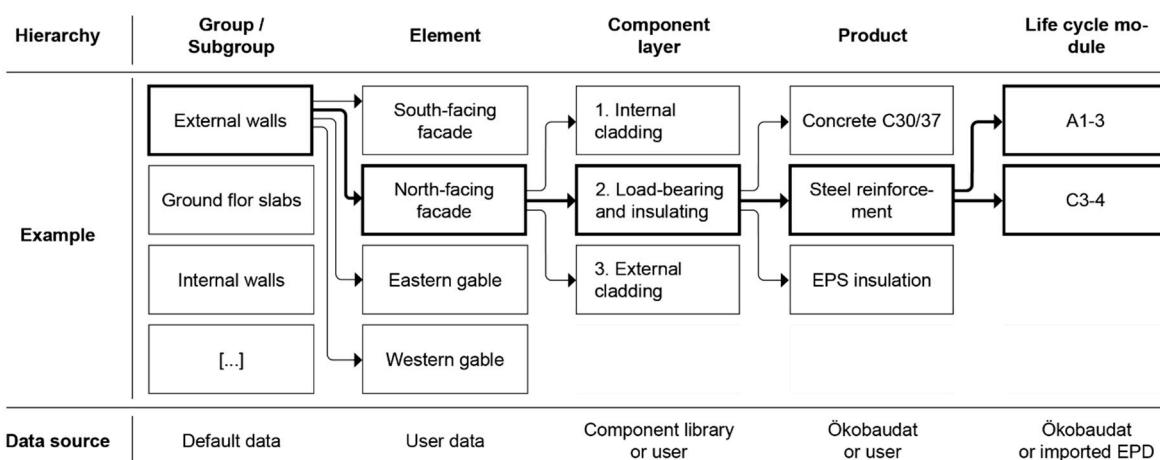


Figure 3. Building model structure.

3.3.2. Component Library

The component library consists of 375 predefined building components. They cover typical solutions and variants for the building types: Detached home, multi-storey apartment building, office building and educational institutions. The components were selected and developed by the LCAbyg team with contributions from consulting architects, engineers, manufacturers and contractors. All predefined building components consist of details about material use per unit of construction, typically per m². These material uses are linked directly to the environmental impacts determined by the Ökobaudat LCIA database. The technical quality and variety of the library was evaluated by an external consultant. Solutions are modelled following a conservative approach of over- rather than underestimating quantity, material selection and impacts. A test has shown that results for LCA based on default components and available default quantities exceed a detailed, specific modelling approach by maximum 20% [51].

Inspired by an earlier LCA tool [18], components are defined as one out of three functional component layers, which constitute each building element (Figure 3, Table 3). The three-layer structure introduces a new aggregation level between elements and products, targeting design decisions and performance optimisation. As each layer follows a logical function, designers can explore alternatives with low emissions in the library among components of the same layer. On the building element level, the user can combine the component layers to make a complete element. Table 3 shows how the layer structure is manifested for each element group.

Table 3. Component layers and their function.

Element Group	Comp. Layer 1	Comp. Layer 2	Comp. Layer 3
Foundations	Foundations	-	-
Ground floor slabs	Flooring	Load-bearing system	Insulation and underlay
External walls	Inside finishing	Load-bearing and insulating system	Façade system
Internal walls	Finishing	Load-bearing and insulating system	Finishing
Floor decks	Flooring	Load-bearing and insulating system	Ceiling
Stairs and ramps	Structure	Flooring	Balustrades and handrails
Columns and beams	Columns and beams	-	-
Balconies	Platform	-	-
Roofs	Roof cladding	Load-bearing and insulating system	Ceiling
Windows, doors, glazing systems	Profiles	Panes	Solar shading
Building services	Production unit	Distribution	Terminal unit

Calculation of impacts from module B6, the operational energy consumption, requires user input on the demand as well as the energy source. Two energy grid scenarios can be selected, a static scenario and a dynamic scenario based on projections of the national energy production until year 2050.

The idea behind the function with default components was to offer the most typical solutions, which may be sufficient in screening LCA, but can be adapted to more specific detailing when needed. The survey respondents preferred to have a component library with a greater variety. This result, however, has to be seen in the context of the LCA training. Here, respondents had experienced not being able to find perfectly suited default solutions during their exercises, because they were asked not to adjust components or generate custom components. Some commented, accordingly, that the need for more default components was less important, as they knew about the general possibility of adjusting components. Others pointed out that default components cannot possibly match specific projects completely.

The technical quality of default components was predominantly rated neutral (73%) or rather good. No detailed comments on the quality were given. Both might be due to the lack of time to assess the quality in a one-day course, as one respondent stated.

3.3.3. Quantity Estimation Guide

Based on building information available in sketch design, the tool can assist in estimating quantities of building components such as roof area, length of ventilation ducts or the length of strip foundations.

A quantity estimation guide appears automatically, on the right side of the modelling pages, as soon as a sub-element with available quantity estimates is activated (Figure 4). A textbox on top of the guide explains the underlying assumptions and formulae as well as help for choosing items in the form. The calculated quantity is transferred to the sub-element by a click. Estimations depend on the element subgroups, see Figure 3. The estimations use mandatory and optional user input (Figure 2) along with simple geometrical information such as the building perimeter or number of apartment units. Some of the estimations merely exploit already made user inputs, for instance the calculation of the sloped roof area using the formula (GFA/no. of floors)/cos (slope angle). Estimations for building services, balconies, and foundations use integrated default values retrieved from industry practice. The tool's quantity estimator was rated positively by 52%, while 38% submitted neutral replies. Furthermore, 10% replied negatively; however, five out of these seven “not useful” ratings were justified by already available quantities in their project, therefore lacking the need for estimations.

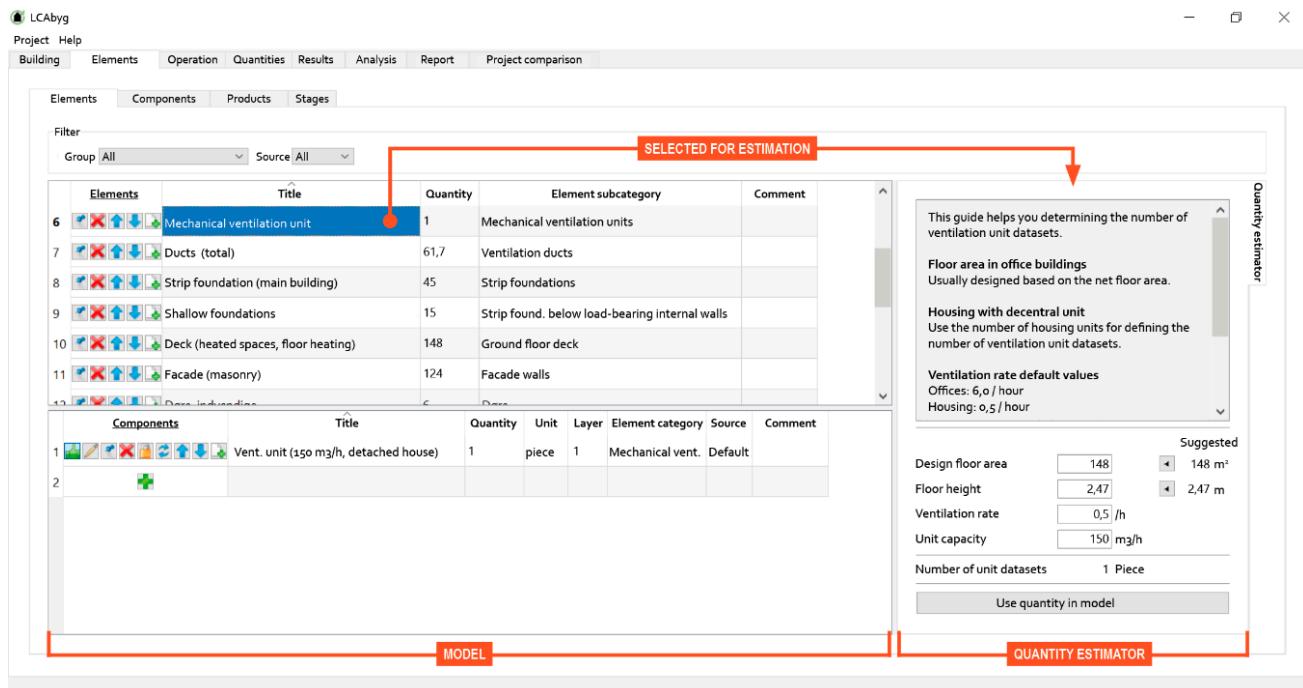


Figure 4. Quantity estimation guide.

3.4. Tool Feature—Versatility

3.4.1. User Profile and Level of Assessment

The tool can be used for LCA of new buildings, renovations or demolitions. Renovations include newly installed components and waste management of removed parts. A feature that allows the calculation of shares of component life cycles based on the remaining service life is under development for the next tool version.

Another model is to perform simple assessments during sketch design or architectural competitions in the development team, and then consult the corporate environmental analyst in later stages of the project. However, the possibility of exchanging data from different sources and across different projects requires that data can be organised and managed in the tool. Currently, data can be created, copied, deleted or edited on all instances, either in the containing folder or in a list view. For labelling information, users can rename items or attach comments. However, a visual data organization with a file and folder tree and advanced preview, labelling or editing options could be a meaningful extension. Further, user libraries are saved in project files and are not embedded in the tool itself. An improvement would be the possibility of linking the tool to shared libraries, where manufacturers can submit components and products such as Baubook [54].

3.4.2. Model Data Exchange

Data exchange is allowed on all levels of the model hierarchy including building components, products or life cycle modules. Users can make libraries or corporate templates outside the tool using LCAbyg file types for each instance. Performance comparisons in the modelling sections and results of the analysis can be saved as tables and image files. Users can integrate this information in reports and presentations or use the information for subsequent analyses. The tool can read xml-files, which may be produced by BIM tools, thus transferring material and quantity data. This solution requires the user to write a script, which is not part of the tool.

Interfaces between performance analyses and graphical design tools are a major point of interest and discussion [55]. The survey data from the training courses confirm that projects apply numerous workflows and design platforms relating to the diversity of company profiles, contract types, project scales or typologies. Variation also occurs within the course of a project, where some use 2D or 3D CAD models in sketch design and eventually use BIM at later stages, while others apply BIM from the start. Overall, 61% of the participants' projects were either using BIM or expecting to do so later on. However, only 8% expressed a demand for linking BIM to the tool. One of the key tasks is mapping the heterogeneous use of classification models used in the Danish building industry [56] to the tool's data model. The present solution in LCAbyg is flexible, but requires the user to make a script using a guide on the tool website. In order to make this interface accessible to all users, independent of programming resources, a more convenient solution should be developed. The fact that the actual demand for automated interfaces across platforms is not fully analysed, was one of the motivations for focusing on and optimising manual user input. The need for such links will be dependent on how LCA will be integrated into consultancy, relating to the frequency of assessments, their scope and purpose in the coming years. In general, interfaces have to be developed carefully, and design workflows might have to adapt, when BIM is to be used as a reliable input method [7,57–60].

3.5. Tool Feature—Environmental Feedback for Informing Design

The tool calculates results and graphs for analysis immediately. When making overall inputs with consequences for the results, such as reference study period or starting year, the user is asked to confirm this choice. During building model input, the user can perform a performance comparison of library items, both default and user-generated items. The comparison feature resembles that on the modelling pages (Figure 5). This is helpful when exploring variations of items of the same component layer such as façade claddings or floorings. All results can be exported as numbers or images.

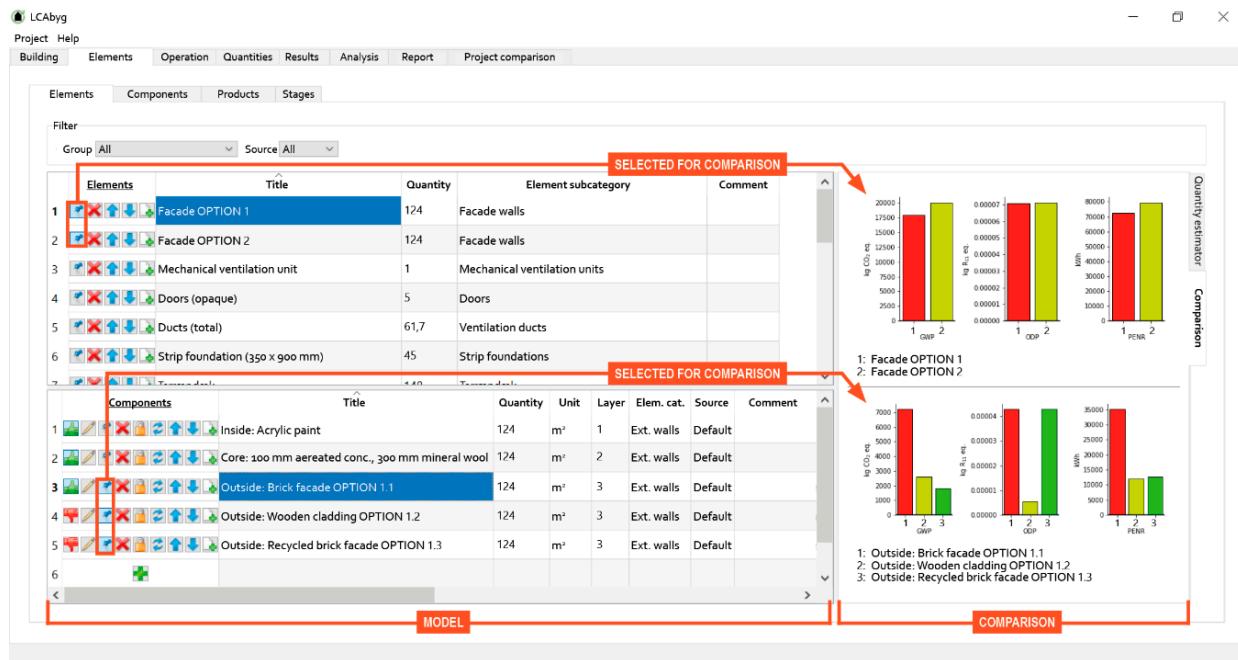


Figure 5. Quick comparison. Performance comparison of items within the same hierarchy level on the modelling pages. Here, three product and two life cycle modules are selected.

Analysis

The integrated analyses illustrate results with seven types of graphs (see examples in Figure 6). Each graph can be filtered to levels of the building model, environmental indicators, material types or reference units. Most used is the overall hotspot analysis of the 10 highest-ranking elements, components or products. The graphs include results regarding:

1. Hotspot analysis (Figure 6a);
2. Material types: Mineral, metal, insulation, wood, plastics, other;
3. Life cycle stages;
4. Accumulated embodied and operational impacts (Figure 6b);
5. Total embodied versus operational impacts;
6. Heat and electricity share in operational energy;
7. Element groups.



Figure 6. Visualisation of results in the tool. Selection of two out of seven available graph types in the tool. The Hotspot analysis shows building model items such as elements or products in order of their impact, while the Accumulated graph includes curves for operational (orange) and material (blue) impacts over the reference study period.

Additionally, a graph documenting the results regarding the DGNB reference values is included. The positive effect on lowering environmental impacts using target values have been studied [8] and expressed by responses in the user survey.

Feedback functions provide users with a palette of analysis tools for better understanding the results and the model. The offered functions allow for identifying datasets with relatively high impacts, at the levels of the product, component or element. A key purpose of analyses is suggesting improvement potential of the model, which is best done via accessible, visual means during the design process [22,60–62]. This is confirmed by the overall satisfied user rating (85% useful/very useful, 14% neutral, 1% less useful).

3.6. Tool Feature—Transparent Results

Quantities and Results

The Quantity table sums up the project's material use (Figure 7). It includes all quantities and service lives entered by the user, and the tool's conversion into mass, aggregated on all levels of the building model. The table is useful for checking the model on manual input and unit conversion errors. Using the same structure, the results page (Figure 8) displays all impacts and replacements.

Here you can see the project by weight and quantity

	Description	Filled in quantity	Calculated quantity	Weight	Service life
Materials	Element category	-	-	170,081 kg	-
Foundations	Element subcategory	-	-	132,588 kg	-
Strip foundations	Element	-	-	23,938 kg	-
Foundation in concrete	Component	52 m	-	23,938 kg	-
Strip foundation (350 x 900 mm)	Construction	-	-	23,938 kg	-
Concrete C30/37	Building product	0,17 m ³ /m	9,1 m ³	21,840 kg	120 y
Thermo block - string	Building product	0,08 m ³ /m	4,16 m ³	1,964 kg	60 y
Thermo block - insulation	Building product	0,1 m ³ /m	5,2 m ³	135 kg	60 y
Floor deck	Element category	-	-	108,650 kg	-
Ground floor deck	Element subcategory	137 m ²	-	108,650 kg	-
Ground deck w/ EPS insulation (750 mm)	Construction	-	-	108,650 kg	-
Concrete C25/30	Building product	0,1 m ³ /m ²	13,7 m ³	32,880 kg	100 y
Steel, reinforcing steel	Building product	4 kg/m ²	548 kg	548 kg	100 y
EPS insulation (Styrofoam ®) for ceilings / floors and as edge insulation B / P-035	Building product	0,35 m ³ /m ²	47,95 m ³	1,242 kg	60 y
Capillary break layer (Shingles 2-15 mm)	Building product	0,3 m ³ /m ²	41,1 m ³	73,980 kg	100 y
External walls	Element category	-	-	34,664 kg	-
External walls	Element subcategory	-	-	22,745 kg	-
Facade OPTION 1	Element	90 m ²	-	22,745 kg	-
Outside: Brick facade OPTION 1.1	Component	-	-	22,745 kg	-
Aerated concrete 472 kg/m ³	Building product	0,1 m ³ /m ²	9 m ³	4,248 kg	80 y
Mineral wool, regular	Building product	0,2 m ³ /m ²	17,55 m ³	461 kg	80 y
Bricks, facing	Building product	0,09 m ³ /m ²	8,37 m ³	15,066 kg	120 y
Mortar, masonry mortar, regular mortar	Building product	0,02 m ³ /m ²	1,98 m ³	2,970 kg	120 y

Numbers in green are not added up in the total building sum (demolition)

Help Hide all Show all

Figure 7. Quantity chart.

Help Marking Building products Results Per m²/year Hide all Show all

	Description	Replacements	GWP [kg CO ₂ -Equiv.]	ODP [kg R11-Equiv.]	POCP [kg Ethene-Equiv.]	AP [kg SO ₂ -Equiv.]
Building	Unit	-	1,22e+01	2,83e-08	8,83e-03	2,88e-02
Operation	Sum	-	7,86e+00	1,39e-10	3,63e-03	1,83e-02
Electricity	Sum	-	9,15e-01	5,20e-12	2,03e-03	3,64e-03
Heating	Operation	-	6,95e+00	1,34e-10	1,60e-03	1,47e-02
Materials	Sum	-	4,37e+00	2,82e-08	5,20e-03	1,05e-02
Foundations	Element category	-	1,72e+00	3,99e-09	3,95e-03	2,23e-03
Strip foundations	Element subcategory	-	3,68e-01	7,32e-10	4,10e-04	4,74e-04
Foundation in concrete	Element	-	3,68e-01	7,32e-10	4,10e-04	4,74e-04
Strip foundation (350 x 900 mm)	Component	-	3,68e-01	7,32e-10	4,10e-04	4,74e-04
Concrete C30/37	Building product 0	1,42e-01	4,46e-10	2,49e-05	2,04e-04	
Concrete C30/37	Product stage	-	1,41e-01	4,46e-10	2,38e-05	1,96e-04
Concrete C30/37, EOL	Waste treatment	-	8,37e-04	4,52e-14	1,03e-06	7,89e-06
Replacements	Replacements 0	0,00e+00	0,00e+00	0,00e+00	0,00e+00	
Thermo block - string	Building product 1	1,28e-01	2,71e-12	8,90e-06	1,41e-04	
Aerated concrete 472 kg/m ³	Product stage	-	6,39e-02	1,35e-12	4,09e-06	6,81e-05
Waste, building, waste treatment	Waste treatment	-	3,57e-04	5,54e-15	3,59e-07	2,52e-06
Replacements	Replacements 1	6,42e-02	1,35e-12	4,45e-06	7,06e-05	
Thermo block - insulation	Building product 1	9,76e-02	2,84e-10	3,76e-04	1,29e-04	
EPS insulation (Styrofoam ®) for ceilings / floors and as edge insulation B / P-035	Product stage	-	2,61e-02	1,42e-10	1,88e-04	5,93e-05
Waste, synthetic, incineration district heating	Landfill	-	2,27e-02	3,97e-14	2,87e-07	5,40e-06
Replacements	Replacements 1	4,88e-02	1,42e-10	1,88e-04	6,47e-05	
Floor deck	Element category	-	3,26e-09	3,54e-03	1,76e-03	
Ground floor deck	Deactivated Main groups	-	3,26e-09	3,54e-03	1,76e-03	
Ground deck w/ EPS insulation (750 mm)	Element subcategory	-	3,26e-09	3,54e-03	1,76e-03	
Concrete C25/30	Construction	-	6,1 Total	90e-05	3,14e-04	
C	Building products	Per m ²	Per m ² /year	Per m ² /year	Per m ² /year	
	Stages	Total, normalized				

Figure 8. Results chart.

It is possible to highlight a specific hierarchy level in order to check the results or to compare specific items. As with all other output functions, available reference units can be displayed as total, per m² and per m²/year. All information from both views are united

in the table file export, which gives a complete overview of input and output for further analysis, revision or visualisation outside the tool. The total results can also be reviewed by comparing the project with other projects in the tool. Analysis for uncertainty of results are not yet included in the tool. Uncertainty in an LCA can for instance be reduced by improving the data quality of sensitive input parameters, and thus improve the robustness of design decisions in the building. Future development of the tool should, therefore, consider sensitivity analysis of inputs, such as first-order approximation or Monte Carlo simulation, and scenarios. Typical uncertainties in building-LCA are temporal aspects due to the long service life of buildings. Here, scenarios to consider are the variability of reference service lives of building products, the reference study period, as well as operational energy scenarios.

The overall rating of the pages displaying quantities and results tables is positive (69% useful/very useful, 24% neutral, 4% less useful). However, not all respondents have made use of them due to the exercises being mostly focused on the analysis pages. Some respondents commented to have used the results and quantities tables for error inspection. The quantities and results pages were considered more difficult and not sufficiently visual. This is not viewed as a downside of the tool usability, since a variety of visualisations is provided among the analysis functions. Furthermore, visualisation can be performed freely when exporting the results. The scientific notation for LCA results is generally confusing for non-engineers such as architects or clients. In addition, some had difficulties understanding the outputs given in units of environmental indicators or resource use, most likely due to a lack of background knowledge given in the short training.

4. Conclusions

This paper provides insights from the development process of the Danish building-LCA tool LCAbyg. The aim was to provide general learnings from the process and approach, which can be useful for the development of building-LCA tools tailored to other contexts.

The first research question referred to the requirements for building-LCA tools that are relevant within their respective contexts. In Denmark, the starting point of tool development was the definition of key methodological choices in order to create the foundation of a broad adoption of LCA in the industry. This process proved to be inevitably entangled with the development of the tool itself. The actual tool development work took advantage of a close stakeholder involvement before the initial launch and during the evolution of the tool. The four overall themes, available default data and settings, versatility, environmental feedback for informing design and transparent results, led the development of detailed tool features. Key elements of the tool include a default component library, based on products from the LCIA database, which are suited for modelling the most common Danish building types.

The second research question referred to the uptake of the tool by building professionals, expressed by a survey. Some responses suggest extending the library to cover a greater variety of solutions. Hence, the pre-defined component library will require regular updates or extensions. Another area in progress is the digital data flow in the building industry. With the emerging requirements for quantitative performance assessments, building design work has gradually been immersed by data analysis. Yet, at the current state, most projects do not exploit the potential of shared building models for collaboration in performance assessments—including LCA. The chosen manual input approach in LCAbyg, however, is being challenged by frontrunners in digitalisation. Better data exchange possibilities need to be added to the manual approach in order to maintain the ambition of supplying the entire range of users and providing a tool for the entire industry, not the least in a regulatory context. Participants mostly used the tool's visual data output and expressed an overall positive rating. Tool pages showing detailed lists with quantities and results were met with more reservation from users, presumably because this information aligns more

to specialists' work. However, some interested users acknowledged the usability of these output formats for error checking or a more in-depth insight into the LCA model.

Future Development

A new tool version, supporting compliancy with the Danish voluntary sustainability class (VSC), is currently under development. Here, the new LCA modules for transport from factory to building site, the construction process and loads and benefits beyond the system boundary will be included. Clients testing VSC on their projects are asked to submit LCAbyg project files as a part of the documentation. Project data will be collected and analysed, leading to an evaluation after the two-year test period. Evaluation data will be used to review the Danish LCA method and further develop the LCA tool. Other ongoing projects will improve the usability of the tool for existing buildings, including an extension of default data, review the user interface and develop solutions for data exchange with digital building models. Furthermore, functions for uncertainty management should be included in order to support robust decision making.

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Appendix A

Table A1. Questionnaire (At the Beginning of the Course).

Topic: Your company

Q1.1 How many employees does your company have? (1 answer)

- 0–2
 - 3–10
 - 11–20
 - 21–50
 - 50+
-

Table A1. *Cont.*

Topic: Your company

Q1.2 What type of company is it? (1 answer)

- Engineering consultancy
- Architectural practice
- Contractor
- Other consultancy
- Other company type

Obligatory text

Q1.3 Does the company have employees, who work with sustainability across projects? (1 answer)

- Yes and I am one of them
- Yes and it is only me
- Yes, but not me



Q1.3.1 What tasks belong to your position (multiple answers)

- Energy and/or renewable energy
- Life cycle assessment (LCA)
- Sustainability certification schemes
- Sustainable/circular use of materials
- Indoor climate
- ICT including i.e., BIM, analysis tools, Be18
- Other sustainability

Obligatory text

- No
- No, but this position is being considered for the future
- I don't know

Q1.4 Is LCA part of the company's services today? (1 answer)

- Yes
- No
- Under development
- Considered
- I don't know

Table A1. *Cont.*

Topic: Your company

Q1.5 Has your company experienced barriers in offering LCA services? (1 answer)

- Yes, the following Obligatory text
 - No
 - I don't know

Q1.6 Has your company experienced demand for LCA-based services? (1 answer)

- Yes (explain) Obligatory text
 - No (explain) Obligatory text
 - I don't know

Topic: Your professional background

Q1.7What is your education? (multiple answers)

- Architect
 - Engineer
 - Drafter
 - DGNB consultant
 - DGNB auditor
 - Other education in building technology or sustainable building

Q1.8What is your experiences as a building professional? (1 answer)

- No professional experience
 - 1–2 years
 - 3–5 years
 - 6–10 years
 - 10+ years

Q1.9 What project stages have you primarily worked with during the last 5 years? (multiple answers)

- Architectural competition (or similar)
 - Project management
 - Project preparation

Table A1. *Cont.*

Topic: Your professional background

- Concept design
- Building permit
- Developed design
- Technical design
- Construction, handover, close out
- Other Obligatory text

Q1.10 In what technical field do you have special expertise? (multiple answers)

- Building operation
- ICT
- Fire safety
- Operational energy
- Thermal indoor climate
- Ventilation
- HVAC
- Acoustics
- Daylight and lighting
- Structural design
- Accessibility
- Building economics
- Tendering
- Other building professional expertise Obligatory text

Q1.11 Estimate your competence in the field of environmental assessment/LCA (1 choice)

Low	Average	High
-----	---------	------

Q1.12 How many whole building LCA have you conducted? (1 answer)

- 1–2
 - 3–5
-

Table A1. *Cont.*

Topic: Your professional background

- 5+
 - None, but I have performed LCA on building parts
 - None

Q1.13Have you ever used LCA tools? (1 answer)

- Yes

**Q1.13.1What LCA tools did you use?
(multiple answers)**

- I have used LCAbyg in my education
 - I have used LCAbyg in my professional practice
 - I have (also) used the following other LCA tools Obligatory text

- No

Q1.14What is your aim with this course? (free text)

Obligatory text

Appendix B

Table A2. Questionnaire (at the end of the course).

Topic: Your project and documentation

Q2.1 About your project (free text)

Q2.2 What project documentation did you bring?

- Hand sketches
 - Hand drawing
 - CAD model
 - CAD print

Table A2. *Cont.*

Topic: Your project and documentation

- BIM model
 - BIM print
 - Description
 - Project brief
 - Other

Q2.3 What project stage does your project documentation refer to? (multiple answers)

- Strategic definition
 - Preparation and brief
 - Concept design
 - Developed design
 - Building permit
 - Technical details

Q2.4 What is the documentation's level of definition? (1 choice)

Regarding the structural concept:

Undefined Somehow/partly Defined

Regarding the building element area:

Undefined Somehow / partly defined Defined

→ Obligatory
text

Regarding the component detailing:

Undefined Somehow / partly defined Defined

Q2.5 Why did you choose this type of documentation for the project?

Obligatory text

Q2.6 Will a BIM model be developed at a later stage?

- Yes

Q2.6.1 When do you expect this to happen?

- Strategic definition
 - Preparation and brief

Table A2. Cont.

Topic: Your project and documentation

- | | |
|---------------------------------------|---|
| <input type="checkbox"/> No | <input type="checkbox"/> Architectural competition (or similar) |
| <input type="checkbox"/> I don't know | <input type="checkbox"/> Concept design |
| <input type="checkbox"/> Other | <input type="checkbox"/> Developed design |
| | <input type="checkbox"/> Building permit |
| | <input type="checkbox"/> Technical design |
| | <input type="checkbox"/> Other Obligatory text |

Q2.7 Who will be responsible for the BIM model?

Obligatory text

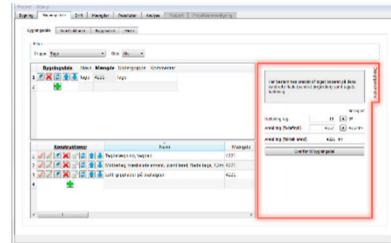
Topic: The tool

Q2.8 How do you rate the tool's quantity estimation support?(1 choice)

Not useful	Neutral	Very useful
------------	---------	-------------

Q2.9 Do you have any comments on the quantity estimation function (figure)?

Optional text



Q2.10 How well does the tool meet the level of detail in your project documentation?(1 choice)

Not at all	Neutral	Very well
------------	---------	-----------

Optional text

Q2.11 How do you rate the available number of default components?(1 choice)

Too few	Adequate	Too many
---------	----------	----------

Optional text

Q2.12 How do you rate the technical quality of the default components?(1 choice)

Unacceptable	Neutral	Very high
--------------	---------	-----------

Optional text

Q2.13 How do you rate the output functions?

- | | Not useful | Less useful | Neutral | Useful | Very useful |
|----------------------|------------|-------------|---------|--------|-------------|
| a) "Quantities" tab: | | | | | |
| b) "Results" tab: | | | | | |
| c) "Analysis" tab: | | | | | |

Table A2. Cont.

Topic: The tool

Q2.14 Did you miss functions, which would have helped you performing the exercises today?

No

Yes

Q2.14.1 What functions?

Obligatory text

Q2.15 Would you change your approach when performing the exercises again?

No

Yes

Q2.15.1 How?

Obligatory text

Q2.16 What would you like to have tried or learned, if the course would continue?

Optional text

Q2.17 Do you have other comments regarding the tool or the course?

Optional text

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