Comparative Overview on LCA Software Programs for Application in the Façade Design Process

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Abstract

Façades impact the environmental performance of a building by their passive contribution to operational energy demand and by embodied energy and emissions during each life cycle phase. LCA is a method widely used to quantify the environmental contribution. The use of LCA software programs in façade planning can guide design decisions and contribute to environmental optimisation.
A large amount of LCA software programs have been developed so far, all of which differ in their focus and requirements. This paper aims to address these differences and investigate the capability and suitability of these programs for façade design. It is structured in four sections. The first part introduces LCA in the building and façade design context. The second part introduces categories to understand the different capabilities of LCA software products. Hereafter, eleven products are evaluated based on these categories. The fourth part focuses on the suitability of software products for simple or complex façades. The study concludes that there are different software choices available for almost every level of user knowledge. While Gabi, Simapro, and Umberto require users to work to a high level of proficiency, software programs like eLCA, CAALA, and 360 Optimi do not require much user knowledge over LCA, but provide a range of other opportunities.

Keywords

Life Cycle Assessment, LCA software programs, façade design, environmental impact

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1 INTRODUCTION - DEVELOPMENT OF LCA IN ARCHITECTURE AND FAÇADE ENGINEERING

In the 1960s, life cycle assessment (LCA) flows were initially calculated for the depletion of resources and the generation of energy. (Guinée et al., 2011; Jensen, Hoffman, Møller, & Schmidt, 1998) Decades later, a broad range of information was developed for the building materials. The environmental assessment of buildings mostly gained attention in the 1970s when more careful calculations for operational energy demand were required due to the oil crisis. The number of green building certificates has increased significantly in the last three decades, alongside a growing awareness of a building's different life cycle phases. The production phase of a building's life cycle – along with the end-of-life scenarios – were integrated in the sustainability assessments and received increasing attention. Environmental Product Declaration (EPD) provided information for building materials according to the ISO standard 14025 (DIN, 2011). The variety of databases and software programs that have been developed so far provide the user with the opportunity to devise environmental decisions at different planning phases. Many metrics and standards have since been developed to quantify the environmental impacts of buildings. Life Cycle Assessment (LCA) is considered to be one of the most prevalent and reliable methods to date (Klöpffer & Grahl, 2009).

Against the background of a design and planning process which includes increasingly more information, software products become faster at processing complex data. The developments to support building information models provide the opportunity to include ecological information in the planning process with a comparably small workload.

Successful LCA software tools reflect both development in the building planning process and variations in applying the LCA method. In the last two decades, a large variety of LCA software products were introduced to the building industry and the number is growing. The overall goal of this paper is to encourage the application of LCA as a means to reduce the environmental impact of the façade. As both the façade and the LCA method are complex in nature, the application of LCA software products is intended to be encouraged here, by providing the means to understand the potential of specific software products. Furthermore, the goal is to explain the capabilities of software products and refer them to planning situations. This paper provides categories to understand the scope of software products and support to choose the most suitable LCA products by explaining different purposes of LCA software products. On the basis of this overview, façade planners can examine the suitability of the individual programs in terms of their own previous knowledge and the complexity of their design.

2 METHODOLOGY

The research follows the question: Which LCA software programs are more suitable for façade engineering according to different user experiences and different degrees of complexity in façade design?

In order to answer this, the paper is structured in four parts. The first introduces façade design and its environmental dimension. Here, findings from other studies regarding the ecological impact of façade typology are described (Hildebrand, 2014). The ecological scope and user experience is characterised by seven categories in the second part. These are based on the evaluation of software products published in Bach and Hildebrand (2018). In the second part, the categories are briefly introduced. After that, a comparison model is developed based on six of these categories. The model is based on a radar graph in which the six categories are spread along the axes and by travelling from the centre to the outer layers, the comprehensiveness of the said criteria increases. In the third part, the model is applied to eleven LCA tools which have been chosen among the 26 evaluated software products as the most useful in the façade context. The result is a set of graphs that provide the ability to be compared. The fourth part reflects the LCA software products regarding the user's experience and planning tasks with different extents of complexity.

3 LCA IN FAÇADE DESIGN

3.1 ENVIRONMENTAL IMPACT OF FAÇADES

The relevance of the material and construction contribution to the overall ecological performance of buildings increased with sinking (non-renewable) energy consumption during the usage period. The building's substance was identified as having potential to further decrease the negative effect of the built environment to the natural environment. In the last 20 years, a variety of studies on building and building element level have been published in which different planning alternatives or built examples are compared to one another. For example, in Blanchard and Reppe, (1998) the authors presented the ratio of operational and embodied energy for a typical American home. Finnveden et al. (2009) reviews the differences in LCA methods; Guardigli, Monari, and Bragadin (2011) use LCA to evaluate construction alternatives; Lasvaux, Habert, Peuportier, and Chevalier (2015) address the topic of generic and product specific LCA flows; Lüdemann and Feig (2014) present an overview of software products; Meex, Hollberg, Knapen, Hildebrand, and Verbeeck (2018) investigate the application of LCA tools in the architectural context; and Takano, Winter, Hughes, and Linkosalmi (2014) compare different databases used for LCA.

As there are no benchmarks for the ecological performance (for the building substance) available, in LCA planning alternatives are compared to one another. Studies like Villares et al. (2017) and Hildebrand, (2014) state that LCA at early planning phases gives neither final nor accurate results, but it can have a great impact on the environmental performance especially when comparing alternatives. It is recommended that the solution showing the lower results (most commonly considering primary energy rather than renewable, also called embodied energy, and the global warming potential which is also called embodied carbon) should be realised.

Among the building elements, generally the building structure accounts for the highest ecological impact due to its high weight. Its impact can be significantly reduced with a lighter construction made from renewable materials. By optimising the cross section, only smaller reductions are possible. Most typically, the building's envelope accounts for less environmental impact in comparison to the building structure. However, due to the variety in typology and material, the bandwidth for environmental impact is very broad (Hildebrand, 2014). Fig.1 shows the impact of the façade typology; light façades, like a wooden post-and-beam construction, consisting of one structural layer, accounts for the lowest amount of embodied energy. Solid façades, like masonry or concrete façades with one layer are heavier and show higher values. Double- façades with a high proportion of aluminium or steel construction show the highest amount of embodied energy. This evaluation shows the relevance of the typology for the environmental impact of façades. With the choice for one typology, the span of impact is predefined.

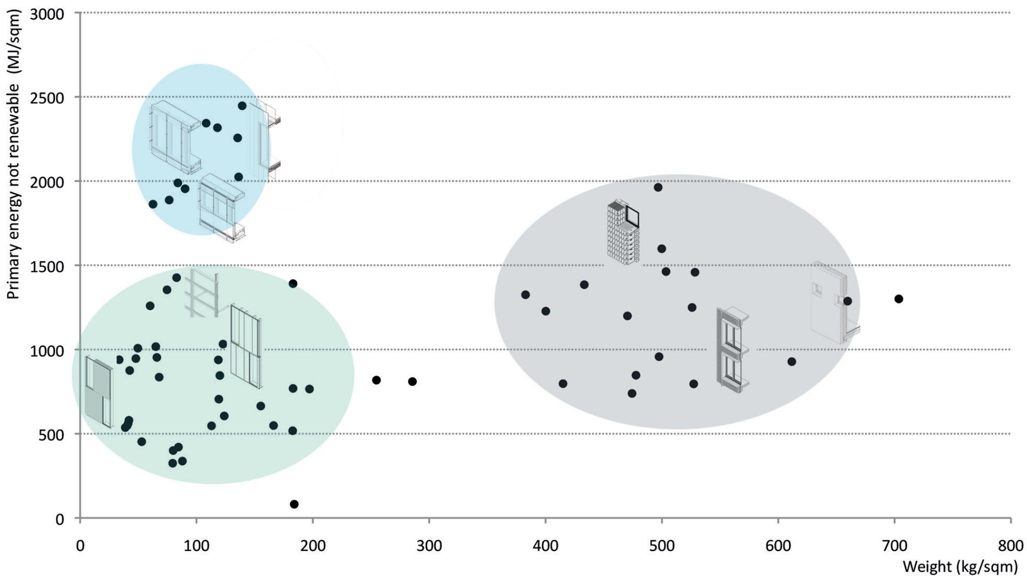

FIG. 1 Embodied energy in different façade typologies. (blue: double façades; green: post-and-beam construction; grey: solid façades) *(Hildebrand, 2014)*

3.2 SOFTWARE PROGRAMS TO ASSESS ENVIRONMENTAL PERFORMANCE

In façade design, energy demand is impacted by the passive properties of the façade. So far, there are various software programs such as EnergyPlus, TRANSYS, OpenStudio, etc. developed specifically to calculate the energy performance of a building during its operation. While, on building level, the link between embodied and operational energy can be found (for example, Caala), it is rarely found at building element level. In the context of façade design, trade-offs between operational and embodied energy are possible. A link between the two can be useful. This calls for the close cooperation of façade engineer, architect, and HVAC engineer. Integrated software solutions are not part of this paper. In order to contribute to bridging the disciplines, this paper presents the differences in LCA software programs.

In this context, a consideration of operational energy can inform about the relevance of embodied energy and carbon dioxide. For a building with high operational energy (supplied by non-renewable energy sources), it makes sense to reduce the energy efficiency first before optimising the building substance. For buildings with low (non-renewable) energy demands, such as nearly zero energy buildings, the optimisation of the building substance can contribute to an improved overall environmental performance. The application of LCA software programs in façade development, without the context of the building, can also contribute to a better environmental performance. It can be used to optimise the amount of material used in a façade element and/or to choice of a specific material with a low environmental impact. Furthermore, it can be useful to check whether the combination of products supports a circular production chain and whether reuse or recycling is possible.

LCA in the building sector is relatively new. However, some façade companies have picked up on this development and provided life cycle data for their products. The motivations for an architect or façade engineer to include a LCA in the planning process may include the following:

- review the façade concept in terms its ecological impact
- decide upon the façade typology and quantify its scope
- compare different planning alternatives
- optimise the construction and material choice in the façade
- review the performance of new materials regarding their ecological performance.

Currently, two ways of integrating LCA in the planning process can be observed: either an external LCA expert is involved or an engineer in the company performs the LCA. For the planning process, the internal solution offers advantages as changes can be easily incorporated. Regarding the choice of an LCA software, the user's level of knowledge - whether they are a LCA professional or planner - is decisive. Beyond this, LCA can be motivated by auditing for a green building certificate. In this case, the building is assessed with regard to its ecological performance and evaluated in a reference system. It is not integrated in the planning process, but conducted when it is completed.

In order to approach façade engineering in the context of this paper, the range of planning tasks is simplified into more simple and more complex façades. While simple façades consist of a small range of materials and standard construction typology, complex façade systems include a high degree of diversity on technical aspects, construction type, and material choice. Solid or layered façades are typical simple façades. Double façades or customised façade elements account for complex façades.

4 CATEGORIES TO CHARACTERISE LCA SOFTWARE PRODUCTS

In order to create a proper basis for the comparison of different programs, it is first needed to determine suitable categories to differentiate the programs based on them. In the following, categories to differentiate software products are introduced based on those described in Bach and Hildebrand (2018), in which a more elaborate description can be found. For this study, all categories are adopted with two exceptions: the level (building, component, material) is not discussed as the focus here is on façades that belong to the group of components. The accessibility is also excluded as this paper addresses architects and façade engineers for which this criterion is less relevant than for students. Here, optimisation is included as working hours are very relevant in the commercial context.

1 Origin

The origin of a software program can be categorised by the developer, country of origin, and year of publication. The developer can be a research institution or a company, which can be a hint in terms of its accessibility and scope. The country is relevant in regard to the national background, as it indicates the use of the national database. The year of publication indicates the actuality. Programs that have been available on the market for many years have already gone through several optimisation cycles, whereas programs that are still in the beta phase usually address current research results and problems in order to close gaps in earlier programs.

2 Required user knowledge
LCA software tools are designed for different user profiles: no previous knowledge of LCA, basic knowledge, and expert knowledge. Programs developed for users with expert knowledge usually have highly editable pre-settings, so that the assessment can be adjusted. These programs are mainly used in research and consulting. Programs for users with little or no previous knowledge in the LCA include limited access to change settings.

3 Data source

Software products have either a predefined database, which cannot be changed, or they are open to different databases or single data sets. Often, databases refer to a national context which makes the choice for any particular one relevant, as, for instance, the share of renewable energy varies, which leads to different primary energy coefficients in different countries.

4 Entry format

LCA calculations are based on mass and volume related data. The input of this data can be supplied in spreadsheet and geometric-based format. Geometric-based programs require 3D- geometric data input. Software programs based on spreadsheet format require the manual entry of mass or volume related data, which must be calculated separately in a previous step.

5 Optimisation

The ideal application of LCA includes an optimisation, which can either be conducted manually (LCA results are analysed, changes in the planning are made, and LCA is conducted again) or computational (LCA is conducted and a computational optimisation follows). Usually, spreadsheet programs require manual iteration. For 3D programs with access to LCA, an optimisation is easier to include but until now has seldom been found.

6 Default settings

Default settings provide a basic structure to facilitate the applicability and execution of the LCA for the user. The more default settings are specified, the faster and easier the first statements can be made. For higher accuracy, it can be useful to adjust to specific situations. This includes the settings of the database, the life cycle phases, and the considered life span.

7 Life cycle phases

In general, LCA is divided into three groups of life cycle phases: production, use phase, and end-of-life. Standard EN 15804 (DIN, 2012) differentiates them into 17 stages. There are few programs that look at all these phases. In general, a distinction can be made between three levels: programs that consider only part of the production process: A1-A3; others that also include part of the deconstruction and recycling process: A1-A3, C3-C4, D; and programs that consider parts of all life cycle phases: A1-A3, B6, C3-C4, D.

The categories discussed above describe the essential characteristics of an LCA software program and help to identify the most suitable choice for a specific application. In the following, they are embedded in a model and applied to each program individually.

5 MODEL DEVELOPMENT AND SOFTWARE COMPARISON

In this section, different LCA programs are analysed according to the categories described in the previous chapter. To do so, a chart was structured, in which the discussed categories in the previous section are spread along the chart's axes. The inner circle represents relatively limited and less accurate statements about LCA, whereas the outer circle illustrates a more holistic, broad and more detailed analysis. As a consequence, by traveling from the inner circle to the outer one, the LCA software provides more comprehensive, reliable calculations, which also require more a professional level of working knowledge. On the other hand, software programs closer to the inner circle provide simple comparisons and quick statements with less effort.

The 'origin' criterion is excluded from comparison since it is a region-based characteristic which the user has to select based on their project and it does not represent the level of comprehension of a software. As a result, the remaining six categories were spread along the chart for comparison. In some categories, there are two steps and in others, there are three steps of comprehensiveness. In the following, the software programs are introduced in the order of their development.

The German Ganzheitliche Bilanzierung (GaBi) [Holistic Assessment] (Fig.2, right) and the Dutch Simapro programs (Fig.2, middle) are regarded as the earliest software, having been introduced in the early 90s. Following that, Umberto (Fig. 2, left) was developed to address material assessment. Today, GaBi, Simapro, and Umberto have evolved into (LCA-) expert tools based on very detailed information. Moreover, they provide the ability to edit many different settings within the program to adjust it more to the project condition. They are mainly used to assess products (for example for the Environmental Products Declarations), and are highly detailed and relatively accurate in their calculations. However, their complexity and high user knowledge requirements make it more difficult for building sector users to handle them. Fig. 2 shows the similarity of these software in the six studied criteria.

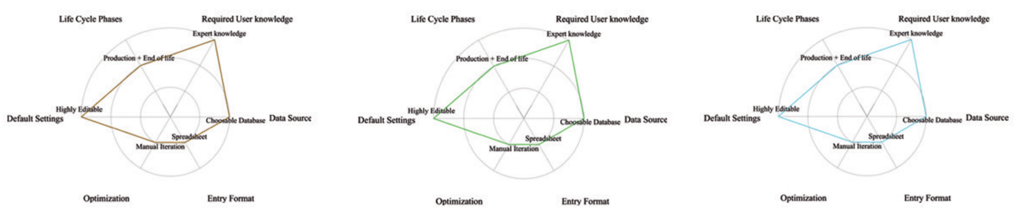

FIG. 2 Analysis of the early LCA tools and their similar functionality (from right to left: Gabi, Simapro, Umberto)

The focus of the German software Legep (Fig. 3), released in 2005, is on building materials; the entry format is spreadsheet based. To increase the number of users, the Open LCA program (Fig. 4) provides free access and includes a broad variety of databases (which are only partly free of charge). Athena (Fig. 5), established in Canada, is focused on material selection, by using the US units of building materials.

The spreadsheet-based tool eLCA predefines its entry mask and provides a large amount of default settings, which allows for easy calculation at the building element level. eLCA (Fig. 6) is able to compare planning alternatives to strengthen the application as a basis for decision-making, rather than simply documenting the results. This free tool motivated the integration of LCA for the German context.

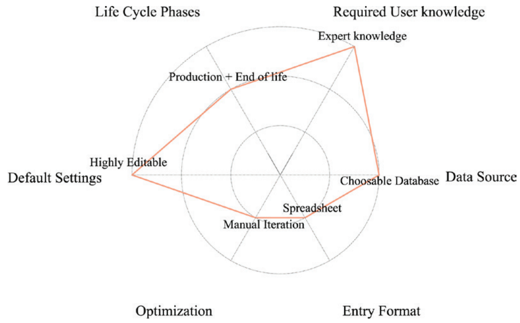

FIG. 3 Application of model on Legep software program

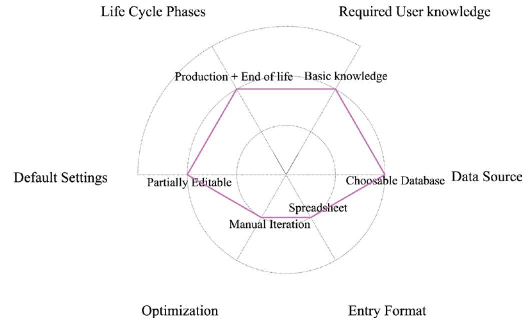

FIG. 4 Application of model on Open LCA software program

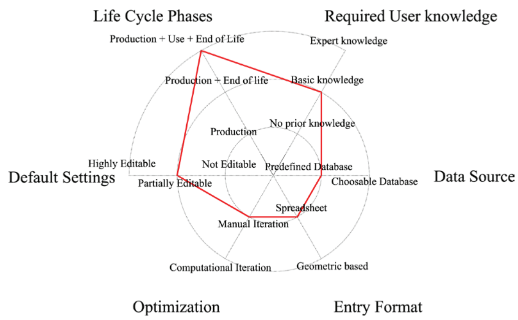

FIG. 5 Application of model on Athena software program

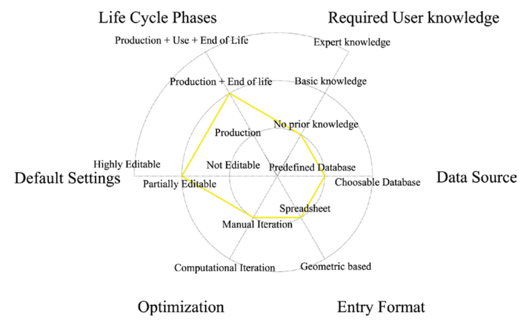

FIG. 6 Application of model on eLCA software program

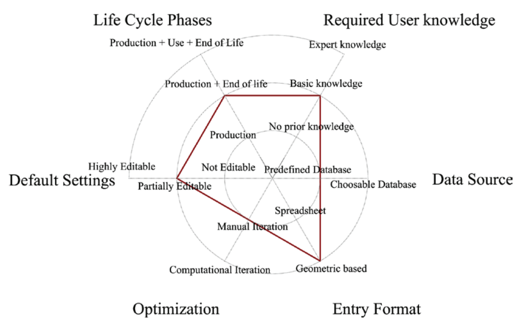

FIG. 7 Application of model on Tally software program

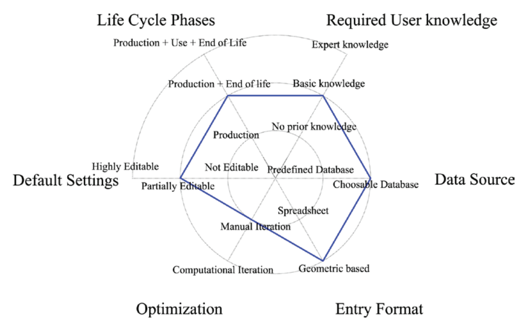

FIG. 8 Application of model on 360 Optimi software program

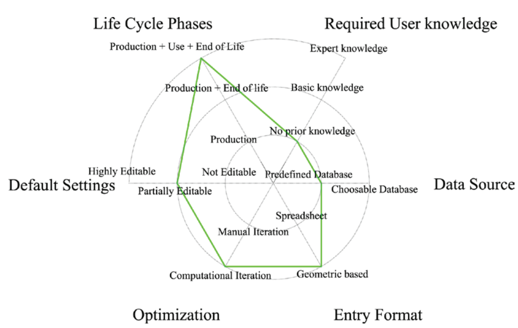

FIG. 9 Application of model on CAALA software program

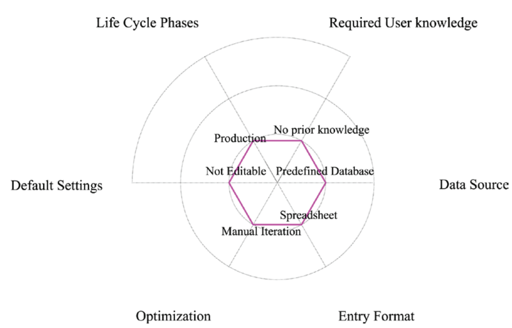

FIG. 10 Application of model on BEES software program

The software programs Tally (Fig. 7) and 360 Optimi (Fig. 8) provide the link between 3D data and different LCA databases. On the other hand, CAALA (Fig. 9) connects to Ökobau.dat and includes an optimisation feature, which assesses the ecological impact of the building fabric and relates it to a simplified (operational) energy calculation. A growing number of add-ons for computer programs like Revit (Autodesk) or Rhinoceros (McNeel) are also available, while software programs like BEES (Fig.10) use a much more simple, and non-editable interface to provide an easy platform.

Fig. 11 depicts the overall comparison of all the eleven analysed LCA software programs. The comparison also reflects that most of the software programs available focus on the production and end-of-life phases of a building's lifespan, and only Athena and CAALA take the use-phase into account. The comparison also illustrates that there are different software choices available for almost every level of user knowledge. While Gabi, Simapro, Umberto, and Legep require a high level of user proficiency, there are still software programs like CAALA and 360 Optimi that do not require much user knowledge of LCA, but still provide a good range of other opportunities. Although BEES (Fig. 10) is considered to be a program that requires no prior knowledge, it has fewer editable options and therefore provides less accurate statements. Similarly, eLCA is a tool that provides more editable options, which makes it an easy-to-use tool for designing simple façades.

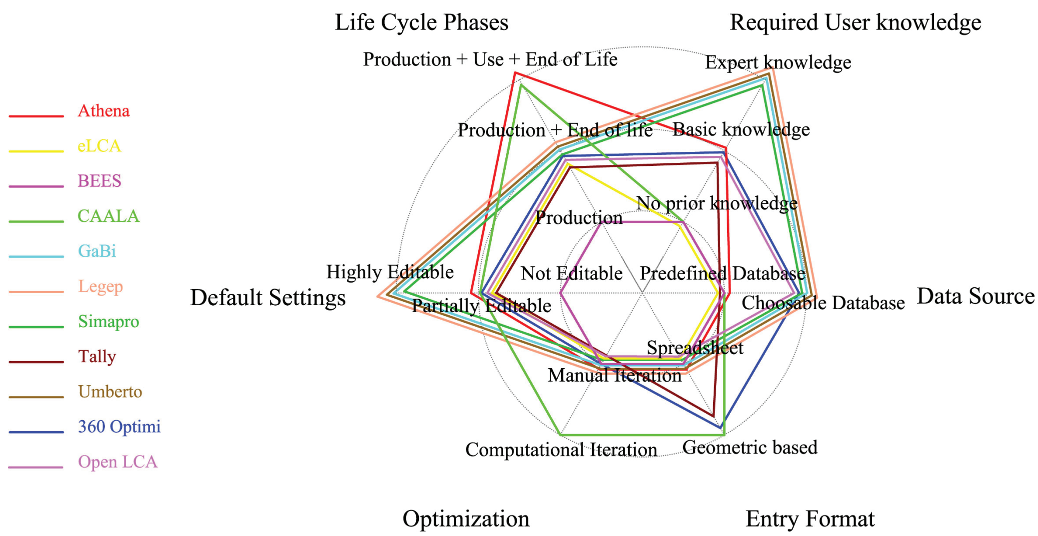

FIG. 11 Comparison of eleven LCA tools based on façade engineering aspects

It is also understandable from the graph, in terms of default settings, that the more editable options the programs provide, the higher the level of user knowledge required. This inevitably leads to a switch to less editable (and therefore less accurate) software when an inexpert user tries out LCA tools. Therefore, it is more challenging to choose an appropriate software when there is a shift towards partially editable software, as these offer different capabilities when compared to one another. For example, Tally and CAALA provide good optimisation with a geometric based entry, while 360 Optimi is recommended when there is a need to be able to choose from different data sources.

While the graph shows a balanced distribution of the type of data sources that different software use, it is clearly visible that still most of them use spreadsheets rather than geometric entries. Greater use of spreadsheets makes it difficult for designers to work with the software programs as this group normally works with 3D geometries in their projects. Moreover, use of 3D geometries often provides the ability for an easier recalculation of environmental impact of a façade when there is need to change an element. As a result, modifications and optimisation in geometry-based software are more convenient for the user.

All in all, the almost symmetrical, widespread graphs indicate that there are many different tools for addressing different criteria at different building levels. Therefore, it is crucial to advise users on what software to choose, when it comes to planning the façade, which is the main core of the following chapter.

6 SOFTWARE CLASSIFICATION FOR FAÇADE DESIGN

When preparing a LCA study, it is essential to consider the context in which it will be carried out. When selecting a LCA software and the corresponding database, the national context as well as the actuality and degree of elaboration of the program should be taken into account. The selection of the life cycle phases considered is important for the comparability of the studies. Differences in the method of LCA over the last two decades can be observed. In the beginning, only the production phase was considered. Later, generic End-of-Life scenarios for material groups were introduced, which found broad application. Considering or excluding the End-of-Life can impact the LCA significantly. For a comparison between a customised and a prefabricated façade element, the exclusion can favour the first one, as material can be reduced for a specific building and values can be lower. Including the capability for application in multiple usage cycles may require that an element be oversized for its current use. For this, including specific End-of-Life scenarios is useful.

The categories' entry format and optimisation process provide information about the basic structure of the tools. For BIM-based and architectural planning processes, programs with a 3D geometry-based entry format with computational optimisation processes are recommended. These programs prevent errors due to manual entries and transfer errors. Otherwise, these categories depend on the preferences of the user.

The category 'default settings' goes closely together with required user knowledge: the more editable the settings of a program are, the more expert knowledge is needed and vice versa. For example CAALA, which is currently in the Beta phase, shows the greatest number of default settings that are currently non-exchangeable. In this way, design decisions regarding the cubature and material choice can be optimised and the LCA methodology can help to reduce the environmental impact of a building. For research and consulting purposes, it is mostly the established spreadsheet programs, which have highly editable default settings and thus require expert user knowledge, that are being used.

All in all, the most essential criterion for choosing a software tool is the required user knowledge. Programs should be chosen depending on the planner's knowledge level on LCA. Looking at the development of LCA software programs, the younger ones are 3D geometry-based, while the more established programs work with spreadsheets. 3D based programs or building information models tend to show advantages in decreasing the working time as it supports an integrated, rather than an iterative, planning process.

In Fig. 12, the evaluated software tools are classified into an overview according to the criteria 'required user knowledge' and the planning assignment. Most of the evaluated LCA programs are suitable for simple to slightly complex façade planning. They mainly differ in their requirements in terms of the user's previous knowledge and their scope. CAALA, 360 Optimi, and Tally are suitable for simple to slightly complex designs. They require very little to no prior user knowledge. Data input takes place via geometric drawings and CAALA offers a computational iteration process. Thus, they can be easily integrated during the design process. Athena and Legep are similar, both being used in simple to slightly complex façade designs. The default settings of these programs are partly to highly editable, so previous knowledge to expert knowledge, in case of Legep, is needed. As Fig. 6 of Chapter 5 states, eLCA is partly editable but the database is not selectable. The pre-structure of eLCA is specifically created for building components, which makes it partly suitable for complex façade designs with little prior user knowledge. However, it is necessary to insert the data manually, which can be time-consuming when dealing with a large number of individual building elements. Against the background of the increasing amount of information linked to building volume, 3D software tools that provide reference points between information and building materials are increasingly more common (Building Information Modelling – BIM). This offers the chance to connect ecological data and include it in the early design stage, rather than during the phase of construction when the scope of intervention regarding environmental impact reduction is limited.

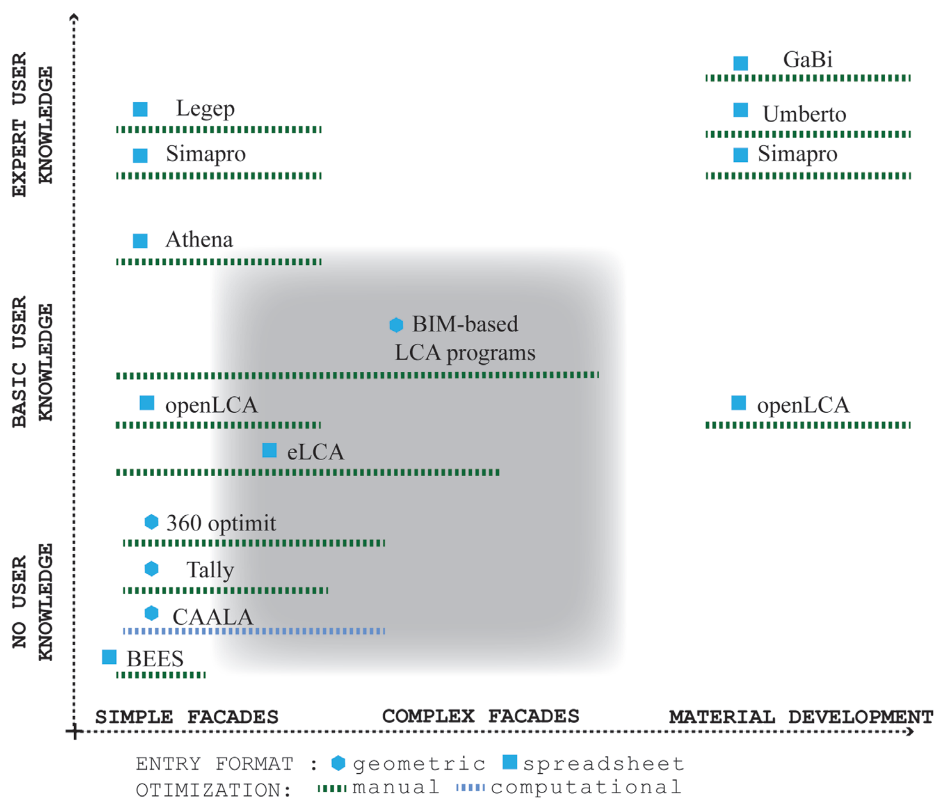

FIG. 12 LCA Software products organised according to user knowledge and planning assignment. The grey field marks the most suitable products for façade design and engineering.

In addition to the axis alignment from simple to complex façade design, the aspect 'Material Development' was added to this axis in Fig.12. Depending on the desired level of detail of the assessment, material development can be carried out for both simple and complex façade designs.

At this level, there are the programs GaBi, Simapro, and Umberto, which were mainly developed for calculations on material level. It is possible to perform LCAs for façades and buildings using these programs. However, this involves a great deal of effort because there are no pre-structures for components or building elements, so everything would have to be designed in small scale at material level.

This graph shows that the evaluated LCA calculation programs, which are among the most common tools in the construction sector, are mostly suitable for simple façade designs. The scope of the software programs is displayed as a green or blue dottedline, as it can be used for different purposes. It is used to demonstrate the range. The form of the blue dot shows the entry format, either geometric or spreadsheet. For the highly complex façade designs, software tools from façade manufacturers, for example, were developed. Since they are not publicly accessible, they could not be evaluated within the scope of this paper. Nevertheless, these manufacturer-specific programs are currently very well suited for assessing complex façade designs, because these tools are specially customised for the planners' needs. Their default settings and pre-structure were developed to calculate façade systems at every level of complexity and they already have the specific data sets of the company's components and elements included. This can be an advantage, when the façade typology and the product are defined and only details like dimension change. Earlier in the design process, programs with access to generic data provide variety.

Otherwise, interfaces can be developed to integrate the LCA processes into the façade design program. For example, the plugin Tortuga was developed for the integration of LCA in Grasshopper processes. Such programs are currently being developed and are still in the optimisation phases.

7 CONCLUSION

The façade typology already predefines a certain environmental range. While light post-and-beam construction accounts for the lowest amount of embodied energy and emissions, solid single layered façades show slightly higher values. Double façades with high metal and glass content result in high environmental impact. This study provided an overview on the categories that façade planners should consider when selecting a program. The paper showed different existing LCA software products, which are suitable for different levels of user knowledge. It was demonstrated that a number of software are available for simpler façade design, such as eLCA or CAALA. Whereas Gabi, Simapro, Umberto, and Legep require high levels of user proficiency. If material innovation requires the LCA for a specific material, GaBi, Legep, or Umberto are suitable. In this regard, an (external) person with expert knowledge on LCA is required due to the complexity of the programs (highly editable). For complex façades, the link between a 3D geometric model and information shows the highest potential, since most of the programs still use spreadsheets rather than geometric entries. The growing number of tools in this field shows high potential for planners with basic knowledge of LCA.

The study also reveals that most of the software programs available focus on the production and end-of-life phases of a building's lifespan, and only Athena and CAALA embed the use-phase into their analysis at building level. Taking into account that there is currently a severe gap in considering both embodied and operational energy at the same time, it becomes clear that more effort is required to develop software choices that address both simultaneously and through all life cycle phases, including the use-phase to provide a more holistic environmental analysis.

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