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Abstract. Connecting Life Cycle Assessment (LCA) to parametric design has been suggested as a way of facilitating performing environmental assessments in early design stages. However, no overviews of potential approaches and tools are available within recent research. Also, no characterisation frameworks adapted for parametric LCA tools are present. In order to guide the development of workflows for environmental analysis aimed at the early design stage of buildings, the goal of this paper is to provide such a framework, and to demonstrate its use by characterising a number of available LCA plug-ins for the commonly used parametric design framework Grasshopper® (GH). First, a framework for classification and characterisation of tools based on workflow, adaptability, and required user knowledge was developed. Second, a tool inventory was performed, identifying 13 parametric LCA plug-ins for GH. Finally, four of these plug-ins were further investigated using the developed evaluation framework, a user persona approach, and a simplified test case. It was found that the characterisation framework was able to differentiate tools based on the level of LCA expertise integrated in the tools, and the allocation of responsibility for data entry and interpretation. A contrast was found between streamlined tools, and tools which provide more versatility. The characterisation framework, and the resulting overview of approaches can be used to guide the future development of parametric environmental analysis frameworks.

Keywords: Early-stage design, life cycle assessment, tool characterisation, parametric design, sustainable architecture

1. Introduction

Buildings have a great environmental impact in terms of greenhouse gas (GHG) emissions and material extraction [1], which needs to be considered in their design process. The most widely accepted method of quantifying environmental sustainability is Life Cycle Assessment (LCA), which involves quantifying energy and resource use, emissions and waste, and environmental impact of buildings, from a life cycle perspective [2-3]. However, LCA is a complex methodology, which requires detailed knowledge on the components of the studied building. This information is usually collected in a bill of quantities (BoQ). The material quantities are multiplied by their environmental impact coefficient from a database. This complexity and the required time for data gathering and calculations, along with the difficulty of interpretation by non-experts means LCA is typically performed by experts late in the design process [2-3].

However, at this point, the results are no longer useful to improve the design, as the changes they imply would be too costly. This motivates the development of simplified LCA methods (both in terms of data collection and interpretation), which could be implemented by architects in earlier design stages, where LCA results have the largest potential to improve the environmental impact of the design [4].

Parametric design is widely used as a means of dealing with the uncertainties inherent in the early design stage, such as rapidly evolving design and decisions which are made in later design stages [2-3]. This approach has several advantages: a parametric model allows for quick design alternative generation, comparison, and evaluation, and allows the design to change with little effort according to changing project requirements [5]. Furthermore, it allows for the utilisation of optimisation techniques [2-3]. In contrast to other LCA approaches, such as generic tools (not specialised for buildings), spreadsheet tools, online component catalogues, and Building Information Modelling (BIM) based tools, Hollberg [3] introduces the concept of Parametric Life-Cycle Assessment (PLCA), where an LCA model is built from 1) geometric information, 2) building materials and services, and 3) determining factors such as user or climate data. Relevant parametrised data is retrieved from the Computer Aided Design (CAD) model and from relevant databases. Once data has been collected and the calculation performed, both overall and partial results of the LCA are output and visualised in order for the user to understand the effect of all design choices on the environmental impact.

The parametric design frameworks most commonly adopted in current practice [7] are Grasshopper® (GH), for Rhinoceros 3D® (Rhino) [8], and Dynamo, for Autodesk Revit® [9]. As Dynamo largely interacts with the BIM model within Revit, it is more relevant when studying BIM/LCA interaction rather than purely parametric LCA tools. Hence, LCA plug-ins for GH is the main topic of this study.

1.1. Previous studies

Literature for this section was collected both from works known to the authors, and through a search in the Scopus database using keywords such as “LCA”, “life-cycle assessment”, “buildings”, “early design”, “review”, and “tool”. Further literature was collected from works citing or cited by these works. As the concept of parametric LCA is comparatively novel, only works from 2012-2022 were considered for this study.

Several studies have reviewed tools for LCA in the early design stage. [10-11] provide overviews of tools for refurbishment decision support, including LCA. [12] review tools, frameworks, and databases for LCA in buildings. [4] provide an overview of LCA tools, and note that, at that time, “parametric approaches for building LCA are rare”. [13] review the user-friendliness of four LCA tools from the perspective of architects. [14-16] review strategies for BIM-LCA integration. [17] categorise and compare twelve programs for LCA. [18] provide an extensive literature review of research on LCA in the building design process. [19] provide a list of approaches to LCA in early design stages and develop an explorative approach. [20] review different approaches to visualising LCA results.

None of the mentioned works provide an overview of approaches to parametric LCA. Also, there is no characterisation framework available which can support a comparison of parametric LCA tools. This research gap serves as motivation for the present work.

1.2. Purpose and research question

The purpose of this study is, firstly, to provide a framework for critically characterising parametric LCA tools qualitatively, and, secondly, to provide an inventory of available, actively developed parametric LCA tools aimed at the early design stage. Thirdly, for demonstration, the characterisation framework is applied to some relevant tools in order to assess its ability to identify alternative approaches to implementing LCA in a parametric design environment.

Two research questions have been identified: *How can parametric LCA tools be categorized and evaluated?* and *What are potential alternative approaches to implementation of parametric LCA tools in Grasshopper®?*

The goal of the study is to find various approaches to parametric LCA which can serve as inspiration for developing frameworks for a holistic environmental assessment in early design stages. Hence, the goal is a qualitative assessment of the features of each approach, not the precision of the assessment.

1.3. Scope and delimitations
The following scope has been defined for the present study:

- only tools which perform LCA are considered
- only tools readily available and updated within the last five years are considered
- only tools for Grasshopper® are considered
- tools are investigated from the perspective of architects active in the early design stage,
- tools are qualitatively evaluated based on potential for integration in architectural design workflows, not quantitatively, based on, e.g., precision
- tools are only investigated based on sample scripts and test cases, not in real design processes.

2. **Characterisation methodology**
This section describes the characterisation framework developed, and the methodology used to test and demonstrate the use of the framework.

2.1. Benchmarking framework
The first step of tool characterisation is a classification based on how the tools interact with design software. For parametric LCA, three approaches were identified, as shown in Figure 1. For approach 1, geometry is modelled in GH and compiled into a bill of quantities, typically a spreadsheet format, which is then used as input to an external LCA software. In approach 2, everything is conducted within the GH environment: geometry definitions, material choices and calculations. Approach 3 is when Rhino or GH geometry is directly exported to an external engine for the LCA calculations.

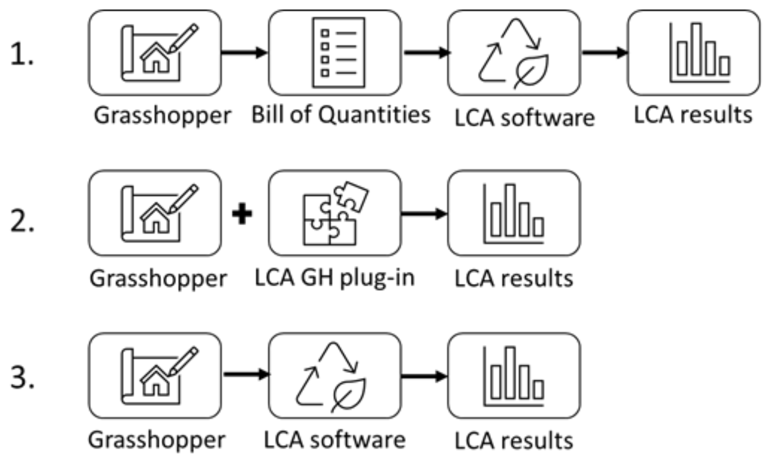

Figure 1. Classification of approaches for LCA integrated in a parametric design environment (Grasshopper®), based on [13].

The developed classification of parametric LCA tools is based firstly on a classification framework proposed by Wastiels and Decuypere [15], who classify LCA tools based on their integration with BIM and secondly on a characterisation approach presented by Hildebrand and Bach [17, 21], which allows for comparison of software based on several categories. These frameworks were adapted to fit the context of parametric design.

As for characterisation of tool features, Hildebrand and Bach specify eight categories: 1) origin, 2) data source, 3) required user knowledge, 4) accessibility, 5) entry format, 6) level, 7) default settings, and 8) LCA phases. By evaluating the programs with regards to each category, a comprehensive comparison of the tools can be established [21]. For the present study the categories evaluated were adapted to suit the purpose of the tool characterisation framework and to capture the main characteristics of the plug-ins regarding their integration in the architect's workflow. For this, nine categories were defined for the characterisation. The categories and their explanations are compiled in Table 1.

Table 1. Categories used to characterise the parametric LCA tools.

Category	Characterisation parameters	Explanation
Required knowledge	Low, moderate, high	LCA knowledge level needed to use the tool based on the user persona.
Geometry input	Surface, volume, curves	Type of Rhino/Grasshopper geometry accepted by the plug-in.
Default settings and adaptability	High, moderate, low	Possibility to adapt the built-in predefined settings. For example: change database, add materials, change scope of LCA.
Modelling level	Material, component, building	Level where one can start an LCA. Are there predefined materials, component and/or building specifications
Output of results	Report, charts, surface colouring	Visualization of LCA results. The results processed into a report, charts and or surface colouring (hotspot).
Intended application	Education, design evaluation, complete assessment	Specify the purpose of the development and use of the tool.
Data source	Material database	Specify the database that is used and eventual possibility to use other databases or import own materials and components.
LCA modules	A1-A3; A4-A5; B1-B7; C1-C4; D	Included LCA modules from EN15978
Impact categories in addition to GWP	Yes / No	Impact categories included in the plug-in beyond GWP

2.2. *User persona*
Since the goal of this study is to gather information for developing tools and frameworks that are useful to architects in the early design stage, a user persona was developed to be able to perform this characterisation from this point of view [22].

The user persona was defined by the following set of assumptions and points of departure:

- The user is an architect with basic skills in Rhino and Grasshopper
- The user knows the fundamental principles of LCA/considered building performance indicators
- The user is mainly interested in evaluating design alternatives in early stages
- The user can spend limited time/effort to perform the analysis. The situation could be a meeting with a client or a brainstorming session as part of a design competition
- It is assumed that the core of the script has been modelled previously, that is, that the role of the user is to adapt an existing script to the project at hand

2.3. *Test case*
For the purpose of assessment and demonstration, each plug-in investigated in order to demonstrate the characterisation framework was used to model and perform an LCA on a 1x1x1m box, with one face containing a glass window, and the other surfaces modelled as two material layers stacked elements, 50 mm mineral wool and 50 mm cross laminated timber (CLT). The assessment was delimited to LCA modules A1-A3. To perform the tool characterisation, information was gathered both through reading of documentation provided by the tool developers, and testing of the plug-in using sample files provided by the developer. It should be mentioned that the nature of the GH environment allows for alternative ways to use the same plug-in and customise scripts for the specific purpose at hand. Hence the results of the characterisation procedure could have differed in another context.

2.4. *Tool inventory*

Tools were mainly located using the search engine of the Rhino plug-in community food4Rhino, which is a service by McNeel, the developer of Rhino, and contains the most up-to-date plug-ins for Rhino and GH [23]. Searches were made using alternative combinations of the keywords: "LCA", "life-cycle assessment", "Grasshopper", "plug-in", "tool", and "embodied carbon". Further tools were identified from the literature study, and from the knowledge of the authors.

3. **Demonstration of characterisation framework**

The results of the tool inventory are shown in Table 2. Thirteen tools were found. Each tool was classified as using one of the approaches outlined in Section 2.1. Based on the inventory, four tools were selected for detailed characterisation based on being free, open-source plug-ins which showed a high maturity and potential for early-stage design process integration: the BHoM LCA toolkit, Bombyx, Cardinal LCA, and Tortuga. A summarised comparison of the tools is presented in Table 3.

Table 2. Tools found in the inventory. The plug-ins marked in bold were characterised in order to demonstrate the characterisation framework. EC refers to Embodied Carbon.

Tool	Year[a]	Developer [reference]	Scope[b]	Type	Country
BHoM LCA toolkit	**2020**	**Fisher A. and May R., Buro Happold [24]**	**LCA**	**2**	**UK**
Bombyx	**2021**	**ETH Zürich [25]**	**LCA**	**2**	**Switzerland**
CAALA[b]	2021	Hollberg A., CAALA GmbH [26]	LCA	3	Germany
Cardinal LCA	**2021**	**Chen J., Kharbanda K., Loganathan H. [27]**	**EC**	**2**	**USA**
COVE	2021	cove.tool [28]	LCA	3	USA
E2B2 LCA tool[c]	-	IVL Svenska Miljöinstitutet AB [29]	EC	3	Sweden
EPiC	2022	Stephan, A. and Prideaux, F., KU Leuven [30]	LCA	2	Belgium
IDGB	2016	Department of Civil Engineering, DTU [31]	LCA	2	Denmark
LCA tool 1	2021	Berger-Vieweg L. [32]	LCA	2	Sweden
LCA tool 2	2021	Tjäder M. [33]	LCA	2	Sweden
One Click LCA[a]	2021	Bollinger+Grohmann, One Click LCA [34]	EC	2	Finland
Tortuga	**2016**	**Thumfart M. [35]**	**EC**	**2**	**Germany**
ZEB-tool[a]	2019	Norwegian ZEB research centre [36]	LCA	1	Norway

[a] Year of latest update in food4Rhino or equivalent repository
[b] LCA: Life Cycle Assessment, EC: Embodied Carbon
[c] Grasshopper plug-in integration to existing LCA software
[d] Currently in development

Table 3. Characterisation of the LCA tools investigated in detail.

Category	BHoM LCA toolkit	Bombyx	Cardinal LCA	Tortuga
Required knowledge	Moderate – high	Low – moderate	Low	Low – moderate
Geometry input	Surface, curves, volumes, points, etc.	Surfaces	Surfaces, volumes	Surfaces, volumes, curves
Default settings and adaptability	High adaptability of default settings	Moderate adaptability of default settings	Low adaptability of default settings	Low adaptability of default settings
Modelling level	Material	Material; Component; Building	Material	Material
Output of results	Impact divided into impact categories	Impact divided into impact categories	Report, bar charts, surface colouring	Impact divided into impact categories
Intended application	Design evaluation	Education, design evaluation	Design evaluation	Design evaluation

Data source	Quartz, ICE, EC3, Boverket, Ökobau.dat, EPiC	KBOB, EcoKomposit, Bauteilkatalog	EC3, ICE V3.0	Ökobau.dat, Quartz
LCA modules	All modules available	A1-A3; A4-A5; B4; B6; C1-C4	A1-A3	A1-A3; C3;D
Impact categories in addition to GWP	Yes	Yes	No	Yes

The summarising table covers the workflow characteristics and scope of the LCA performed using the tools. The tools were assessed and characterised individually using the aforementioned characterisation framework and user persona, and a comparison of their characteristics are summarised as the take-away points from the framework demonstration. In the following, the tools are described in more detail, with attention focused to the workflow for the user, the adaptability in terms of settings for the user and scope of LCA, and the required knowledge for applying the tool in comparison with the user persona. Example screenshots of the test scripts developed for the assessment are available online at [37]. Test scripts are available for scrutiny upon request to the authors.

3.1. The BHoM LCA toolkit

The Buildings and Habitats object Model (BHoM) is an open-source project developed by Buro Happold to improve collaboration in computational development across disciplines in the built environment [24]. BHoM provides a common language to link several softwares into one application, with user interface within GH, Dynamo and Excel [38]. An LCA toolkit was added to its repository in 2020. The intention was to provide a tool for building designers to quantify the environmental impact, mainly embodied carbon, of the designs in a transparent way throughout the entire design process [39]. The overall workflow of the BHoM LCA toolkit goes through a specific hierarchy, built up by the four levels, Scope, Objects, Materials and Datasets. The modelling of the LCA starts on the highest level, the scope in which the outline of the assessment is defined. For instance, the life-cycle stages, impact categories and building elements included. In this way a consistency in the assessment is achieved. Objects are then connected to the scope from the model and assigned a material from one of the datasets included in the toolkit [40].

The adaptability of the BHoM LCA toolkit is high and mainly concentrated to the scope objects where one can define the entire scope of the LCA and thereby increase the extent of the assessment or narrow it down. The vast number of options by the inclusion of several databases, impact categories and LCA modules makes it a versatile tool throughout the entire design process, and this is in line with the intention of the BHoM project. In addition, its transparency and richness allow for detailed and professional approach to LCA.

The high adaptability and its optional settings demands knowledge from the user mainly regarding the scope definition of the assessment. This is required to achieve a consistency between the results of the LCA and its application to the design process. But when the scope is defined the toolkit allows to easily assign the information to the model.

3.2. Bombyx

Bombyx is a plug-in created to be implemented in the education at ETH in Zürich and is heavily Swiss oriented. It was primarily intended to be used by students in architecture and engineering [25]. The plug-in consists of 24 components sorted into five panels. The investgated version is Bombyx 2.0.8.

The LCA procedure in Bombyx is structured into two approaches: bottom-up and top-down, and the integration of predefined materials, components and building typologies allows for modelling on several levels of detail. The geometry import is in both cases based on surface geometry structured into eleven layers named after the type of building element.

The top-down approach allows for analysis on building level design. The workflow starts with specifying the parameters on building level, such as the building size, the intended user, the energy performance standard, and main structural material. These four building specifications together with the building geometry categorised into building elements is basically all the information needed to perform the analysis. The results are presented as average, maximum, and minimum values for each impact category.

The bottom-up approach requires more information about the building but is offering a more detailed assessment and transparency. In this approach the workflow starts with assigning material properties to the layers and thereby building up the inventory of materials in the building, the impact of which is summarised for the entire building. The result in this approach is divided into embodied impact, replacements, and end-of-life, and thereby it captures the life-cycle stages of the building materials.

Both approaches also include the operational energy calculations that are presented separately with monthly results on energy demand and total impact for each impact category. The energy demand is calculated according to Swiss standards, SIA 380/1. Included is the space heating, hot water demand and electricity demand [25].

There are also components for calculating the impact of transportation of material and people, as well as the impact from building services.

Altogether, the combination of the two approaches extends the applicability of the tool in the design process, from the earliest stages where a comparison of the main features and system of the building is made, such as structural concept and building geometry, until the assessment on material level. Thereby the potential use of the tool is extended from quick simple assessments into more detailed calculations. This makes it possible to adapt the tool after the available time and, known information and purpose of the assessment.

For the simplest top-down application of the project there is a low level of knowledge required to be able to use the tool as most of the assumptions and limitations are built into the components. But for the bottom-up method the detail of the analysis can be increased. This allows for the use of Bombyx further into the design process and consequently more knowledge is needed to keep consistency.

3.3. Cardinal LCA

Cardinal LCA is a plug-in created for early-stage assessment of the environmental impact of buildings. It is intended to be used by LCA non-experts, to make conscious decisions in the concept stage of building design [27]. It is developed by Chen J., Kharbanda K. and Loganathan H. The investigated version is Cardinal LCA v0.01 from 2021 which is the current trial version available.

The plug-in consists of eleven components sorted into the four categories: import, material selection, compilation, and output. These categories very much define the workflow provided by Cardinal LCA and the sparse library of components is easily overviewed. It follows a bottom-up approach where the geometry with different materials is in separate layers are assigned a material and then added up to the total building level. The results are then either visualised as a hotspot analysis by surface colouring on the model or in bar charts and the results can also be exported to a CSV file.

Overall, Cardinal LCA is focused on its intended use and the functionality are therefore limited to its specific scope. Only the product stage modules are included and solely GWP is calculated. But the tool allows for several sources of material data. Either using the ICE database and selecting material by selecting material category and then the specific material, or using the component for the EC3 database. In that case material data can be based on either specific data, based on an EPD from a manufacturer, or on average data, which is the average calculated from several EPDs in the same material category. There is also an option to customise your own material by providing a material name, material category and specify density and global warming potential.

Due to its streamlined approach Cardinal LCA is easily overviewed and there is a visual and coherent relation between the inputs and the results. Hence the effect of design changes is easily observed in early stages.

3.4. Tortuga

Tortuga was developed in 2015 by Thumfart M. The intended application of the tool is to assess the environmental impact of materials used in construction of buildings focusing on global warming potential [35]. The plug-in is built-up by 14 components divided into 4 panels.

Tortuga is based on an LCA modelled from the material level. Materials are selected from the database and assigned to corresponding geometry, volumes, surfaces, and profiles. It is possible to stack materials on the same geometry which can be used to create components consisting of several materials. The LCA results are then calculated through summation of all included materials and given as total values separated into six impact categories, including GWP.

Tortuga largely offers similar functionality as Cardinal LCA. Nevertheless, the experience is that it demands more of the user. There are no default settings or predefinitions except the included databases that simplify the procedure. Hence the user must possess a larger amount of knowledge in LCA to conduct an assessment for the specific purpose at hand. The functionality of the plug-in offers the choice of which of the LCA modules to include in the assessment as well as results separated into several impact categories. In that way the scope of the LCA can be altered to some extent. There is also a possibility to import a database in CSV format. Moreover, Tortuga allows for several types of geometries as input, such as surfaces, volumes and curves, making it possible to use for a more intricate 3D model.

4. **Discussion**

The compilation in Table 2 indicates that the most common approach for integration of LCA in GH is approach 2, where the calculations are implemented within the Grasshopper environment. This utilises the benefit of GH assembling all analyses within the same workspace.

To summarise the main characteristics of the investigated tools, the most defining features are the amount of LCA expertise integrated in the tools, and the extent to which the responsibility of data entry and analysis is placed upon the user.

The BHoM LCA toolkit offers the most comprehensive functionality but Bombyx is the most complete tool of the ones characterised with regards to the applicability in the early design stage for architects with limited experience in LCA. A significant advantage with Bombyx is the possibility of using a top-down approach besides the bottom-up approach which all characterised tools provide.

Cardinal LCA can be considered the most streamlined of the plug-ins in terms of work process. It is focusing on few modules and impact categories and the functionality is strict yet obvious for the novice. Tortuga in turn is like Cardinal LCA with regards to the workflow, but not that specified in its core functions. This is the tool with the least predefined functions and information guidance for the user in the interface.

Bombyx and Cardinal LCA are clearly intended to be used exclusively in the early design stage, which is exemplified by the limited effort needed by the user to apply the tools, and by how that effort is converted into results. There is a clear relationship between the input data and the results which is logical to follow. The results are on the same level of detail as the information fed into the tool.

Conversely, the top-down procedure, only available in Bombyx, is expanding few or simple inputs into more comprehensive results based on the built-in assumptions and expertise. However, this only holds true to some extent: in the earliest design stage, until the assumptions are overruled by detailed specifications, at which point the analysis diverges from reality.

Altogether, due to their integration in the GH environment, all plug-ins possess obvious integration with a geometrical model defined in either Rhino or parametrically within GH, making them possible to relate to the design process. Bombyx and Cardinal LCA are exemplifying well developed and user-friendly workflows and are good role models for future tool and workflow development. When considering the user persona, these tools would likely have the lowest barrier of entry, as they require limited knowledge of both Rhino/GH, and of LCA methodology, and provide rapid results for design support. But the BHoM LCA toolkit, which itself is in active development, offers the best opportunities for more advanced users due to its versatility in terms of the connection to several major databases, adaptation to external software, and the possibility to shape the scope of the LCA to suit the earliest design stage as well while allowing for detailed and comprehensive assessments in the final design. Hence, if time can be spent by specialists within the practice preparing scripts for use by less technical users, the BHoM LCA toolkit may be preferrable.

This discussion shows that the proposed characterisation framework successfully manages to identify important features and properties of parametric LCA tools for early stage building design. It successfully identifies alternative approaches which are relevant to guide the future development of parametric tools, and to evaluate their potential for integration into holistic design frameworks.

5. Conclusion

In the present study, a characterisation framework for parametric Life Cycle Assessment (LCA) tools was developed, and demonstrated through application using a user persona approach in a tool characterisation, where an inventory of thirteen available tools for Grasshopper® (GH) was collected, and four of these tools were investigated in detail based on their applicability in the early-stage architectural design process.

The proposed characterisation framework firstly allows for classification of tools according to three approaches: 1) using GH to model geometry and export a bill of quantities as input for an external LCA tool, 2) using GH to model geometry and materials, to perform analysis, and to visualise results, and 3) using GH as an interface for an external engine which performs the LCA. From the 13 works found in the tool inventory, most used approach 2, where both modelling and analysis is performed within GH, and this was identified as the most promising approach for large-scale adoption.

Secondly, tools are characterised according to nine categories: required knowledge, geometry input, default settings and adaptability, modelling level, output of results, intended application, data source, LCA modules, and impact categories in addition to GWP.

It was found that the characterisation framework was able to differentiate tools and identify alternative approaches to parametric tools for early design stage implementation of LCA. From the four tools selected for the demonstration of the framework, two main approaches could be identified, where Bombyx, Cardinal LCA, and Tortuga focus on providing a user-friendly interface which allows for use by non-experts, whereas the BHoM LCA toolkit provide more advanced functionality and versatility.

The eventual goal of this study is to use the gathered information to develop a holistic analysis framework which includes LCA and can be integrated in the architectural design process. In further research, the characterisation framework should be applied to further parametric tools, and expanded to cover other design methodologies, to identify further approaches. The two main approaches found in this study should be evaluated using prototyping and user tests.

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