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A cross-platform modular framework for building Life Cycle Assessment

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Abstract. In recent years the application of Life Cycle Assessment (LCA) for assessing and improving the environmental performance of buildings has increased. At the same time, the automated optimization of building designs is gaining attraction for both design and research purposes. In this regard, a number of issues persist when aiming to optimize building's environmental impacts along the design process. Firstly, as LCA applies a life cycle perspective, many aspects have to be considered (e.g. energy demand in operation as well as consumption of resources and energy for production and end of life treatment) and a variety of specific calculations is needed (e.g. building energy performance simulation, material quantity take-off). Secondly, sophisticated software packages are available and being used for each of these calculations (e.g. software for building modelling, dynamic energy simulation, quantity surveying). Though many of these software packages are currently standalone applications that rely on human interaction, there is an increasing trend to provide an application programming interface (API) that enables customization and automation. Thirdly, the mentioned processes and calculations are influencing each other in various ways and several scenarios have to be assessed. Thus, a comprehensive and modular approach is required that promotes interconnectivity of the different software solutions and automation of the assessment. In this paper we propose a modular cross-platform framework for LCA of buildings aiming to support flexibility and scalability of building LCA. We present a conceptual framework, example data exchange requirements and highlight potential implementation strategies.

1 Introduction

The building and construction sector is related to around 40% of global primary energy consumption as well as a similar magnitude of global greenhouse gas (GHG) emissions and waste produced. Assessing and reducing the energy consumption, GHG emissions and other related environmental impacts across the building life cycle – i.e. from material production and construction, to building operation, incl. maintenance and replacement, down to the final processing at the end of life of buildings – has thus become an important point on the global agenda. Most measures in recent years have been focusing on increasing the energy efficiency of building operation in order to reduce energy consumption and the related GHG emissions. However, in recent years, the importance of assessing and optimizing the environmental performance across the building life cycle is becoming evident. In order to achieve a

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science-based quantification of environmental impacts of processes and products, the method of Life Cycle Assessment (LCA) has been developed and is increasingly applied. However, its application to buildings is still hindered by several challenges, e.g. compilation and processing of extensive inventories of the complex product system 'building', mapping of inventories with related data from LCA databases, as well as the handling of trade-offs between embodied and operational impacts, to name just a few. In recent years, the application of Building Information Modelling (BIM) has gained interest, hoping to increase the applicability of LCA by managing the related data via a digital building data model. This integration of LCA into BIM has since been demonstrated in several papers with different maturity. In the following we give a brief overview into the state of play based on a literature review.

1.1 Literature review

The application of LCA for buildings' environmental assessment has been of increasing interest for more than 5 years in the literature. However most of the papers were focusing on the applicability of BIM for building LCA [1] or the extension of BIM [2] to include environmental data. Soust-Verdaguer and colleagues [3] evaluated the limitations of BIM-based LCA in a comprehensive review. They identified three levels of integration, from which only the third level includes automated data exchange. It is also recognized that this is not the current practice yet. On the other hand Hollberg and Ruth [4] applied a different approach focusing on the parametric definition and optimization of the model instead of starting from a predefined BIM geometry model. They emphasized the advantages of a parametric model in optimization processes and in early design stages. Other studies were focusing on the data management to bridge the gap between the input requirements of an LCA and the data availability in BIM. Cavalliere et al. [5] defined the minimum requirements to include environmental data in BIM models. They developed an "architecture of variables" so that the various parameters can be included depending on the life cycle stage and the available data. Tecchio et al. [6] on the other hand described a hierarchic decomposition structure for building model data and proposed a method to conduct LCA even if the data availability is low and the information is underspecified. Further studies applied LCA on case studies [7]–[9], most of them facilitated some features of BIM (e.g. extract material quantities, visualization of 3D building model, etc.), but they either use some self-developed tools (e.g. Excel spreadsheet) [9] or apply commercial plug-ins [8] to evaluate the environmental impacts. Both approaches have their limitations that is discussed later in this paper. Some papers were focusing on the evaluation of LCA results through different visualization techniques by using the capabilities of a complex 3D building model [10]–[12]. The extended integration of LCA into the design practice [13] and into certification systems [14] is also in focus of recent research.

1.2 Analysis of existing practice

Based on the literature review, there has been increasing interest in the last few years focusing on the application of LCA in building design practice. However, no common practice or exact specification has been developed yet that facilitates the implementation of different software independent from the used methodology. There is an increasing number of existing software tools, and each of them is based on the own considerations of the developer team. In this research, six experts from different countries have been interviewed about their practice in the application of LCA for buildings. The detailed assessment of the interviews is carried out in the framework of the IEA EBC Annex 72 [15], and is out of scope of this paper, but the most important findings are summarized in the following.

There are two major different approaches to achieve the integration of LCA into design practice. The first one has evolved from the traditional practice of design that is based on human interaction between stakeholders supported by CAD drawings and text documents (legacy method). Throughout the years, usually import and export possibilities have been developed to speed up manual work, or automation facilitates the fast processing of the input data. This approach has the advantage that full control over the calculations is in hand of the expert. The other approach is the extension of BIM solutions to include LCA in the workflow. This is a more straightforward solution to support information exchange between stakeholders, but on the other hand the exact specification of the calculations is usually out of the hand of the LCA expert if a deep integration is achieved.

Based on the experts' opinion the following major requirements can be expressed against a platform for building LCA: *Transparency*, that covers both the background data that the assessment is working with (original source, presumptions, uncertainties) as well as the calculation methodology (bill-of-quantities, replacement, energy demand, etc.). *Interchangeability*, that allows the integration of external solutions such as BIM, and finally *automation*, so that the assessment does not need too much manual work, and as a consequence it might be accessible for a wider audience.

1.3 Scope of this paper

There is a high need for the integration of Life Cycle Assessment into design practice [13]. However, there are some challenges that need to be faced before implementing such a system. First, the steps of the calculation need to be interchangeable, which means that alternative solutions should be easy to apply for each component. Second, the framework should be interoperable so that many external existing solutions (e.g. BIM software) can be connected to provide input to the calculations. Third, the system should be scalable in terms of the level of detail of the calculation. In an early design stage low information granularity is available, but after construction the calculation can be done based on much more specific information. The framework should be able to handle this problem.

Additionally, there is high focus in current research [13] on how the calculation can be transparent for externals. This includes the transparency of the source data, the way how the bill of materials is extracted, as well as the consideration of time-specific issues of the environmental impact or the application of generic or manufacturer-specific construction products, etc.

In this paper we propose a conceptual structure that supports the modular implementation and the interchangeability of modules as well as the other requirements stated above. First, we introduce the modules and the components, after that we define the conceptual exchange requirements in the system of the modules. The novelty of this approach is that the focus is on the application of existing solutions for each module instead of creating the next software from scratch. The same requires that a change of one component shouldn't necessarily mean a new structure for the framework.

2 Definition of the modules of the framework

The following concept is based on own considerations concluded from the analysis of the current practice and the requirements of the experts. The structure of a building LCA calculation can be generalized to four major modules: background data, modelling, calculation and postprocessing. The main data flow is represented on Figure 1. In the usual case input is provided to the background data and to the modelling module, however, the background data is established prior to and independently from a single calculation (e. g. database), on the other hand the input to the modelling is given specifically for each calculation (usually manually). Output is provided either directly after calculation (e.g. raw data for further use in other systems), or after post-processing (e. g. visualization). The splitting of the latter two modules is necessary because both incorporate various methodological questions that are independent from each other (e. g. how to account for the replacement of the building elements in the calculation component, or how to aggregate the results into a single indicator in the postprocessing component). Each module consists of components that are described in the following.

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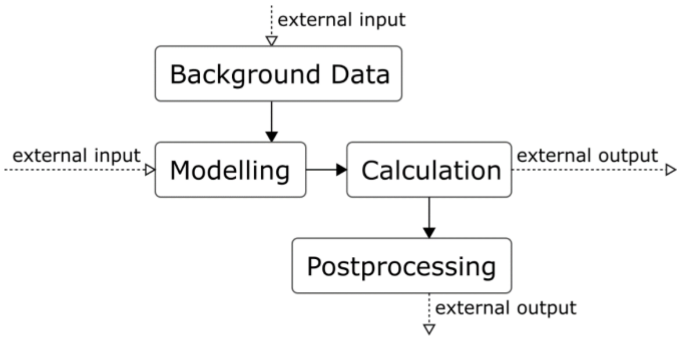

Figure 1. *Conceptual representation of the modules and the data flow in the framework*

2.1 Background Data module

The first separate major module of the framework is called the background data module. This incorporates all the predefined information that is established independently from an assessment case. A component in this module is represented usually by a database (or a table in a simple case) that holds static data. The module includes five optional components (Figure 2).

2.1.1 Material Environmental data

First and most important is the database for material environmental data. There are two different options for this component. The first and most commonly used is a collection of environmental impact information for a wide variety of building materials and for multiple environmental indicators. The impact is quantified on a per mass/volume/piece basis and the characteristics of the impact assessment method (e. g. weighting) is hardcoded into the results. This is called a Life Cycle Impact Assessment (LCIA) database. An example for this case is an EPD database. The other option is a link to a full LCA database, including all unit processes and elementary flows (e. g. ecoinvent processes). In this case the impact assessment method can be later incorporated in the calculation and is not limited to the predefined impact categories. This option also facilitates the update of other related processes in the database (e. g. electricity mix) during calculation.

A further issue related to this component is the inclusion of time- and geographical dependency for the environmental impact associated to the material. Time is an important factor since the reference service period of buildings is most of the times estimated to be longer than the service life of the building components, so replacement is necessary. But the impact associated with the production of the replacement component is going to happen in the future when the available technological circumstances may be different from the current situation. The geographical location is also an important factor since many construction materials are locally produced and may rely on different technology and may use different energy resources (e. g. electricity mix). There are two proposals to overcome this issue: the use of a multi-dimensional database (time and geolocation as the second and third dimension), or the use of an adaptive database, where the environmental impact can be recalculated based on the time and location variables.

2.1.2 Material life cycle data

The second component of this module hold information on the life cycle properties of the materials that are independent from the environmental impact. The most important property is the service life of the materials, but other life cycle related data could be included such as transport and disposal scenario as well.

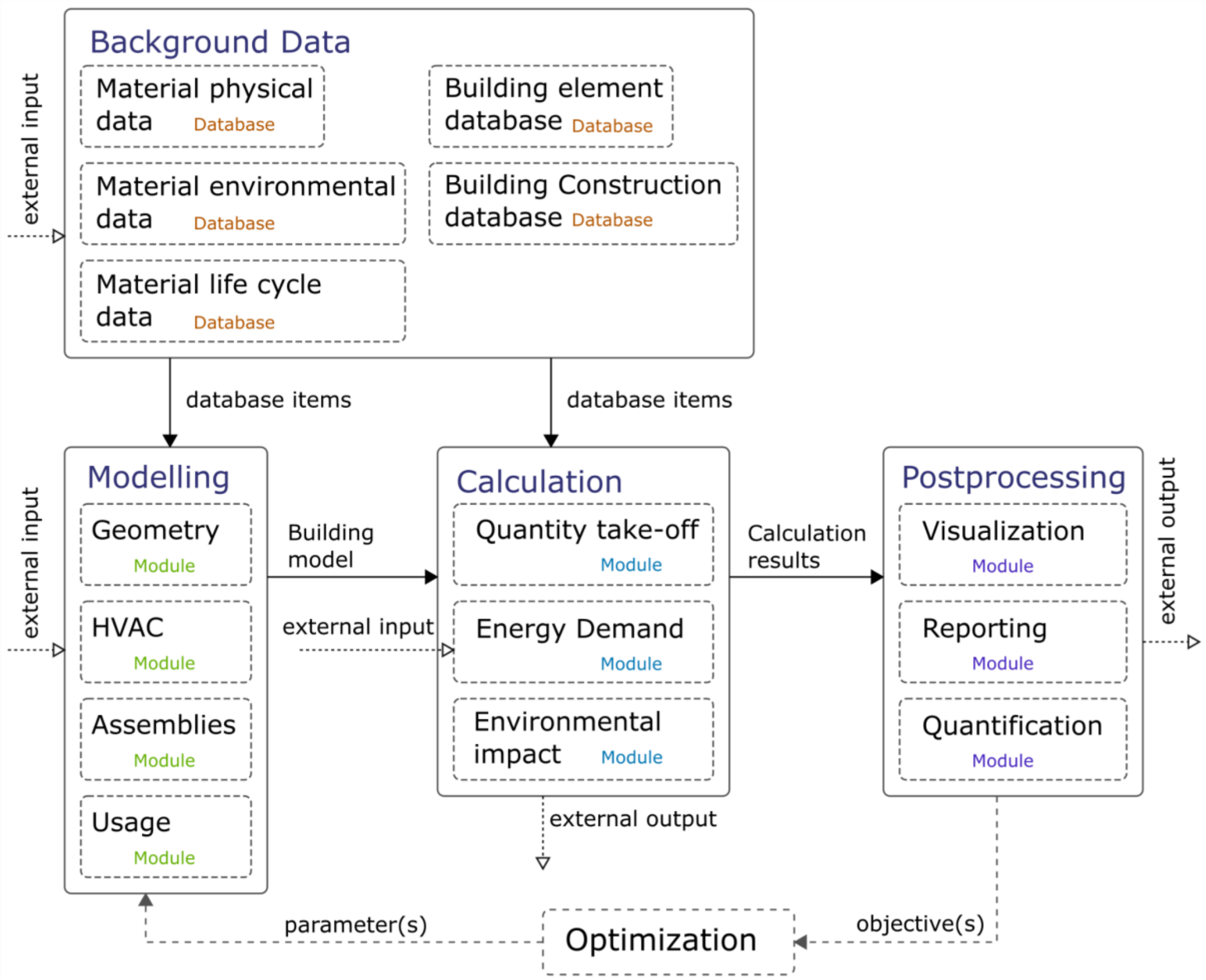

***Figure 2**. Visual representation of the framework structure and components*

2.1.3 Material physical data
The third component incorporates all physical data related to the materials such as density, thermal conductivity (λ) or specific heat capacity. Depending on the type of energy and building physics calculation, the entries can range from a single number to complex temperature- and humidity-dependent functions.

2.1.4 Building element and Building construction data
The last two components facilitate the use of the system in early design stages and for decision support [10]. In this case the environmental impact is associated to a construction (assembly of building materials, e. g. masonry structure) or to a building element (multi-layered construction, e. g. wall). The entries in this database can be established prior to the modelling of a building based on industry practice and existing solutions with help of the Material Environmental Database component.

2.2 Modelling module
The second major module is called the Modelling. This incorporates all actions that aim to establish a complete building model that is further used in the calculation module. The granularity of the model can range from the single definition of surface areas (without explicit geometry) and construction assemblies to the parametrically defined full model including geometry and HVAC systems. At this point many external applications can provide an input such as BIM capable systems. There are four major modelling components described in the following.

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2.2.1 Geometry modelling
This component provides the geometrical information of the model. In a simplified case, the geometry can be defined implicitly by determining surface areas for different types of building surfaces. In a more favourable case, the geometry is defined explicitly in a 3D space. This option supports the 3D representation of the model that can be further used for different LCA visualization options. A third option is the parametrical definition of the building geometry which further includes the optimization possibility.

We can distinguish between two different options for the structure of the geometrical model. The first is based on the practice of energy models, which is usually a surface model divided into thermal zones. The second approach is the exact geometrical modelling of the building elements which is closer to the BIM practice. The advantage of the former over the latter one is the direct input to the energy calculation, but on the other hand there are many simplifications in terms of the bill of quantities (described later). The inverse is true for the "BIM" type of model.

2.2.2 Assemblies
The "assemblies" component describes all composite structures used in the building including the inhomogeneous materials (e.g. masonry made from brick and mortar) as well as the layered constructions (e.g. wall structure). As a further extension, joints can be defined at this point which represent the connection between constructions, and additionally can include geometrical properties too.

2.2.3 HVAC
The last two components of this module are mostly used if an energy calculation is part of the assessment. The "HVAC" component is used to describe technical systems (heating, ventilation, air conditioning, etc.) installed in the building. The level of specification can range from a single general system (e. g. residential gas heating), to very detailed model including all pumps and pipes.

2.2.4 Usage
The last component of this module includes all user-specific information about the building such as occupancy schedules, door and window opening schedules, temperature setpoints, etc. (depending on the type of energy calculation) as well as life cycle related usage information such as renovation cycle, expected type of usage or expected lifetime of the building.

In most of the cases, all the information that is added to the calculation system in the modelling module can be described in a BIM model, however further attention should be paid to the exchange requirements between the database module as well as with the calculation module, an example is provided in the last chapter.

2.3 Calculation module
The calculation module provides the heart of the framework. This module is intended to perform all transformations and evaluations that provide all information which is not included explicitly in the model. The module includes three components described as follows.

2.3.1 Quantity take-off
For a building life cycle assessment, the amount of materials used in the building needs to be quantified in order to calculate the embodied impact as well as other related impacts (transport or disposal). Therefore, this component takes the model of the building as input and provides the bill of quantities (list of materials with amounts) for which the environmental impact can be assigned to.

The required calculations are highly dependent on the type of the model. For example, for the "surface" type of model the volume of material used at the joints needs to be added/subtracted depending on the reference line of the surface in the wall construction (innermost/outermost surface). Inhomogeneous constructions (e.g. wooden roof systems) serve as another good example, as the profile used in the construction may be described indirectly (e.g. beam size and axis distance) without explicit geometry.

The type of output can depend on the purpose and type of the result evaluation. For a simple calculation the list of all materials may be sufficient, but if the assessment aims to locate the surface of the model with the highest impact, the provided amounts need to include a placeholder (where it is located in the building).

2.3.2 Energy calculations
The highest impact related to the operational phase of the building is usually caused by the operational energy use. To include this in the assessment, an energy demand calculation needs to be done. The type of calculation can range from a simple seasonal steady-state method to a very detailed energy simulation with an hourly resolution. The type of calculation again highly influences the required input from the model. This component can take further external input that may not be included in the model, for example weather data for the specified location of the building.

2.3.3 LCA calculation
This component is used to allocate the impact to the materials and energy that is used by the building during its life cycle. Also, other life cycle specific calculations are performed here, such as the counting of replacement of the building components as well as the calculation of transport and disposal scenarios for each material. The required output of this component depends on the type of applied postprocessing. This component can include methodological options, for example static/dynamic LCA calculation or localized/general evaluation. A static calculation means that all input data (e. g. environmental impact of brick production per kg) is expected to remain the same during the life cycle of the building. On the other hand, in a dynamic calculation the environmental impacts of the unit products assumed to change over time (e. g. because of the change in the electricity mix), and therefore they need to be updated during calculation. Depending on the available information, the localization of the building may also influence the results of the assessment (through transport distances and available manufacturing technology).

2.4 Post-processing module
The structure of the framework implies that all manipulation of the raw output of the calculation module is processed in the postprocessing module. This module aims to provide a range of options to communicate and interpret the results of the assessment. In a simple case the output can be a simple aggregated number based on a corresponding environmental impact indicator. In a more detailed case further visualizations can be performed (in graphs or on the 3D model of the building), examples are available in the literature [12], [16]–[18]. In some cases (e. g. certification) a full report needs to be created based on the results of the calculation, which can be done with a designated component. These three components cover a good range of possible postprocessing options, but the list is not limited to them.

2.5 Optimization
In the favourable case of an automized model generation an optimization module can be introduced in the system. The module takes one or several well quantified outputs of the postprocessing module, they serve as objective(s). It modifies the designated variables of the modelling module which act as parameters in the optimization. This way any optimization algorithm can be implemented in the workflow that is independent from the type of problem (e.g. evolutionary algorithms or other derivate-free algorithms). This structure does not support the application of derivate-based optimization processes, because derivates are not available in the mathematical problem associated with building LCA, since many parameters are discrete and non-numeric (e.g. type of material).

3 Example application of the framework using existing software tools

While the aim of the previous chapter was to define the framework as general as possible, in the following we present a case study for the application of the concept where already available software is used for some modules.

3.1 Parametric modelling with building optimization option

The case study introduces a workflow where the focus is on the automatic model generation possibility (Figure 3). This means that manual input is only needed at the initial step, where the fixed parameters and the optimizable parameters of the model are defined. The entire framework is based on Grasshopper[1] environment. The Background Data consist of two components, a predefined custom database for material physical data (e.g. thermal conductivity) and lifecycle information (e.g. estimated service life) and an environmental database (e.g. ecoinvent) in OpenLCA[2]. The Modelling module is based on the Ladybug&Honeybee[3], and only the Geometry and the Assemblies components are used. In this case, default values are used for the HVAC systems and for the corresponding schedules. The energy demand is calculated with EnergyPlus[4] (through Honeybee). The results are visualized with Rhino3D[5] (the modelling tool that the Grasshopper environment is based on). Finally, the optimization is carried out with the Octopus[6] plug-in. In this case only three other custom components need to be created (e.g. using the python component of Grasshopper), the quantity extraction based on the model, the calculation of the environmental impact based on the inventory created by the previous component and the quantification of the selected results to provide numerical input to the optimization module.

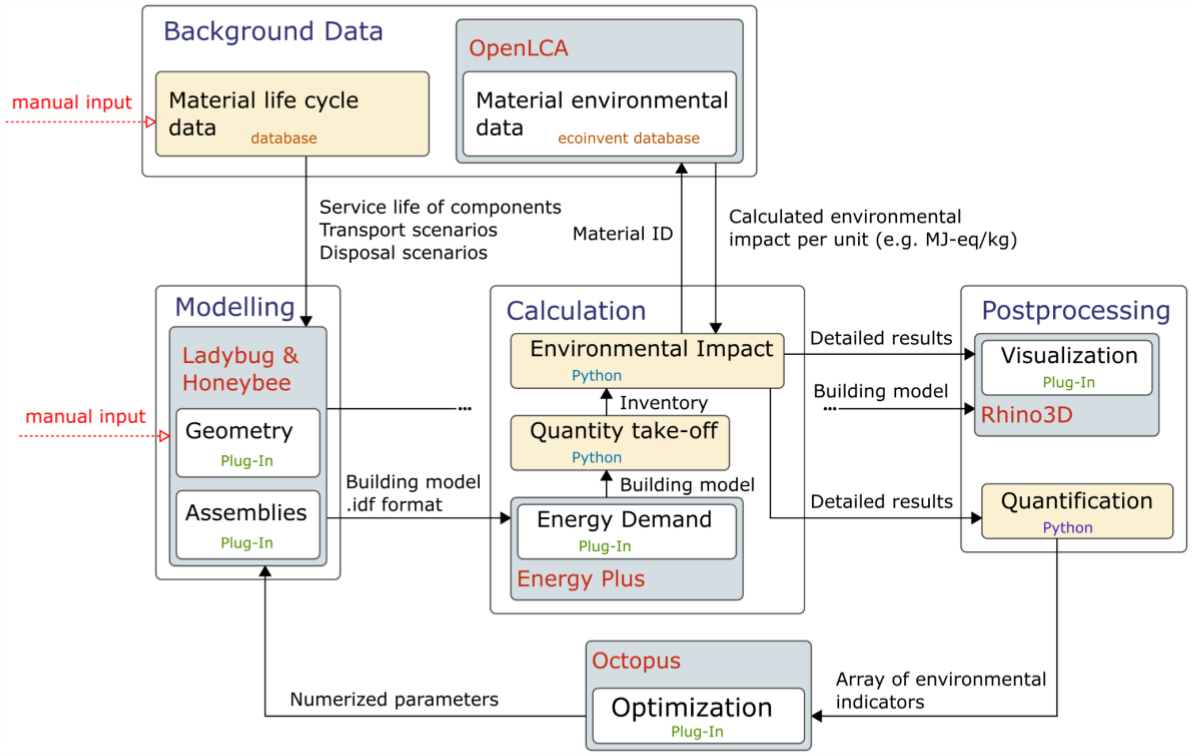

***Figure 3**. example application, setup of the framework and external software used.*

[1] https://www.grasshopper3d.com/
[2] http://www.openlca.org/
[3] https://www.ladybug.tools/honeybee.html
[4] https://energyplus.net/
[5] https://www.rhino3d.com/
[6] https://www.food4rhino.com/app/octopus

This application requires specific exchange information between the components. The modelling module takes additional input from the material database and extends the generated idf model (the standard input file of Energy Plus) with additional information needed for LCA (service lives, transport and disposal scenarios, and a reference ID to the environmental database). The output of the energy demand component is the same building model along with the calculated energy demand. The quantity take-off component uses the same model to create the inventory of the building (including the embodied materials and the operational energy use). The environmental impact is associated with the elements of the inventory based on the database ID. The impact of the inventory elements is provided by OpenLCA. Finally, the detailed results and the building model are passed to the visualization component to create views of the actual solution. In this case the quantification component is only used to extract (or aggregate) selected results to provide a numerical input (as objective) for the optimization component. This optimizes numeric parameters, which are translated into modelling parameters (e.g. different options for insulation material) and the calculation cycle is repeated until a specific criterium is met by the optimization component.

4 Conclusions

In this paper we presented a conceptual structure of a modular cross-platform framework for building Life Cycle Assessment. This approach aims to support interchangeability and interconnectivity of the different available software tools that are used for the specific aspects of LCA. We defined the conceptual workflow and illustrated the exchange strategies between the modules on a case study application. This also showed that for most of the modules existing software can be used by establishing the interface between them. High-level programming environments (such as Grasshopper or Dynamo) make the development of such interfaces easy and fast. During the development, the modules can be created and updated step-by-step so that the first simple version can be utilized from the very beginning. Also, fundamentally different components can be developed side-by-side (e.g. for simulation or steady-state methods for energy calculation) and they can be compared based on the same case studies. This structure also supports the parallelization of calculations that is very useful for the case of optimization especially if the calculations need high computational capacity.

The structure also aims to provide options for different levels of calculation, so that the framework can be utilized already in an early design stage with low information availability as well as at a late stage when detailed calculations can be done.

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