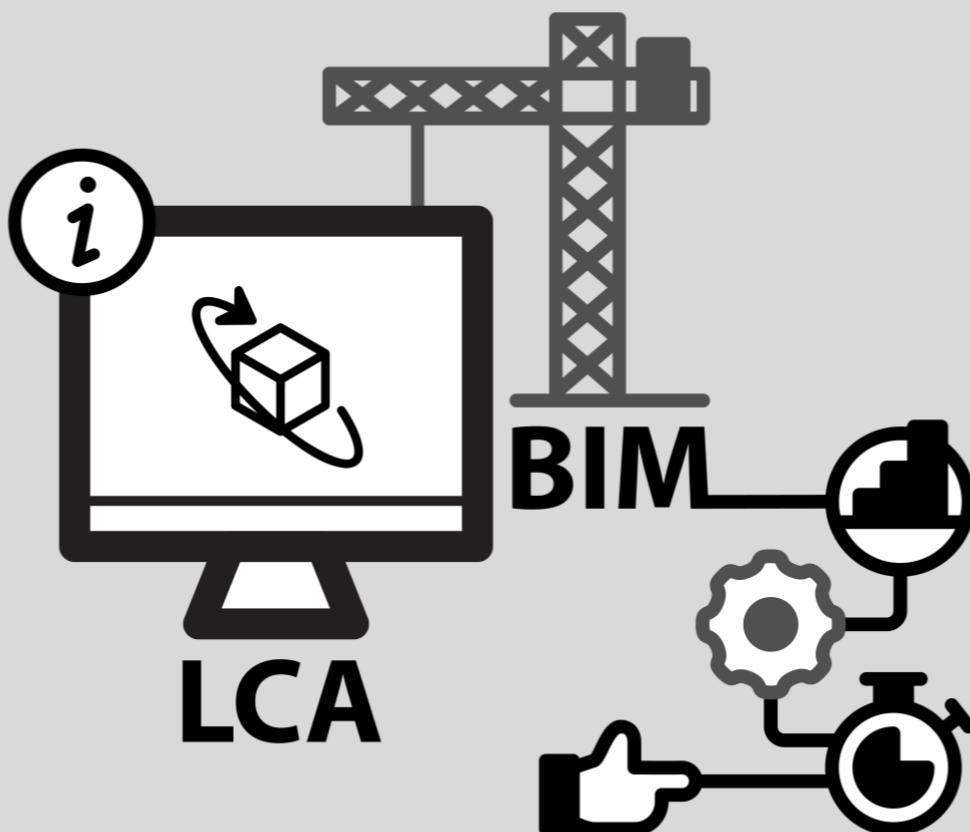


LCA-BIM workflows in the design process

A Contribution to IEA EBC Annex 72

June 2023



International Energy Agency

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Authors

Benedek Kiss, Budapest University of Technology and Economics, Hungary

Tajda Potrc Obrecht, Slovenian National Building and Civil Engineering Institute, Slovenia; Graz University of Technology, Austria

Jakub Veselka, Czech Technical University in Prague, Czech Republic

Martin Röck, Graz University of Technology, Austria; KU Leuven, Belgium

Daniel Plazza, Graz University of Technology, Austria

Michael Ortmann, Graz University of Technology, Austria

Nicolas Alaux, Graz University of Technology, Austria

Bernadette Soust-Verdaguer, University of Seville, Spain

Zsuzsa Szalay, Budapest University of Technology and Economics, Hungary

Alexander Passer, Graz University of Technology, Austria

Contributing Authors

Antonio García Martínez (ES), Hanze Yu (CN), Wei Yang (CN), Dave Dowdell (NZ), Francesco Pomponi (UK), Ricardo Mateus (PT), Julien Martel (CA), Bruno Peuportier (FR), Sebastian Theißen (DE), Ruben Santos (PT)

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Table of content

- Abbreviations and glossary 6**
- Summary 9**
- Introduction..... 9
- 1. A modular framework for building Life Cycle Assessment 9**
 - 1.1 Literature review on BIM-LCA..... 9
 - 1.2 Analysis of existing practice 10
 - 1.3 Definition of the modules of the framework 10
 - 1.3.1 Background Data module..... 11
 - 1.3.2 Modelling module 12
 - 1.3.3 Calculation module..... 13
 - 1.3.4 Post-processing module..... 14
 - 1.3.5 Optimization 14
- 2. Annex 72 assessment workflow survey results 15**
 - 2.1 Environmental assessment tools 15
 - 2.2 Software applied in the environmental assessment workflow 17
 - 2.3 Calculation structure and workflow 18
 - 2.4 Visualization options 24
- 3. Annex 72 assessment LCA- BIM exercise..... 27**
 - 3.1 Aim of the LCA-BIM exercise 27
 - 3.2 The workflow of the LCA-BIM exercise..... 27
 - 3.3 The recommendations of the LCA- BIM exercise 31
- References 33**

Abbreviations and glossary

Abbreviations	Meaning
BIM	Building Information Modelling
BOM	Bill of Materials
BOQ	Bill of Quantities
EIA	Environmental Impact Assessment
GHG	Green House Gases
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCI	Life Cycle Inventory
LOD	Level of Development
LOG	Level of Geometry
LOI	Level of Information
CAD	Computer Aided Design
CED	Cumulative energy demand
CO₂eq	CO ₂ equivalent
EE	Embodied Energy
EOL	End of life
EPD	Environmental Product Declaration
GFA	Gross Floor Area
GWP	Global Warming Potential
IEA	International Energy Agency
IEA-EBC	Energy in Buildings and Communities Programme of the IEA
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LC	Life Cycle
LCIA	Life Cycle Impact Assessment
LCCO₂	Life Cycle CO ₂ equivalent
NZEB	Nearly zero energy building or nearly zero emissions building
NRE	Non-Renewable Energy (fossil, nuclear, wood from primary forests)
NRPE	Non-Renewable Primary Energy
OECD	Organization for Economic Co-operation and Development
PE	Primary Energy
RSL	Reference Service Life
RSP	Reference Study Period
ZEB	Zero Energy Building
ZEH	Zero Energy House
ST1	Annex 72 Subtask 1: Harmonised methodology guidelines

ST2	Annex 72 Subtask 2: Building assessment workflows and tools
ST3	Annex 72 Subtask 3: Case studies
ST4	Annex 72 Subtask 4: Building sector LCA databases
ST5	Annex 72 Subtask 5: Dissemination

Term	Definition
CO₂ Intensity	The total CO ₂ emission embodied, per unit of a product or per consumer price of a product. [kg CO ₂ eq /unit of product or price]
CO₂eq	CO ₂ equivalent - a unit of measurement that is based on the relative impact of a given gas on global warming (the so-called global warming potential). [kg CO ₂ eq]
Contractor	Synonym: Service provider
Clients	Synonyms: financier, building owner, tenant, user
Cradle	Where building materials start their life
Cradle to Gate	This boundary includes only the production stage of the building. Processes taken into account are: the extraction of raw materials, transport and manufacturing
Cradle to Site	Cradle to gate plus delivery to site of use.
Cradle to Handover	Cradle to site boundary plus the processes of construction and assembly on site
Cradle to End of Use	Cradle to handover boundary plus the processes of maintenance, repair, replacement and refurbishment, which constitute the recurrent energy. This boundary marks the end of first use of the building.
Cradle to Grave	Cradle to handover plus use stage, which includes the processes of maintenance, repair, replacement and refurbishment (production and installation of replacement products, disposal of replaced products) and the end-of-life stage, which includes the processes of demolition, transport, waste processing and disposal.
Embodied Energy	Embodied energy is the total amount of non-renewable primary energy required for all direct and indirect processes related to the creation of the building, its maintenance and end-of-life. In this sense, the forms of embodied energy consumption include the energy consumption for the initial stages, the recurrent processes and the end-of-life processes of the building. [MJ/reference unit/year of the RSP]
Embodied GHG emissions	Embodied GHG emissions is the cumulative quantity of greenhouse gases (CO ₂ , emissions methane, nitric oxide, and other global warming gases), which are produced during the direct and indirect processes related to the creation of the building, its maintenance and end-of-life. This is expressed as CO ₂ equivalent that has the same greenhouse effect as the sum of GHG emissions. [kg-CO ₂ eq /reference unit/year of the RSP]
Energy Intensity	The total energy embodied, per unit of a product or per consumer price of a product. [MJ/unit of product or price]
Energy carrier	Substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes
Energy source	Source from which useful energy can be extracted or recovered either directly or by means of a conversion or transformation process

Gross Floor Area (GFA)	Gross Floor Area [m ²]. Total floor area inside the building external wall. GFA includes external wall, but excludes roof. GFA is measured from the exterior surfaces of the outside walls.
Global Warming Potential (GWP)	A relative measure of how much a given mass of greenhouse gas is estimated to contribute to global warming. It is measured against CO ₂ eq which has a GWP of 1. The time scale should be 100-year.
Greenhouse gases (GHG)	They are identified in different IPCC reports
Input and Output Tables	The Input-Output Tables are systematically present and clarify all the economic activities being performed in a single country, showing how goods and services produced by a certain industry in a given year are distributed among the industry itself, other industries, households, etc., and presenting the results in a matrix format.
Input and Output Analysis	The use of national economic and energy and CO ₂ data in a model to derive national average embodied energy/CO ₂ data in a comprehensive framework.
LCA	Life Cycle Assessment
PE_{nr}	Primary Energy non-renewable. Nuclear Energy is included.
PE_t	Primary Energy total. Renewable + Non-renewable Primary Energy. Nuclear Energy includes in the Primary Energy total.
Project commissioning	Synonyms: project commissioners, authority, policy makers
RSP	Reference Study Period. Period over which the time-dependent characteristics of the object of assessment are analysed (EN15978:2011)
Sustainability and certification expert	Synonyms: consultant, auditor

Summary

Introduction

This report provides an overview of building LCA frameworks and workflow structures and a generalization of the BIM approach in building LCA based on existing solutions.

In this section:

- We introduce a conceptual modular framework that generalizes the typology of systems for building LCA calculation. This can serve as a starting point for designing tools for building LCA.
- We present the results of an internal survey about the calculation structures applied by experts in 10 countries.
- The results of an LCA-BIM exercise performed as a part of the IEA EBC Annex 72 is presented.

1. A modular framework for building Life Cycle Assessment

1.1 Literature review on BIM-LCA

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 (Nizam, Zhang, & Tian, 2018) or the extension of BIM (Dupuis, April, Lesage, & Forgues, 2017) to include environmental data. Soust-Verdaguer and colleagues (Bernardette Soust-Verdaguer, Llatas, & García-Martínez, 2017) 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 (Hollberg & Ruth, 2016) 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. (Cavalliere, Dell'Osso, Pierucci, & Iannone, 2018) 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. (Tecchio, Gregory, Ghattas, & Kirchain, 2018) 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 (Fernanda, Rodrigues, & Pinto, 2018; Mora, Bolzonello, Peron, & Carbonari, 2019; Soust-Verdaguer, Llatas, García-Martínez, Carlos, & Cózar, 2018), 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) (Soust-Verdaguer et al., 2018) or apply commercial plug-ins (Mora et al., 2019) 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 (Cerdas, Kaluza, Erkiş-Arici, Böhme, & Herrmann, 2017; Benedek Kiss & Szalay, 2019; Röck, Hollberg, Habert, & Passer, 2018a).

The extended integration of LCA into the design practice (Jusselme, Rey, & Andersen, 2018) and into certification systems (Lee, Tae, Gong, & Roh, 2017) 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.

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.

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 Definition of the modules of the framework

There is a high need for the integration of Life Cycle Assessment into design practice (Jusselme et al., 2018). 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 (Jusselme et al., 2018) 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.

The following concept is based on own considerations concluded from the analysis of the current practice and the requirements of the experts (Jusselme et al., 2018). 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.

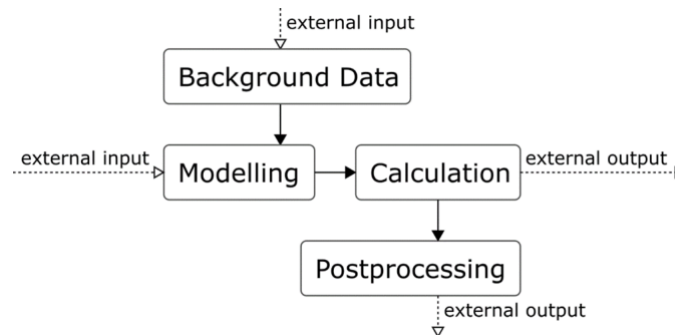


Figure 1 Conceptual representation of the modules and the data flow in the framework

1.3.1 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 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.

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.

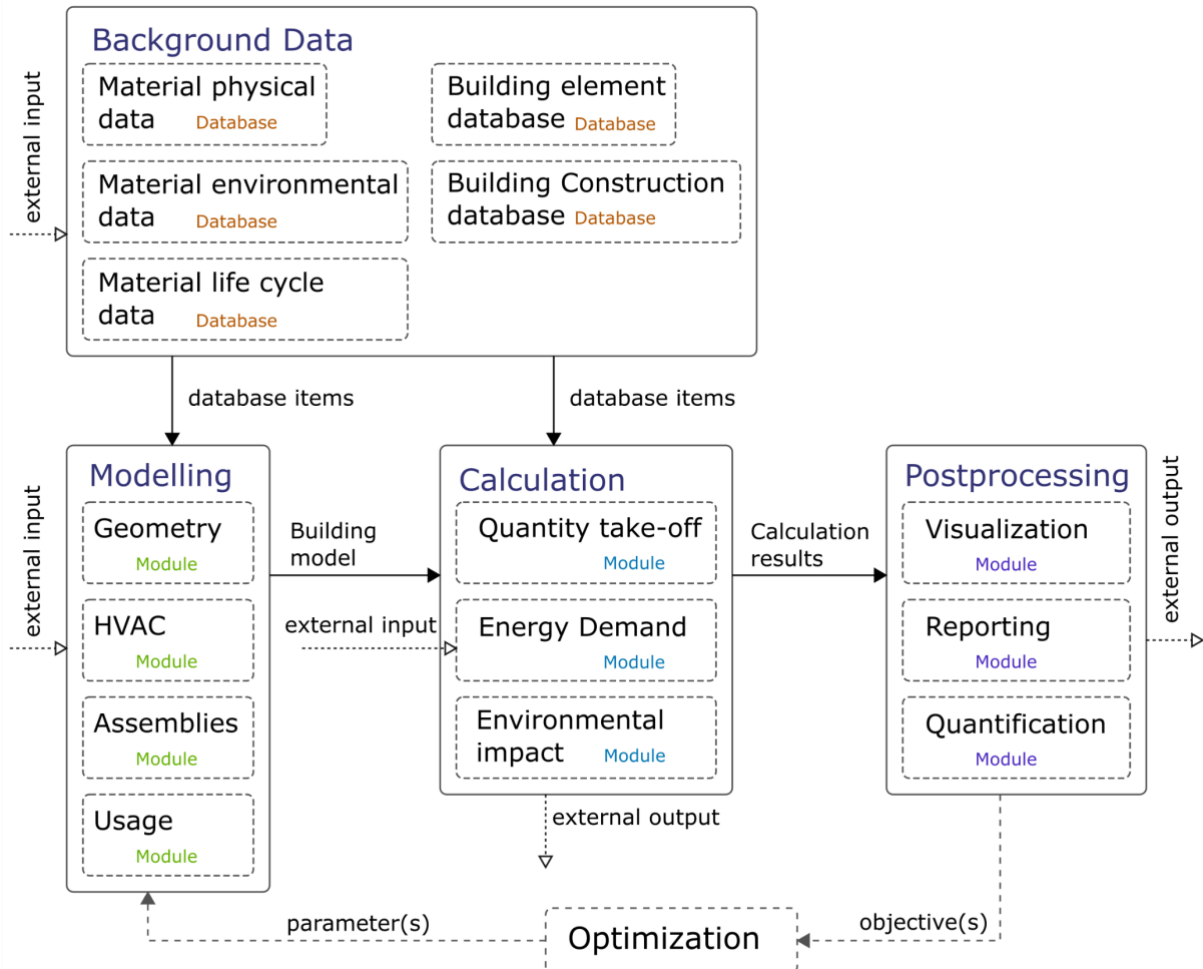


Figure 1. Visual representation of the framework structure and components

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.

Building element and Building construction data

The last two components facilitate the use of the system in early design stages and for decision support (Röck et al., 2018a). 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.

1.3.2 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.

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.

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.

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.

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.

1.3.3 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.

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).
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.

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).

1.3.4 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 (Cerdas et al., 2017; Benedek Kiss & Szalay, 2019; Lamnatou, Motte, Notton, Chemisana, & Cristofari, 2018; Röck, Hollberg, Habert, & Passer, 2018b). 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.

1.3.5 Optimization

In the favourable case of an automated 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 derivatives are not available in the mathematical problem associated with building LCA, since many parameters are discrete and non-numeric (e.g. type of material).

2. Annex 72 assessment workflow survey results

In the framework of this task, we conducted a short survey among the Annex 72 participants to improve our understanding on the calculation procedures and environmental assessment workflows applied in the daily practice. Thirteen partners from 12 countries filled in the survey. The answers are summarised in the following sections. The participating countries were Austria, Canada, China, France, Germany, Hungary, New Zealand, Portugal, Slovenia, Spain, Switzerland and the UK.

The survey contained three major parts. First information was collected about the software types and development options (what existing software is used, what is self-developed in which framework and what is the background data for the calculations). Second, a series of questions was focusing on the structure of the calculations based on predefined modules and information exchange options. Finally, questions were asking the participants about the visualization options available within their framework incl. examples.

2.1 Environmental assessment tools

Figure 3 shows that the 13 respondents are using many different software tools in their practice for environmental assessment. Most participants have different workflows for different purposes, and as a result use different tools or combine these tools in various ways. The application of Excel spreadsheets is widespread: people use Excel either in a standalone way for all the calculations or only for documentation purposes. Five respondents use dedicated LCA softwares with a Graphical User Interface (GUI) and three apply an LCA plug-in for a general CAD software. Many people develop their own LCA calculation in a general framework with scripting capabilities like Grasshopper or in Matlab/ Python. Only one respondent has a complete software package that covers all calculations. None of the respondents use an LCA plug-in for a building energy calculation software, nor a software with Command Line Interface. The questions and possible answers were formulated as:

- What kind of software do you use in your practice for the calculation of Life Cycle impacts?
 - I use a Spreadsheet-based calculation (e.g. MS Excel)
 - I use a plug-in for a general CAD software (e.g. Revit + Tally)
 - I use a plug-in for a building energy calculation software (e.g. DesignBuilder + OneClickLCA)
 - I use a complete software package that covers all calculations
 - I use a standalone software with a GUI (Graphical User Interface) (e.g. SimaPro, OpenLCA)
 - I use a standalone software with a CLI (Command Line Interface) (e.g. BrightwayLCA)
 - I use a general framework with scripting capabilities (e.g. Rhino3D + Grasshopper)
 - I do not use any software

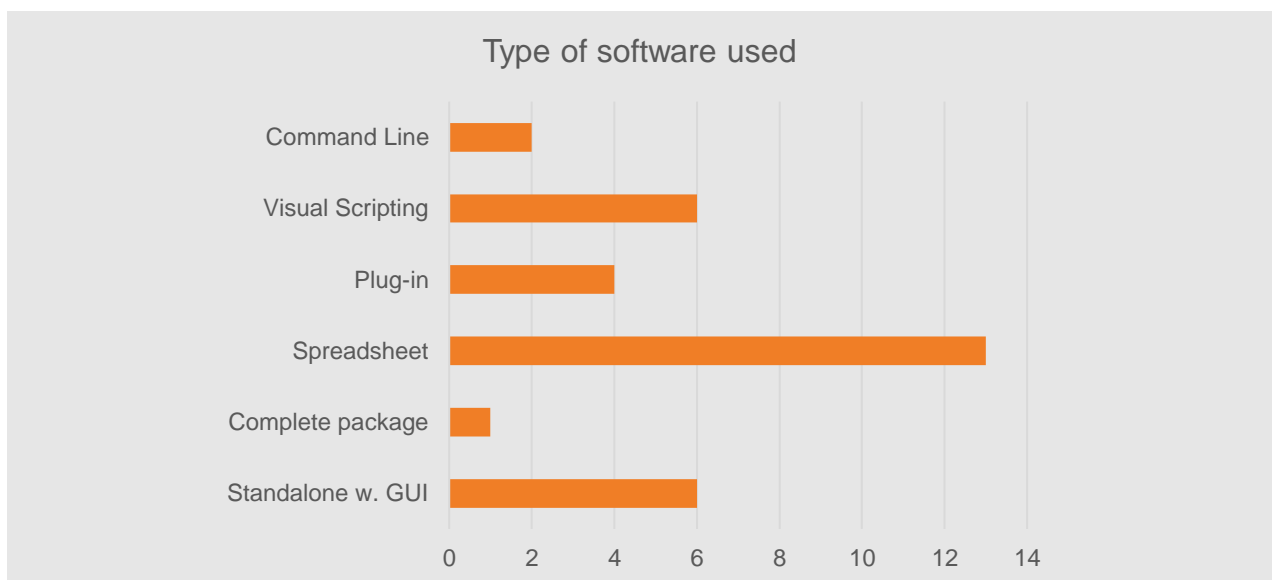


Figure 3: Answers to “What kind of software do you use in your practice for the calculation of Life Cycle impacts?”

As most Annex partners are coming from universities or research institutes, it is not surprising to see that many respondents develop their own LCA software from scratch, either in Excel or in a programming language (Figure 4a). From the 13 answers, only 3 are using independently developed solutions. The popularity of scripting languages shows growing tendency among design professionals, which is also reflected in the survey. 6 respondents use some kind of scripting capability within their framework. None of the respondents are in close contact with the external software developers.

– Do you (your institution) develop your own software (including Excel spreadsheet)?

- Yes, I develop my own software from scratch
- Yes, I use the scripting capabilities of a general framework (e.g. Revit Dynamo)
- No, I use independently developed solutions
- No, but I'm in close contact with the software developers
- No, I don't use any software

Regarding the background LCA database, most respondents use a combination of databases, mostly ready-made LCIA results combined with industry data or LCI databases, such as ecoinvent (Figure 4b). One applies only ready-made LCIA datasets and three only an LCI database. Nobody uses EPD data alone, and two respondents use the combination of datasets without EPDs.

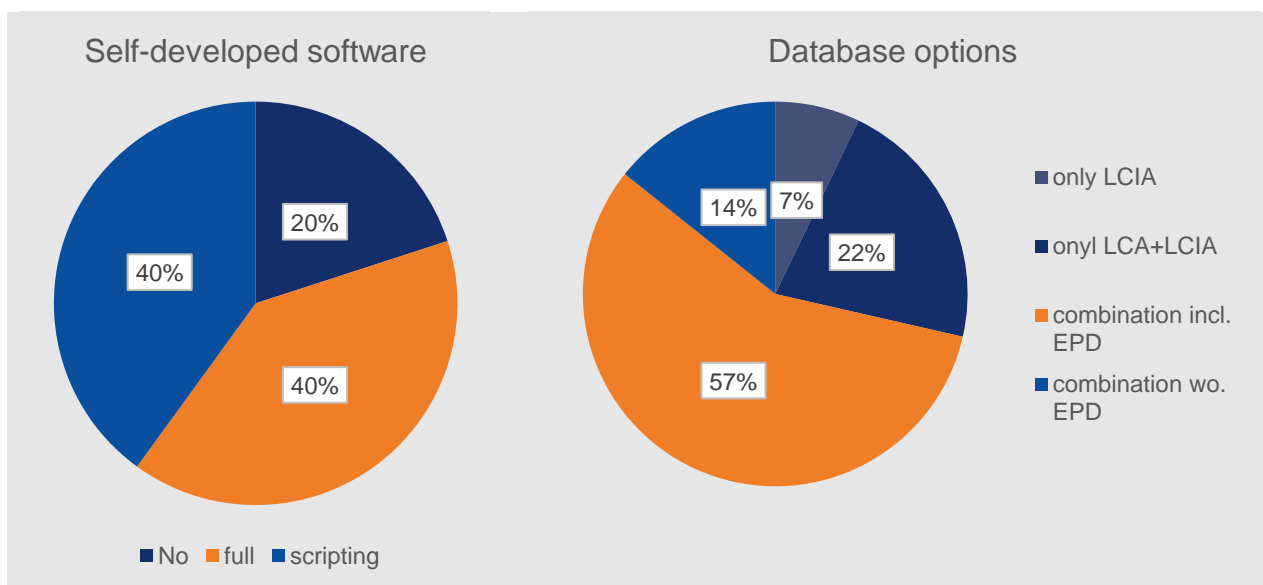


Figure 4: a) Answers to “Do you (your institution) develop your own LCA software (including Excel spreadsheet)?” b) Answers to “What kind of LCA data does your software use?”

2.2 Software applied in the environmental assessment workflow

The survey respondents use a wide range of software tools and their different combinations in their building environmental assessment workflow (Table 1). Only one uses a complete package that is capable of geometry modelling, energy calculation and LCA calculation in one environment (Pleiades – Equer). For geometry modelling, the mostly applied tools are commercial CAD softwares, such as Revit, Rhino and Archicad. LCA calculations are usually carried out in dedicated LCA softwares, plug-ins or self-developed Excel spreadsheets (see previous section). For energy calculation a number of dynamic building energy simulation tools are applied (e.g. EnergyPlus, DesignBuilder, IESVE). In addition, for developing own tools, data analysis tools and programming packages are applied. The popularity of Revit and Excel is clearly visible on Figure 5.

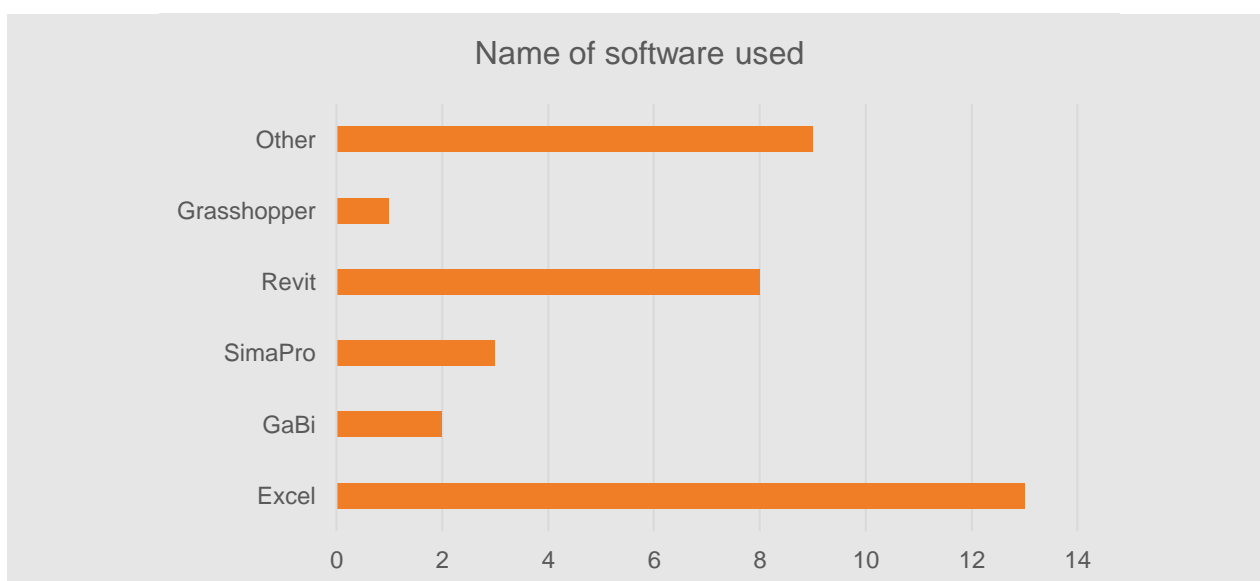


Figure 5: Answers to “Do you (your institution) develop your own LCA software (including Excel spreadsheet)?”

Table 1: Name of software tools used by the survey participants in their assessment workflow

Software type	Software name
Geometry, BOM	Revit, Rhino, Archicad, Autocad, DESITE BIM
LCA calculation	GaBi, SimaPro, OpenLCA, Tally, Caala, Bombyx, eLCA, liNear, own Excel tool (SBToolPT, LCAQuick, US_LCA_Building Systems, KESZ_LCC_LCA)
LCA data	ecoinvent database, SBToolPT, EPDs
Energy calculation	IESVE, EnergyPlus, DesignBuilder, Trnsys, PhPP, EnEV, HULC
Map	Google maps
Data analysis	Presto
Programming	Excel, Python, Matlab, R, Grasshopper, Dynamo
Complete package	Pleiades - Equer

2.3 Calculation structure and workflow

Based on the responses, we created figures to represent the calculation structures and workflows applied by 13 of the partners (Figure 6-19). The calculation workflow includes the following steps in all cases: geometry definition, material definition, bill of materials, life cycle impact calculation and documentation. Four workflows include an optimization algorithm and one a manual Excel-based optimization. Energy calculation is not included in four cases.

The figures show the connections between the different modules of the calculation, with a blue arrow showing automatic and red arrow showing manual information exchange. It is clear that most of the workflows are not completely automatic and a lot of manual interventions are required from the user. As detailed in the previous sections, most partners use different tools for most purposes.

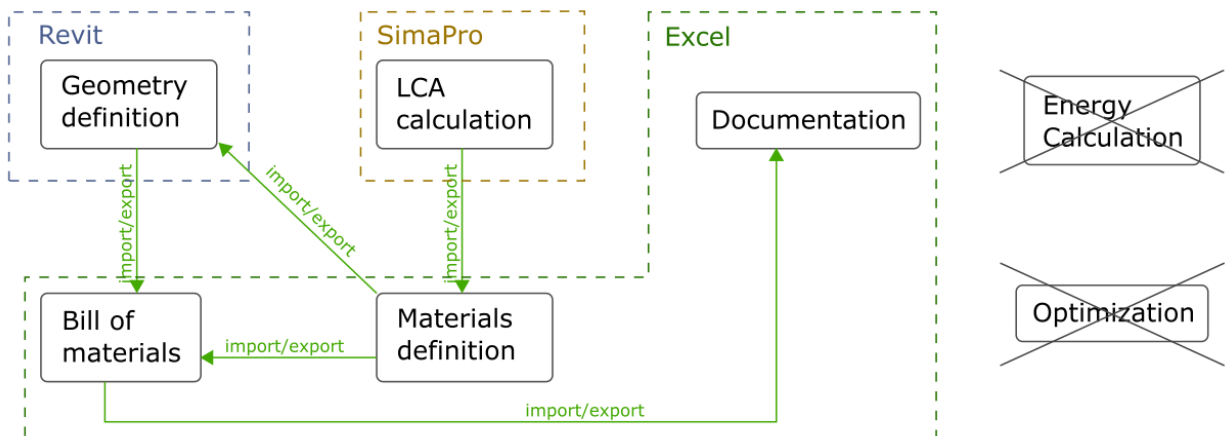


Figure 6: Calculation structure (Austria)

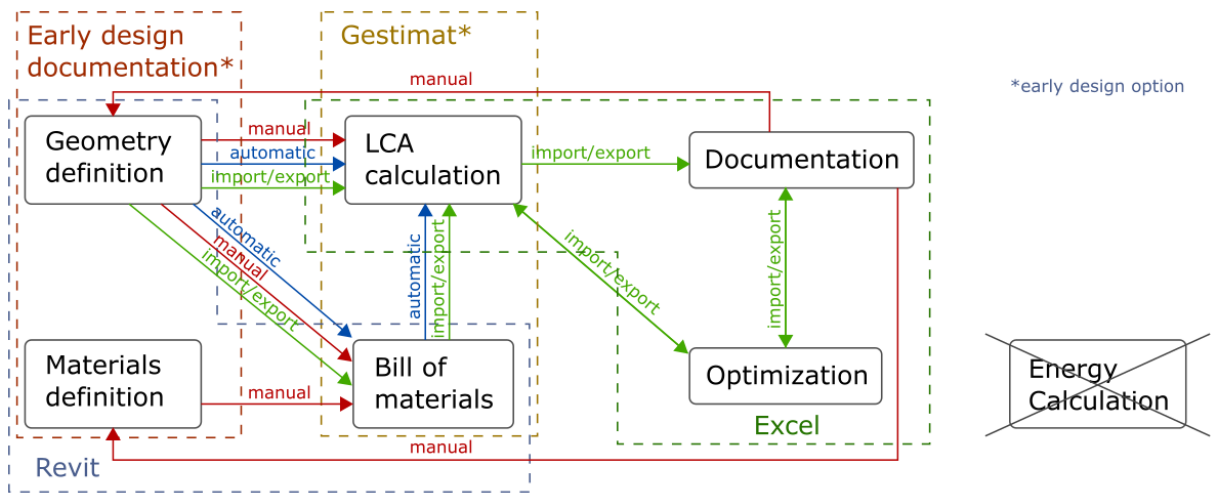


Figure 7: Calculation structure (Canada)

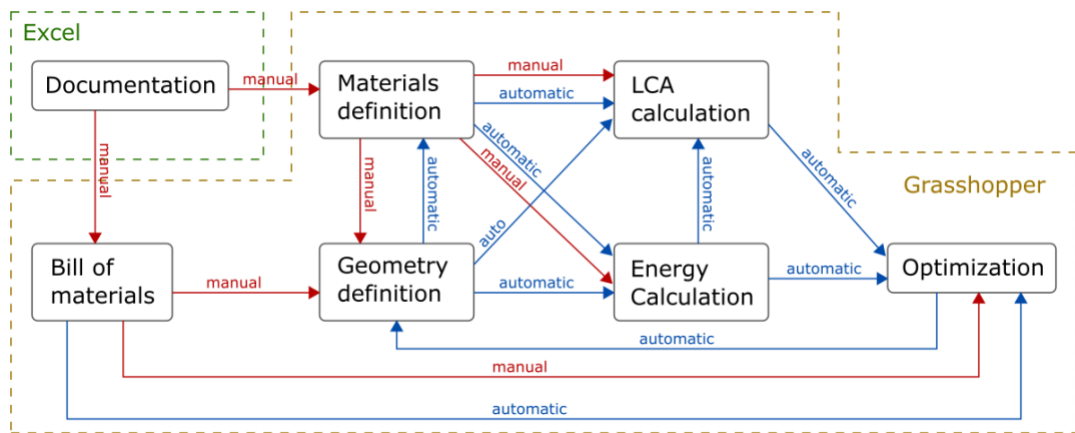


Figure 8: Calculation structure (China)

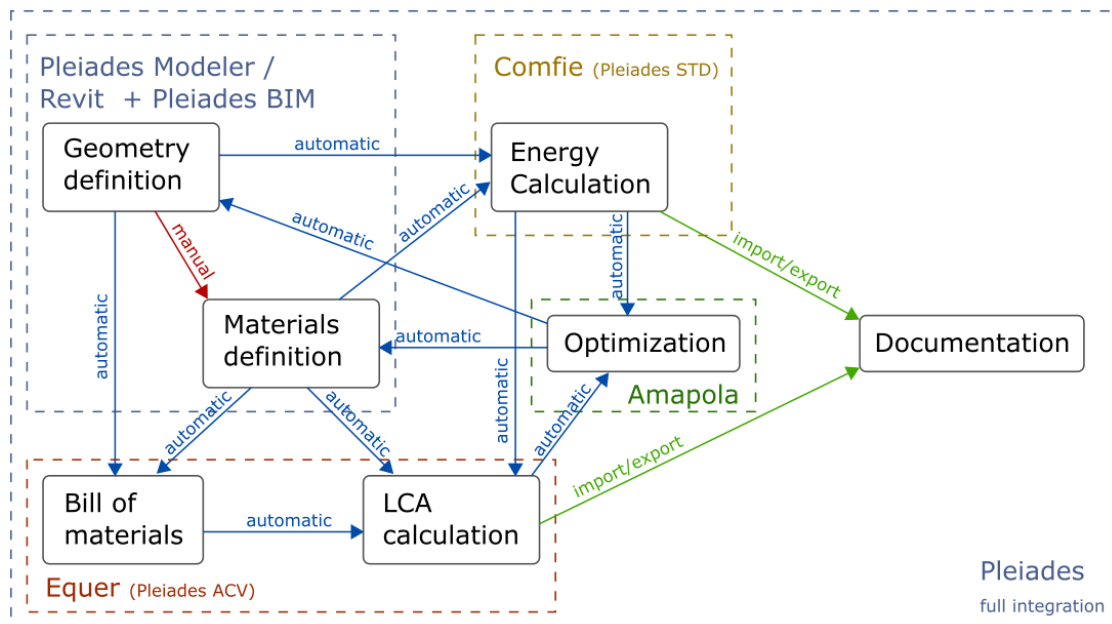


Figure 9: Calculation structure (France)

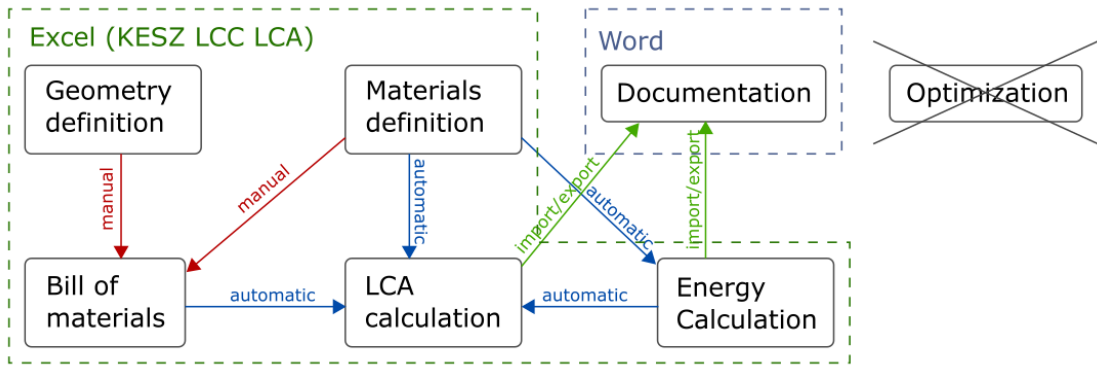


Figure 10: Calculation structure (Hungary1)

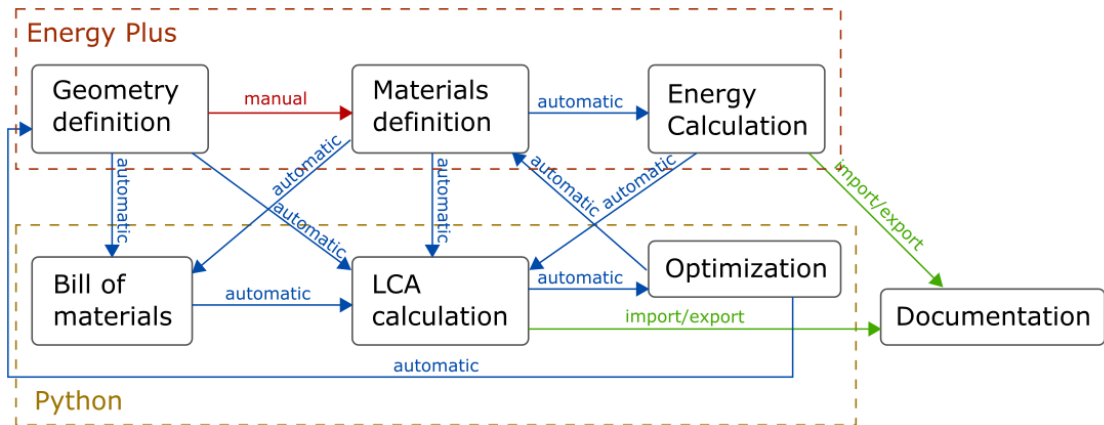


Figure 11: Calculation structure (Hungary2)

The workflow in Figure 11 has been applied in research projects primarily focusing on optimization (B. Kiss & Szalay, 2020; Szalay & Kiss, 2019). Therefore, the automatized data exchange as well as the integrated energy calculations have been prioritized during the development of the framework.

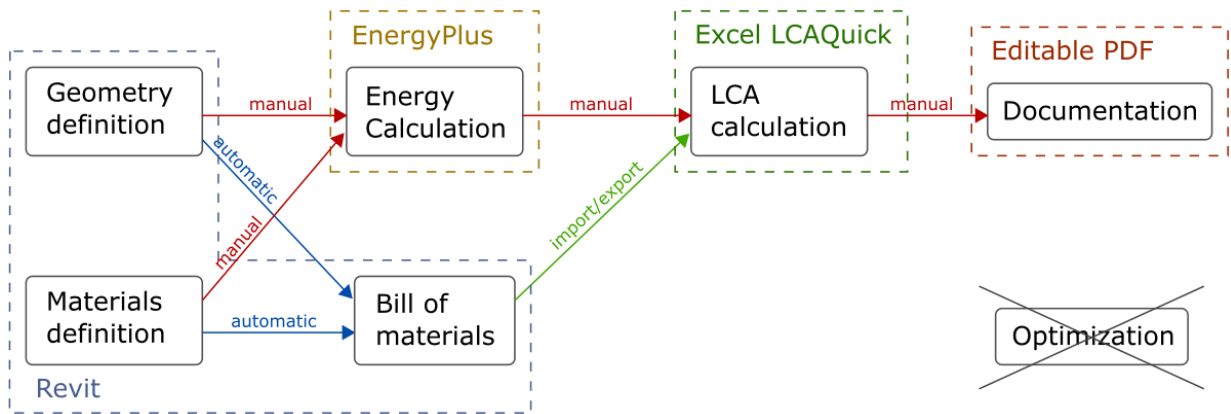


Figure 12: Calculation structure (New Zealand)

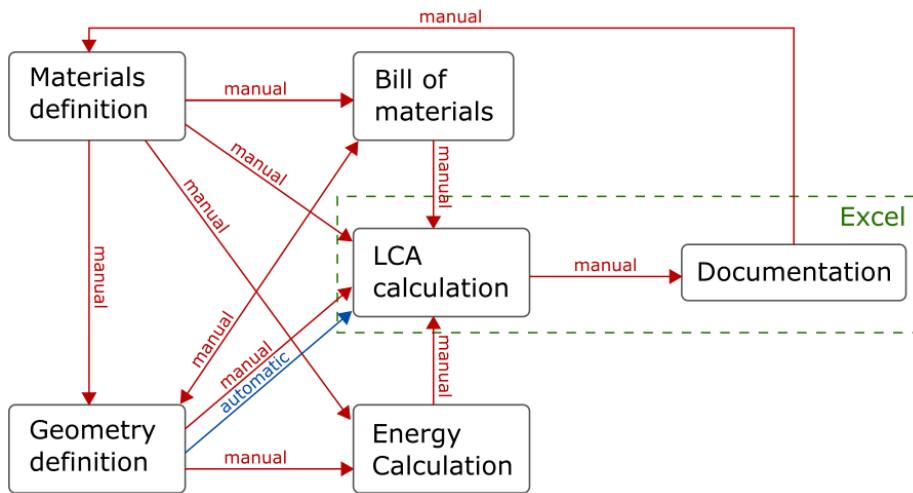


Figure 13: Calculation structure (Portugal 1)

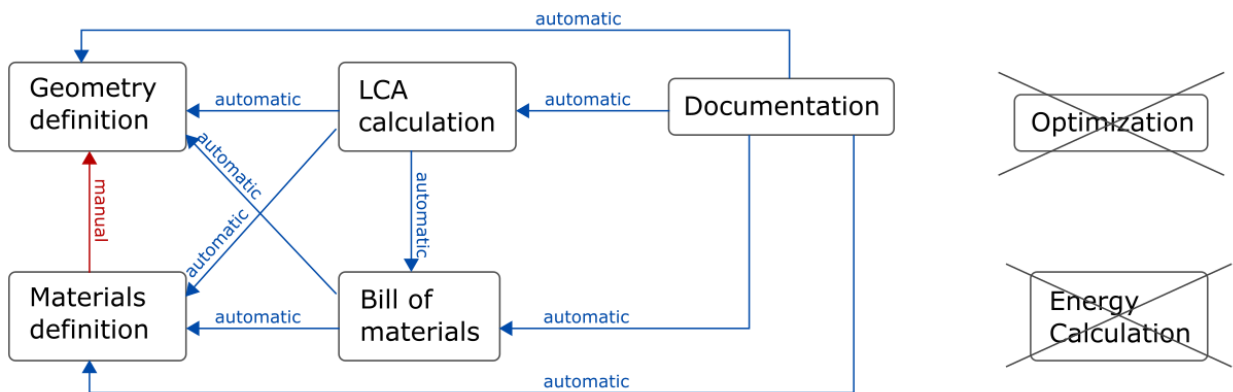


Figure 14: Calculation structure (Portugal 2)

Figure 14 shows a workflow with BIM integration in the primary focus (Santos, Aguiar Costa, Silvestre, & Pyl, 2020). Although optimization and energy calculation are not part of the workflow, a deep automated connection between the other components are presented using the capabilities of BIM.

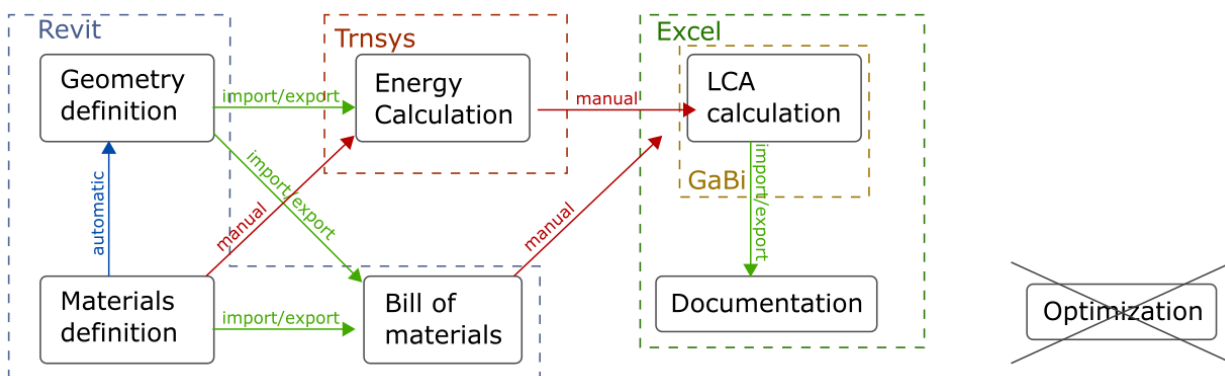


Figure 15: Calculation structure (Slovenia)

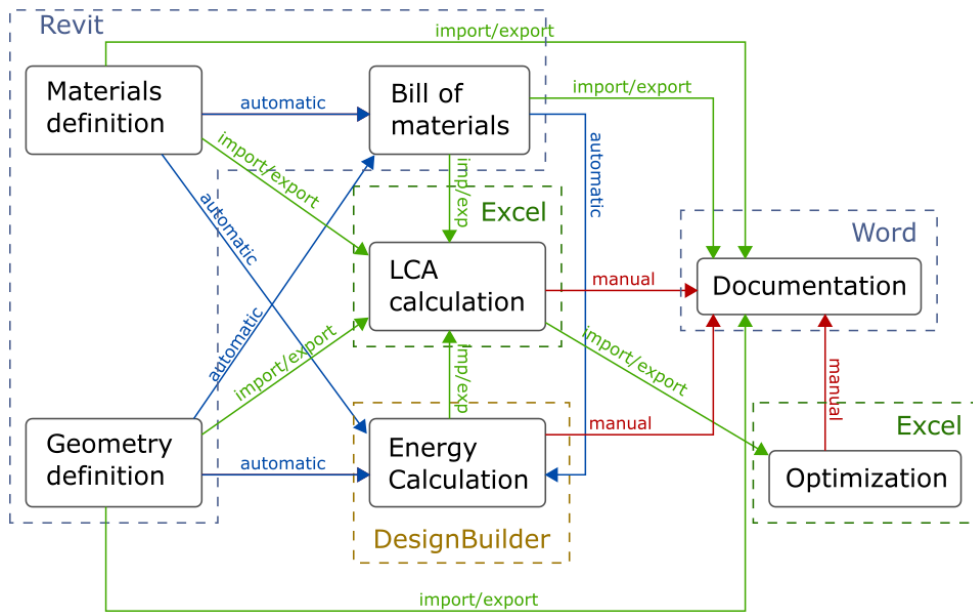


Figure 16: Calculation structure (Spain 1)

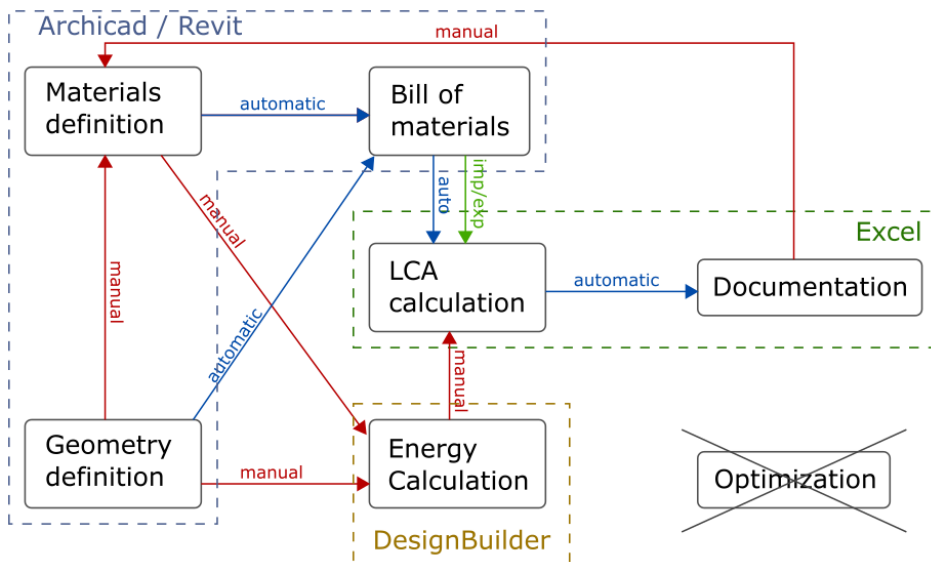


Figure 17: Calculation structure (Spain 2)

The workflow depicted in Figure 17 has been verified in the publications (Soust-verdaguer et al., 2018; B Soust-Verdaguer, Llatas, & Moya, 2020). Although, the optimization with algorithms is not performed, the comparison of different alternatives (solutions) is proposed. The different alternatives are modelled in different BIM files and link to an excel file where the LCA calculation is developed and the information about the compared alternatives is shown.

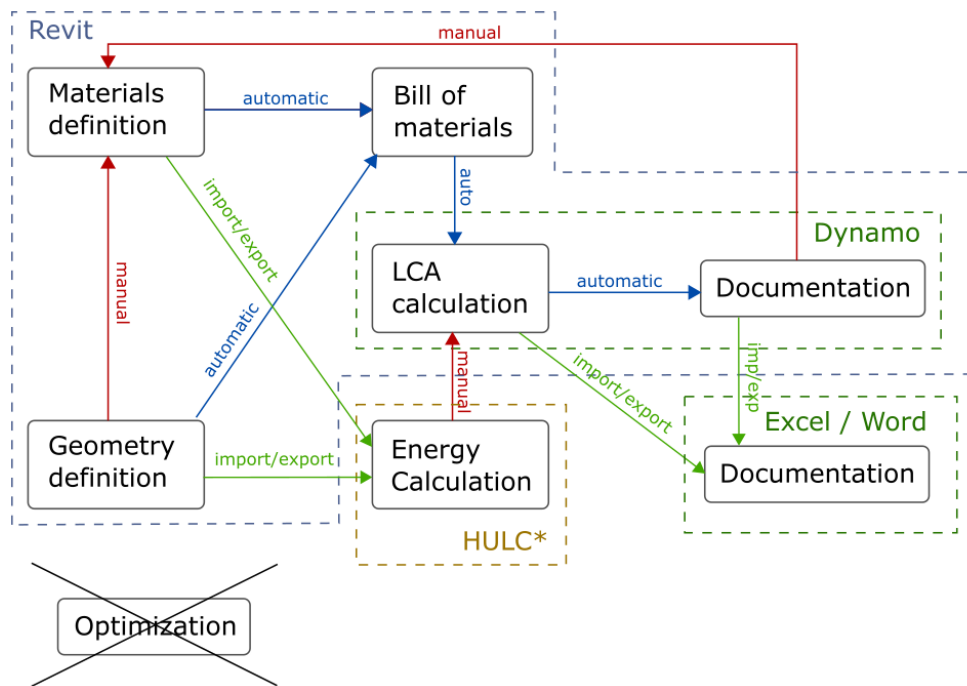


Figure 18: Calculation structure (Spain 3)

Figure 18 shows an additional proposed workflow that is under verification in an ongoing research project. It proposes an automatic solution that can help to obtain the LCA results inside the BIM environment (Revit).

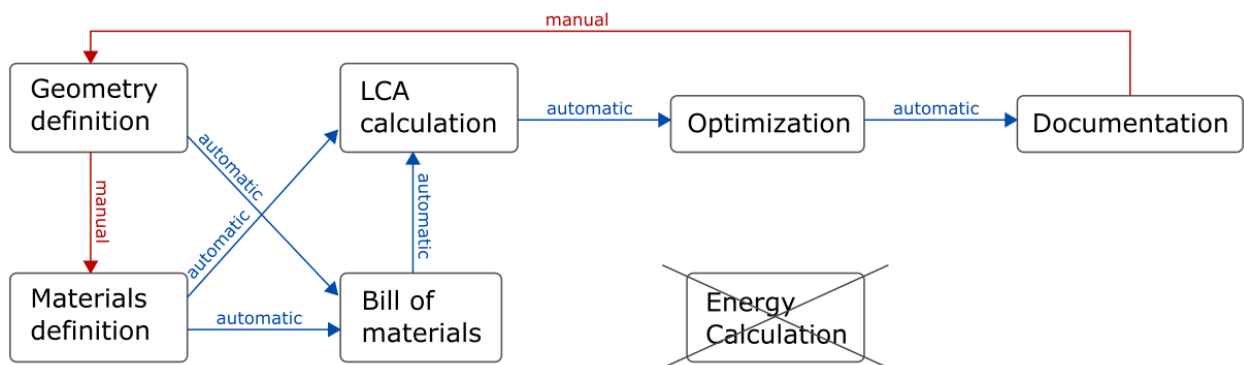


Figure 19: Calculation structure (United Kingdom)

The calculation structure is very specific for each country, but there are some similarities. A common solution integrates The *Geometry definition*, *Material definition* and *Bill of materials* in Revit (Spain, New Zealand, France, Canada, Austria, Slovenia). Most of the times, the *LCA calculation* is fulfilled in Excel, in some cases as a dedicated solution including some extra features (*Documentation*, *Optimization*). For *Energy calculation* a common solution is to apply EnergyPlus/DesignBuilder when simulation is used. In some cases, optimization is included, but not necessarily with a fully automated, integrated system. In general, all experts use multiple software to do building LCA calculations and there is only one country (France) that applies a full integrated software suite for all the modules.

Finally, the structures can be classified into four categories (Table 2) with decreasing integration/automation in the following order:

- *Specialized standalone software (with BIM integration)*: Externally or internally developed software solutions for multiple modules, including BIM integration (either with a plugin to existing BIM software or standalone BIM module). This is the most advanced solution, but it is usually the result of long-term software-development strategies, which is only feasible with industry participation.

- *Modules based on (visual) scripting*: The automated workflow is enabled through (high-level) visual scripting interfaces of existing software (e.g. Rhino Grasshopper or Revit Dynamo) or other scripting languages (e.g. python, Matlab). This option is more available for a wider community including engineers, designers, and researchers, and therefore it is becoming more and more popular.
- *BIM with further spreadsheet-based calculations*: The workflow is based on existing BIM solutions (e.g. Revit), where the required data can be extracted for further evaluation in a spreadsheet-based system. This option is the most flexible regarding external models since the required data export does not require any special rules to be applied to the model. Therefore, this method is often used with real design projects.
- *Manual (spreadsheet-based) calculation structure*: In this (legacy) case all input data need to be added manually to a spreadsheet, where all the necessary calculations are done. This requires time-consuming work, but the data is fully controlled and transparent in return.

Table 2: Classification of calculation structures

Type of calculation structure	Participant
Specialized standalone software (with BIM integration)	CA, FR
Modules based on (visual) scripting	CN, HU2, UK, ES
BIM with further spreadsheet-based calculations	NZ, ES, SI, AT, PT
Manual (spreadsheet-based) calculation structure	HU1, PT

2.4 Visualization options

The third part of the survey focused on the different output (visualization) options to evaluate the results of the LCA calculations. Figure 21 shows the available options regarding result granularity within the frameworks of the participants. Most of the frameworks apply all three impact decomposition options, but the most common is the “impact per building element”. Impact per life cycle stage is also available in 13 tools, and impact per individual materials is available in 11 tools.

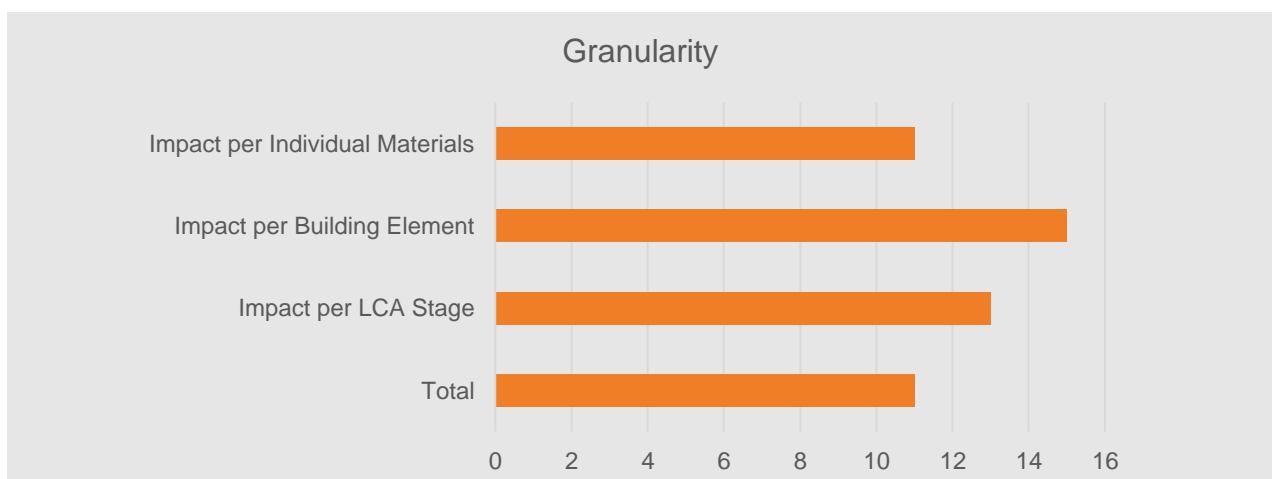


Figure 20: Available result granularity in the respondents' frameworks

Depending on the framework type the result data might be exported as raw data, or reports are generated. Figure 21 summarizes the answers for the question “What kind of results can you retrieve from your software?” All respondents can retrieve charts and single numbers. Six of the participants have the ability to produce building-based visualizations, and seven can export the raw data for further evaluation.

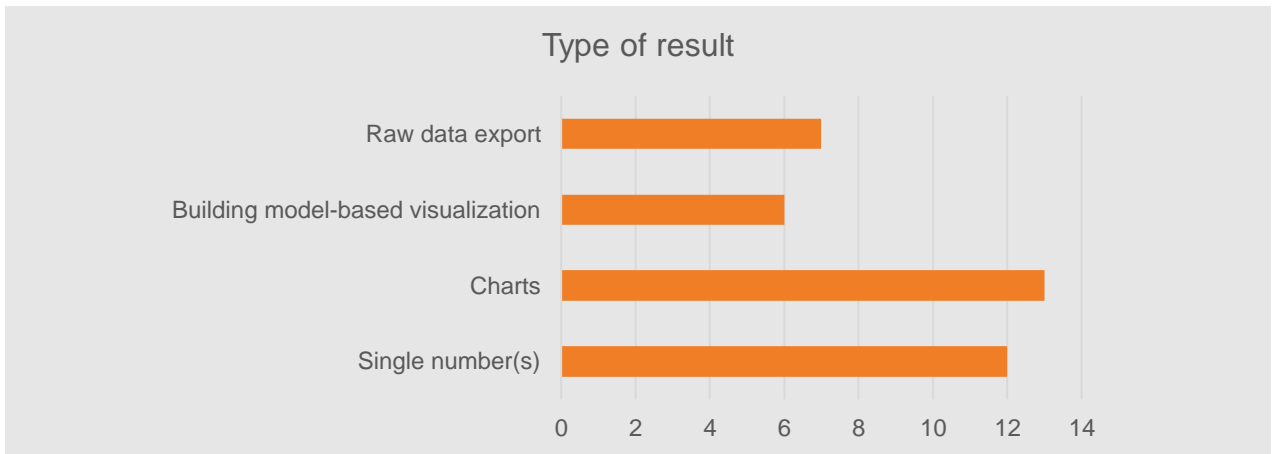


Figure 21: Available type of result in the respondents' frameworks

The next question targeted the focus of the visualization. Figure 22 shows that most of the times, visualization is used for “contribution analysis” or “comparison of design options” but “building optimization and “decision support” is also marked as one of the most frequent focus areas of visualizations. Only four respondents use the visualizations for certification.

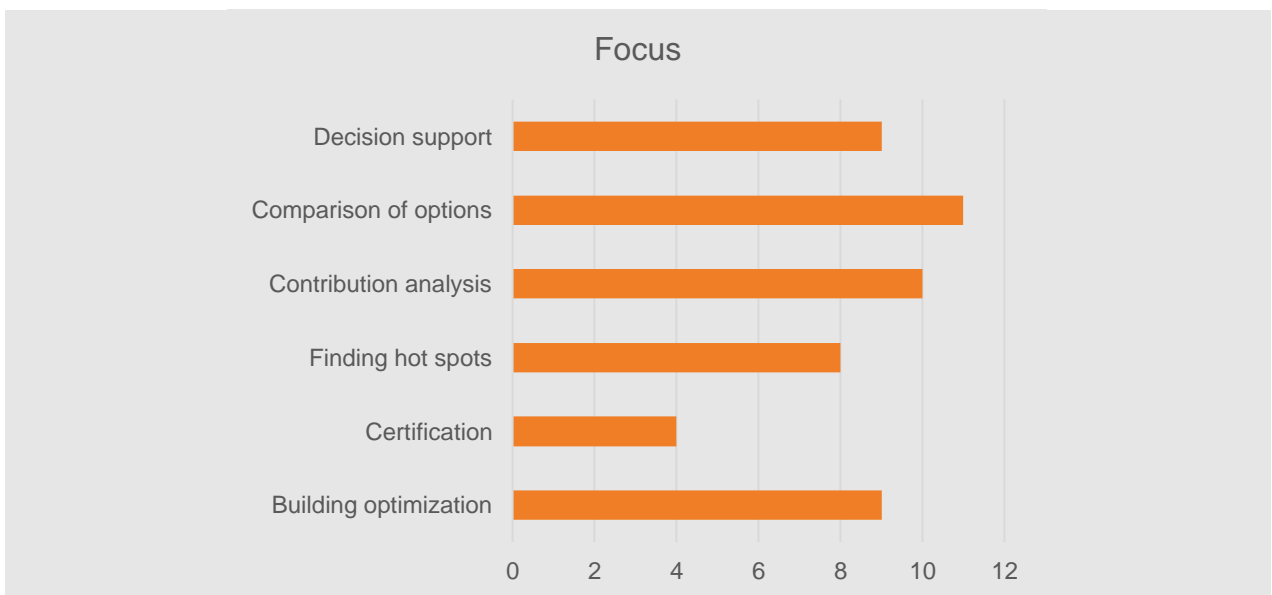


Figure 22: Responds to the question: “What is the focus of the result communication?”

Finally, the different available visualization types were collected. For each type three options (“available in my software”, “I’m interested in”, and “I’m using”) were possible.

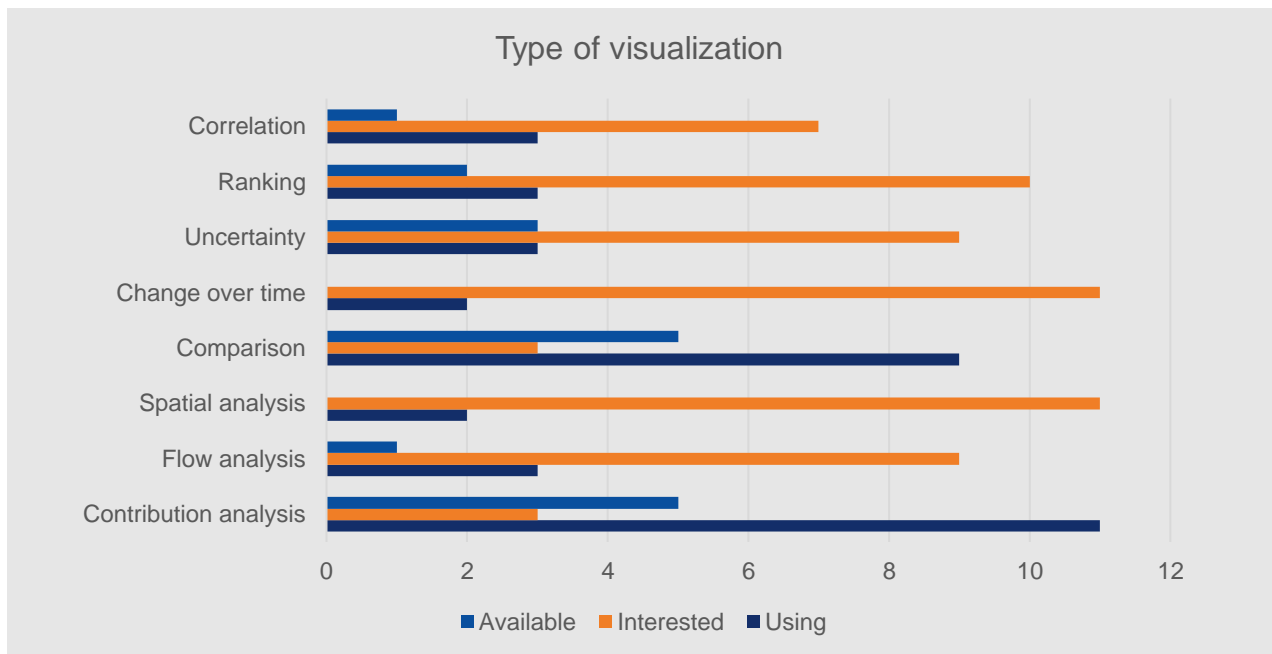


Figure 23: Responds to the question: “Which type of visualization are you using in practice, and which would be interesting for you?”

On Figure 23, it is visible that there is high interest about various types of visualizations, especially with focus on “change over time” and “spatial analysis”. A more detailed description of the characteristics of different visualisation types can be found in the paper published by Hollberg et al. (2021).

Despite of the high interest, these two types are used by only 1-1 of the respondents. The most used and most available options are the “contribution analysis” as well as the “comparison”.

More details about the different visualisation types and the

3. Annex 72 assessment LCA- BIM exercise

3.1 Aim of the LCA-BIM exercise

The objective of this exercise was to investigate how BoQ exported from BIM can influence the outcomes of LCA and how these environmental impacts can be mitigated. The process of extracting BoQ out of the model has potential for causing a problem, therefore identification of possible sources of errors is also included in this study.

3.2 The workflow of the LCA-BIM exercise

The whole work was divided in following parts: (1) survey among participants from various countries; (2) collection and comparison various workflows and BoQ results; (3) identification and summarization potential sources of errors in used workflows; (4) summarization key suggestions for developing BIM models.

Eight partner countries took part in this experiment: Austria, Canada, Czech Republic, France, Germany, New Zealand, Slovenia, Spain and Switzerland.

In the first part an online survey was developed to collect the information about the workflows and the software programs used to perform this exercise. It follows the logical framework in the study of Kiss at al, which was used to collect the typical workflows used in in separate countries. The goal of the survey was to improve the understanding of the calculation procedures and environmental assessment workflows applied in the exercise.

The answers of the survey were analyzed and based on them harmonized flowcharts were created to represent the workflows of each country in a uniform way. An example of the survey is shown below:

AUSTRIAN WORKFLOW: The Austrian Workflow is so far completely manual, which offers detailed insight into the generated Bill of Quantities and will therefore act as a reference workflow in this study.

The list of materials, sorted by building family and type, is exported directly from the Revit model and is further processed with a python script to fit into the workflow template provided. As the BIM-model did not have information on the exchange rates for different building parts, those were added manually according to DIN 276. The excel sheet is then used to summarize the amounts per material/transportation distances per vehicle type for the supported modules.

The workflow allows the calculation of the emissions of the production and construction phase, the use phase except for B5 and the End-of-Life.

The full Life Cycle Inventory is then entered into SimaPro using the respective processes. The results can easily be exported to excel and further analyzed with various tools.

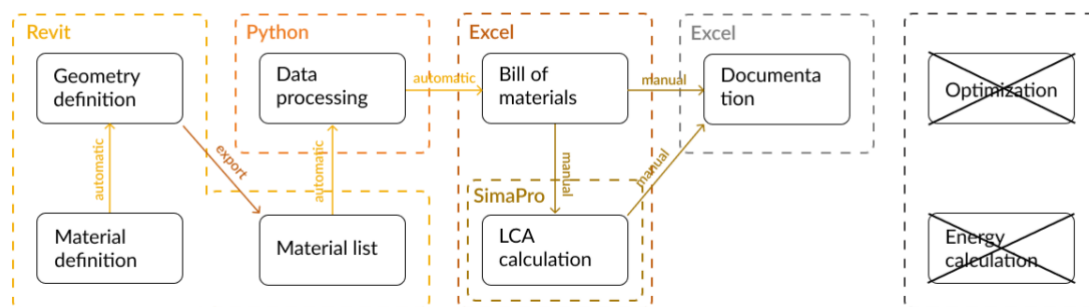


Figure 24: Austrian workflow in the LCA BIM exercise

In the second step the case study was distributed among the participants and the Bill of Quantities were collected. The case study represents the university building Inffeldgasse 13, PZ02 (Fig 25). PZ02 is part of the “Produktionstechnikzentrum”, a complex consisting of several buildings, used as laboratories and administrative purposes of the TU Graz (Innenfeldgasse 13, 2021).



Figure 25: Austrian workflow in the LCA BIM exercise

Each of the study participants used a different type of workflow which is typical in their country. Participants of this study were requested to deliver: (1) edited model with all the data needed for BoQ exported from the model (e.g., classification system); (2) BoQ in the spreadsheet format; (3) form describing used workflow.

In the third step the identification and summarization potential sources of errors in used workflows was performed. The materials, the volumes and the errors were identified.

Material analysis

Since a detailed BoQ was not available for all submissions, only submissions from the following participants could be compared: CZ, DE, ES, NZ, SL. From these submissions, 55 missing materials were identified. The missing materials were investigated, and the following reasons were found. For two materials the source could not be identified. List of all errors is shown in Table 3.

1. Material ignored (n=14). The single material was deliberately not considered for the calculation.

2. Material not decomposed ($n=39$). The composite material which includes the single material was not decomposed. The single material was not considered explicitly.
3. "0" thickness ($n=10$). Some layers in the model have a thickness of 0. In some cases, this meant that the material was not included in the calculations.
4. Not identifiable ($n=2$). The reason for the missing single material could not be identifiable.
5. Included in a similar material ($n=1$). The quantity of the material was joined together with a similar single material.

Table 3: List of all errors

Material	AT	CZ	ES	NZ	SL	Material	AT	CZ	ES	NZ	SL
MS001 mineral wool (glas wool) WF (50 kg/m ³)	✓	✓	✓	✓	✓	MS002 concrete (outer walls)	✓	✓	Σ	✓	✓
MS004 gypsum plaster (1300 kg/m ³)	✓	✓	✓	-	✓	MS003 reinforcement steel	✓	✓	Σ	✓	✓
MS005 plastic-modified bitumen coating	✓	✓	✓	✓	✓	MS006 concrete (roofs)	✓	✓	Σ	✓	✓
MS008 gypsum plaster board (700kg/m ³)	✓	✓	✓	✓	✓	MS007 mineral wool (stone wool) WD	✓	✓	✓	✓	✓
MS009 waterproofing membrane PE root-proof	✓	✓	✓	✓	✓	MS011 concrete (inner walls)	✓	✓	✓	✓	✓
MS010 aluminium sheet powder coated	✓	✓	✓	✓	✓	MS016 concrete (floors)	✓	✓	Σ	✓	✓
MS012 vapour retarder PE	∅	✓	✓	✓	∅	MS033 steel sheet	✓	-	Σ	?	?
MS013 XPS-G (80-100mm (43kg/m ³ m))	✓	✓	✓	✓	✓	MS036 mineral wool (stone wool) WF (40kg/m ³)	✓	=	Σ	✓	✓
MS014 bound split fill	✓	✓	✓	✓	✓	MS040 precast concrete	✓	✓	Σ	✓	✓
MS015 screed (2000kg/m ³)	✓	✓	✓	✓	✓	MS045 concrete (columns)	✓	✓	Σ	✓	✓
MS017 EPS-W 25	✓	✓	✓	✓	✓	MS046 aluminium	✓	✓	✓	✓	✓
MS018 EPS-T 650	✓	✓	✓	✓	✓	MS047 glas	✓	✓	Σ	✓	Σ
MS019 parquet	✓	✓	✓	✓	✓	MS048 argon	✓	✓	Σ	✓	Σ
MS020 EPS-T 1000	✓	✓	✓	✓	✓	MS049 air	✓	-	Σ	-	Σ
MS021 polyisobutylene rubber (930 kg/m ³)	✓	✓	✓	-	✓	MS050 cement	✓	✓	Σ	Σ	✓
MS022 linoleum	✓	✓	✓	✓	✓	MS051 water	✓	✓	Σ	Σ	✓
MS023 terrazzo	✓	✓	✓	-	✓	MS052 water based paint	✓	✓	Σ	Σ	✓
MS024 tilework (2300 kg/m ³)	✓	✓	✓	✓	✓	MS053 glass wool	✓	✓	Σ	Σ	✓
MS025 liquid foil (protective coating)	∅	✓	✓	-	∅	MS054 glass tissue	✓	✓	Σ	Σ	✓
MS031 rubber granulate mat	∅	✓	✓	✓	∅	MS055 water based glue	✓	✓	Σ	Σ	✓
MS032 timber (525 kg/m ³)	✓	✓	✓	✓	✓	MS056 cement bound wood wool	✓	✓	Σ	-	✓
MS037 PE liner	∅	✓	✓	✓	∅	MS057 epdm	✓	✓	Σ	-	Σ
MS038 bitumen coating	✓	✓	✓	✓	✓	MS060 polyamide	✓	✓	Σ	Σ	Σ
MS039 PE membrane LD (920kg/m ³)	∅	✓	✓	✓	∅	MS061 stainless steel	✓	✓	Σ	Σ	Σ
MS041 vapour barrier aluminium	✓	✓	✓	✓	✓	MS062 brass	✓	✓	Σ	Σ	Σ
MS042 extensive roof greening	✓	-	✓	-	-	MS040 concrete (foundations)	✓	✓	✓	✓	✓
MS058 solid chipboard	✓	✓	✓	-	✓	MS049 steel	✓	✓	Σ	-	✓
MS059 steel	✓	✓	✓	✓	✓						

✓ single material present - material ignored Σ material not decomposed ∅ 0 thickness = included in a similar material ? not identifiable

Volume analysis

The volumes of the following materials were examined: MS016 concrete (floors), MS046 aluminum, MS015 screed (2000kg/m³), MS010 aluminum sheet powder coated, MS040 concrete (foundations), MS003 reinforcement steel, MS007 mineral wool (stone wool) WD, MS047 glass, MS017 EPS-W 25, MS008 gypsum plaster board (700kg/m³), MS022 linoleum. The results are summarized in the Table 4

Table 3: Volume comparison

	MS016 concrete	MS046 aluminium	MS015 screed (2000kg/ m ³)	MS010 aluminium sheet powder	MS003 reinforce ment steel	MS007 mineral wool (stone wool)	MS040 concrete (foundati ons)	MS047 glass	MS017 EPS-W 25	MS008 gypsum plaster board	MS022 linoleum	SUM of materials
AT	2174.7	17.8	500.6	11.8	37.1	848.2	347.8	25.3	466.6	326.0	9.5	4765.3
CA	2174.7	9.2	500.6	10.0	37.8	848.2	471.2	28.7	466.6	325.9	9.5	4882.4
CZ	2174.7	17.8	500.6	11.8	37.1	848.2	409.5	25.3	466.6	326.0	9.5	4826.9
DE	2414.4	10.1	652.2	4.5	38.3	774.3	0.0	16.6	669.9	443.8	9.6	5033.6
ES	2226.4	13.4	499.8	10.0	2.3	474.6	359.6	4.6	466.1	325.9	9.5	4392.0
NZ	2174.7	25.9	500.6	2.1	33.5	848.2	347.8	25.3	681.3	326.0	0.0	4965.3
SL	2174.7	15.6	500.6	10.0	37.1	851.7	347.8	59.9	466.6	325.9	9.5	4799.4
Min	2174.7	9.2	499.8	2.1	2.3	474.6	0.0	4.6	466.1	325.9	0.0	4392.0
Max	2414.4	25.9	652.2	11.8	38.3	851.7	471.2	59.9	681.3	443.8	9.6	5033.6
% of difference	9.9	64.3	23.4	82.4	93.9	44.3	100.0	92.3	31.6	26.6	100.0	12.7

In the further step a detailed analysis of the potential sources of errors is developed. The most common sources of errors are the following:

- Composite material decomposition incorrect/partial (n=4)
- Combination of similar materials (n=3)
- Rounding error (n=3)
- Wrong application of factor for decomposition (n=2)
- Generic factor for decomposition (n=2)
- Wrong factor for area to volume (n=2)
- Transposed digits (n=1)

3.3 The recommendations of the LCA- BIM exercise

Based on the analysis a decision making process was developed that should help the practitioners to choose the right process for obtaining the BoQ. The positive (PROs) and negative (CONS) aspects of each decision are highlighted in the Fig 26.

Decision making process

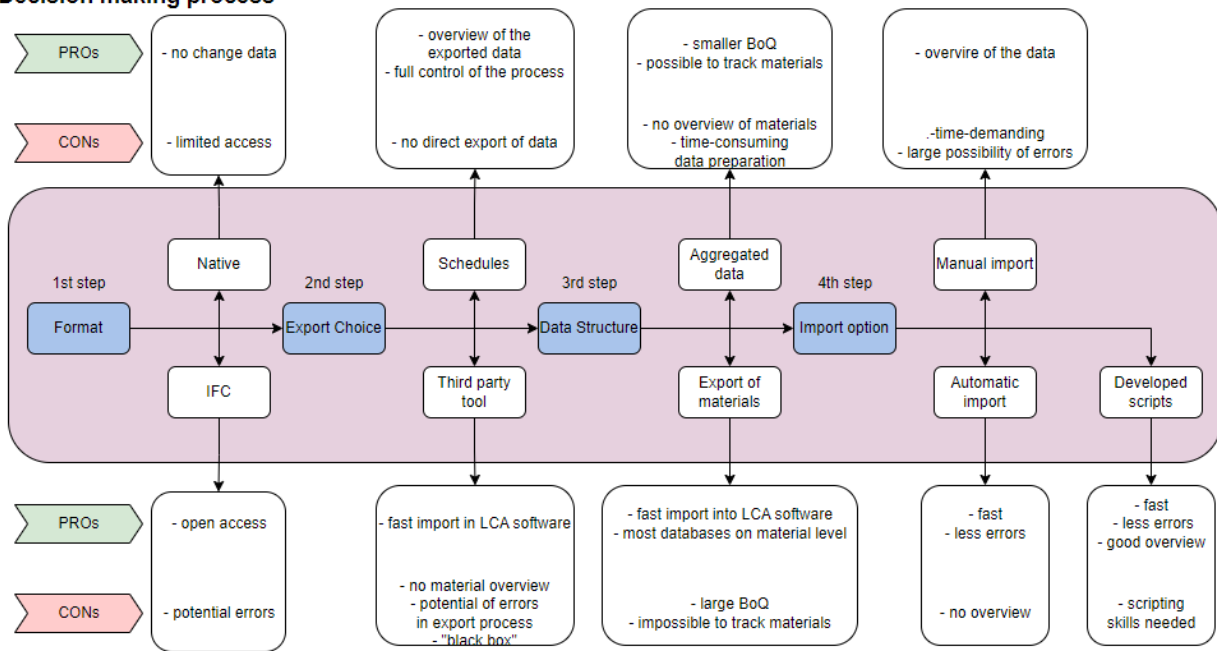


Figure 26: Austrian workflow in the LCA BIM exercise

Additional to the selection of the right process, it is especially important:

- the composed materials are handled with additional care (right materials and right amount of them is taken into the analysis),
- that we do not make any errors when we transforming the units,
- that similar materials are not combined,
- that we are careful to not make rounding errors, transpose the digits.

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