Interoperability of BIM-based Life Cycle Energy Analysis in Early Design Stages

Lothar Kolbeck [1], Kasimir Forth [1]

[1]Technische Universität München, Lehrstuhl für Computergestützte Modellierung und Simulation

Abstract

In the design process, life cycle energy analysis supports the planners with predictions on the building's operational and embodied energy demand. The earlier these predictions are accessible, the more they can influence outstanding design decisions. To encourage the early application, building information modeling (BIM) can structure the design process and eliminate time-consuming manual procedures. Therefore, robust and fast data exchange procedures between BIM-authoring tools and the software performing the life cycle energy analysis (LCEA) has to be established. These procedures are investigated in this paper.

In the first part, current integration approaches are analyzed. Inaccuracies commonly occur at the geometric conversion of the BIM-model to a surface model for multiple thermal zones. For a precise operational energy demand calculation, the boundaries of spaces have to be split to ensure homogeneous thermal properties of the face elements. The split faces are so-called second-level space boundaries. Existing approaches of second-level boundary generation are evaluated by means of a case study, in order to assess their suitability for the early design stages. As a result, none of the commercial or scientific methods is found applicable to our use case.

In the second part, a simplified procedure is applied as an alternative solution, simplifying preprocessing and data exchange. Based on empirical data, the simplified procedure approximates second-level space boundaries in post-processing. Through direct access to building element information, a quick and robust conversion of BIM-models in the early design stages is possible. A software prototype is developed and tested with the CAALA software, leveraging the frequent and didactic usage of LCEA in the early design stages.

Keywords: Life cycle analysis; BIM; BIM to BEM; energy analysis; Early design stages

1 Introduction

The building sector is responsible for a significant part of human environmental impact. It accounts for approximately 40 % of the world's primary energy demand and nearly one-third of global greenhouse gas emissions [1]. To downscale these measures, policy-makers introduced progressively stricter regulations on the operational energy demand of buildings. Due to the effected decrease in the operational energy demand of buildings, the other life phases come into focus as relevant contributors to the energy performance. Therefore, the standardized method of life cycle energy analysis (LCEA) considers operational as well as embodied energy demand. Applied during a design process, LCEA supports the practitioner with a prediction of a planning state's energy performance. The result should guide optimization through changes in geometry, materials, and mechanical equipment. These design changes require less effort and cost the earlier they are applied. Unfortunately, LCEA is commonly applied at late design stages because of the complexity and data demands of the software solutions available [2]. In order to incentivize the early and continuous use of the method, the LCEA method must operate in another context. This context differs in three aspects: First, the person responsible for the design is commonly not a specialized energy consultant, but rather an architect. Second, the data required for the calculations is not fixed, but variable. Third, the effort must not overdemand the user, but enable frequent and didactic usage. Accounting for these requirements, a method based on building information modeling (BIM) is developed, as BIM has the potential to enable an efficient and objective data transfer.

2 BIM-based Life Cycle Energy Analysis

2.1 Life Cycle Energy Analysis in the Early Design Phases

LCEA is a specification of Life Cycle Analysis (LCA). The International Standard defines LCA as “compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle” [3]. Depending on the goal of the analysis, it is necessary to set the scope of a LCA. In our research, the scope is the prediction of non-renewable primary energy demand (PEnR) over all life-cycle phases. The consideration of operational energy (OE) demand has been a common practice in the German building sector for decades. Therefore, the influence of the use phase decreases significantly [4], making it increasingly important to quantify embodied energy (EE) impacts. Given this holistic information, designers can do purposeful design changes to optimize the PEnR impact of a building. This iterative process should begin in the early design stages, when design changes imply little cost and effort for the planners. Unfortunately, in the early design stages information is uncertain. This requires the adaptability of analytical methods according to the uncertainty of available information. Ebertshäuser *et al.* [5] propose to stage the level of analysis from a consideration of building contours in the preplanning stage up to the assumption of fixed material volumes for execution planning. The “function systems” level corresponds to the beginning of the conceptual design stage. On this level of consideration, the geometry of building elements is assumed to be fixed, while the choice of construction is open. Varying the constructions, design variants can be generated and compared. Still, it would be possible to analyze the sensitivity of geometric changes when adapting and extracting the geometric data from a parametrically designed BIM-model. Section 2.2 discusses the integration of BIM and an LCEA according to the scope described.

2.2 BIM-based Life Cycle Energy Analysis

A BIM-model is a digital representation of a building with great depth of information. For LCEA, it is commonly used as an expressive and consistent data source to automate the exchange of three-dimensional geometry and thermal data. The basis of EE demand calculation in LCEA is a bill of material quantities. As material information is assumed to be uncertain and depending on variably assigned constructions, only the surface areas of the building elements are extracted from a BIM-model. A grouping of building elements according to possible constructions needs to be transferred as well, e.g. into interior and exterior walls. Based on these groups, a link to environmental data bases may be created. Forth *et al.* [6] recommended a workflow for this mapping procedure for BIM-based EE demand calculations, which is referred to for a detailed discussion. In our case, the retrieval of appropriate data for OE demand calculations required the greater attention. As shown by Figure 1, an OE demand calculation requires the conversion of a BIM model into a thermal model.

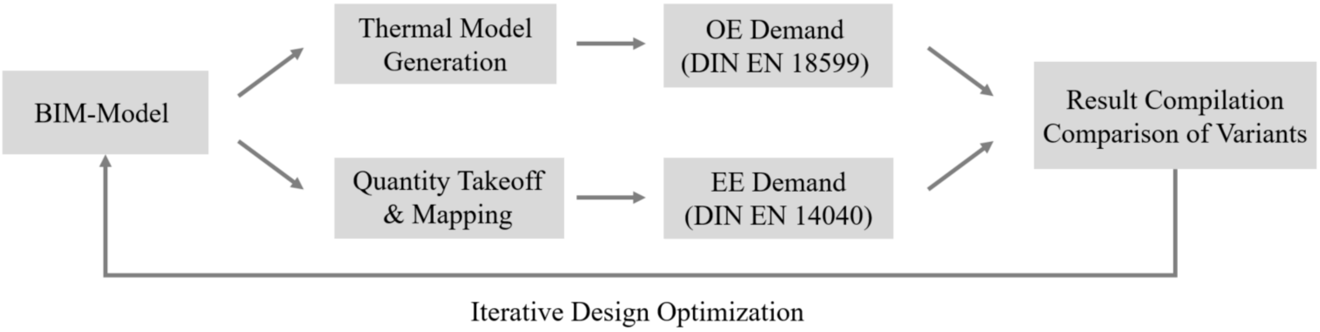

Figure 1: Computation Schema for BIM-Based LCEA in early design stages

The DIN EN 18599 standardizes analytical methods and reference data to calculate the primary energy demand caused by the operation of a building. According to the goal and scope of analytical methods, a variety of influences to PEnR may be considered. As a formal guideline, the German energy saving ordinance (EnEV) prescribes the application of the standard according to building type and construction task. Hence, an EnEV-conform heat demand calculation for newly planned buildings can serve as a well-understood reference when defining the interface between BIM-authoring- and LCEA software. Before applying the monthly or hourly steady-state methods referred to by the EnEV, various inputs need to be combined. In order to encourage the use of LCEA in the early design stages, it is common to reduce the information demand that a designer is asked to provide by means of a BIM-model. Therefore, climate data, usage characteristics or HVAC configurations are compiled in the LCEA software, chosen from reference tables in the DIN 18599. Equally, the variable assignment of constructions to elements happens in the LCEA software, ensuring consistency with the scope and the calculation of EE demand. On the contrary, input specific to the building geometry needs to be retrieved from a digital design model. Thereby, it is a question of debate at what level of granularity the thermal model needs to be described. A detailed thermal zoning increases the accuracy of thermal analysis, but is commonly not available in the early stages. Background and implications of this problem are described in the following section.

2.3 Thermal Model Generation

For heat demand calculations, a building needs to be divided into zones of nearly homogeneous thermal conditioning. The zones can be mapped to thermal data compiled in the DIN 18599-10, indicating e.g. mean temperatures and operating hours. Based on this thermal data, the PEnR of building operation can be derived as an integral of zone balances of energy entry and energy exit over time. This includes transmissive, radiative, or ventilative balances on an abstract level, with differing concrete influences according to building type and climate. In order to distinguish the thermal zones of a building, all spaces inside the conditioned thermal shell are assigned a functionality, e.g. to be a corridor or a living room. In BIM-authoring software, this is conducted by "filling" the clear spaces of the building inside the thermal shell with instances of specialized space classes. These are called "MEP-rooms" in Revit by Autodesk or simply "zones" in ArchiCAD by Graphisoft. At the heart of these spaces is a 3D-solid geometry that should be bordered by building elements. Additionally, semantic parameters specify the categorization according to DIN 18599-10. As soon as the entire clear space inside the thermal shell is divided into zones, a thermal model can be generated. Minimally, this contains threefold information, grouped per zone: First, the heated volume for ventilative considerations. Second, the net floor area, which is an important functional unit of LCA and a scale for heat demand calculations, e.g. to predict the warm water heat demand. Third, the boundaries of the spaces as planar and oriented surfaces, including a thermal classification of the corresponding building element and a reference to the adjacent thermal zones. These surfaces are the basis of transmissive and radiative heat flow considerations. Bazjanac [7] describes them as so-called 2nd level space boundaries (SB). 1st level SB are the faces of simple architectural spaces, 3rd to 5th level SB represent the faces of the narrow element sides. The latter are normally neglected due to the assumption of a one-dimensional heat flow through building elements. To generate 2nd level SB, the 1st level space boundaries need to be split according to thermal discontinuities. Obviously, a discontinuity is a change in construction, as in the case of a window that needs to be differentiated from the surrounding host wall. Less obviously, a 1st level space boundary needs to be split according to the adjacent thermal zones, see Figure 2.

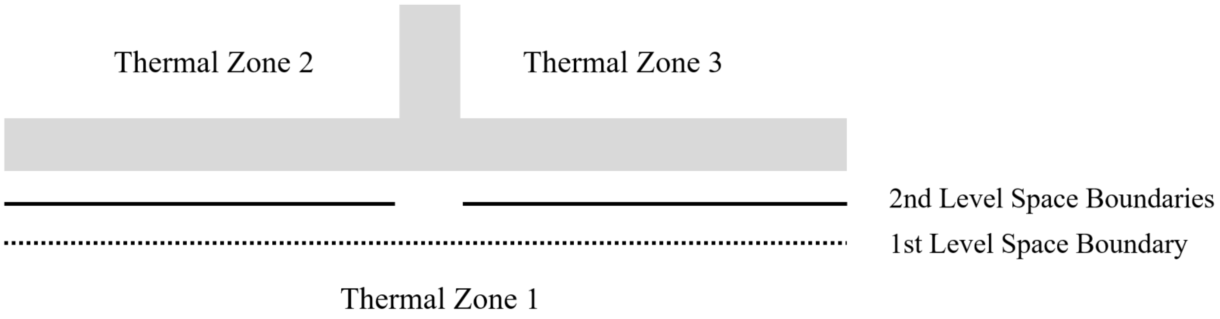

Figure 2: Example of 1st and 2nd level space boundaries [7] for a room with two distinct adjacent thermal zones

Despite the simplicity of the situation shown in the figure, it is easily imaginable that a general solution to the problem is a very complex task, requiring advanced data structures and algorithms. Adding to the complexity, BIM-models in the early design phases commonly contain geometric inaccuracies. Because of these reasons, the BIM-based thermal model generation is a field of ongoing research, with recent contributions attempting to remedy shortcomings in robustness and efficiency of documented algorithms [8, 9].

These shortcomings represent a hindrance to the frequent and didactic usage of LCEA in the early design stages. As an alternative solution, the EnEV describes an approximative procedure, applicable for most building type without cooling systems. Then, the division of zones is estimated empirically, based on the 2nd level space boundaries belonging to thermal shell only. This simplification makes it possible to directly access building element information instead of inserting spaces and processing their geometries, rendering the thermal model generation much simpler. Schlueter and Thesseling [10] as well as Hollberg [2] followed this approach. Lichtmeß [11] agrees that in an early design stage it is preferable to use approximate methods rather than providing no predictions at all. Yet, he recommends a gradual specification of zones throughout the design process, until no remnant needs to be distributed approximatively anymore. Thus, the accuracy of OE demand prediction increases with the decreasing vagueness in a proceeding design process.

Concluding the discussion, it is evident that the interface to OE demand calculations is crucial for the proper applicability of a BIM-based LCEA method in the early design stages. A description of a thermal model should be as precise as possible, but appropriate in effort and input demands. To assess how to ideally meet those requirements, we systematically analyzed current approaches of 2nd level space boundary generation in a case study.

3 Assessment of Thermal Model Generation Approaches

3.1 Case Study

In our analysis, we distinguished three fundamental approaches of BIM-based thermal model generation: First, the use of built-in functionalities of BIM-authoring software (1). Second, scientific contributions available as dedicated middleware (2), requiring an IFC input. Third, implementations of the simplified procedure according to the EnEV (3). The process steps necessary to perform a multi-zone thermal analysis for each of these three approaches are shown in Figure 3.

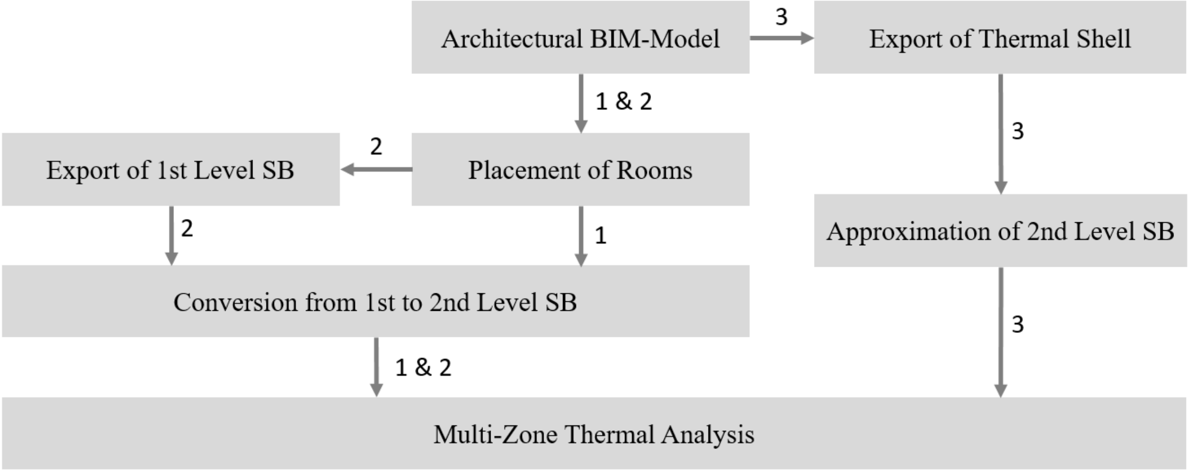

Figure 3: Procedural steps taken to perform a multi-zone thermal analysis distinguishing three possible approaches (1, 2 & 3)

In order to test and compare the suitability of each of the three approaches, we modeled a residential building with commonly expectable complexity in both Revit and ArchiCAD. The model contains a complex geometry as well as a variety of features that require a geometric conversion of 1st level space boundaries. Testing the built-in algorithms of authoring tools, we assigned nine thermal zones to the different rooms in the sample model. Thereby, attention was paid to the precise modeling of elements and the accurate alignment of spaces. The latter was ensured by using granular levels and offsets according to the documentations given. While placing the spaces, the possibilities of visual control were used. In ArchiCAD, this could be done by visualizing the spaces' solid geometries in 3D. In Revit, this is restricted to projected 2d-views. As a remedy to this limitation, Revit has an export wizard that allows a 3D visualization of the thermal zones. Having generated the thermal models in an IFC format, we validated the model with the common energy model test set of the Solibri Model Checker. Around 10 smaller and medium errors were reported in the first iteration of exports from both authoring software. After several iterations, the ArchiCAD export proved no disturbing errors anymore. On the contrary, the Revit-based export still missed a part of the floor below the roof. For the example of Revit, the workflow and the slightly erroneous results are shown in Figure 4:

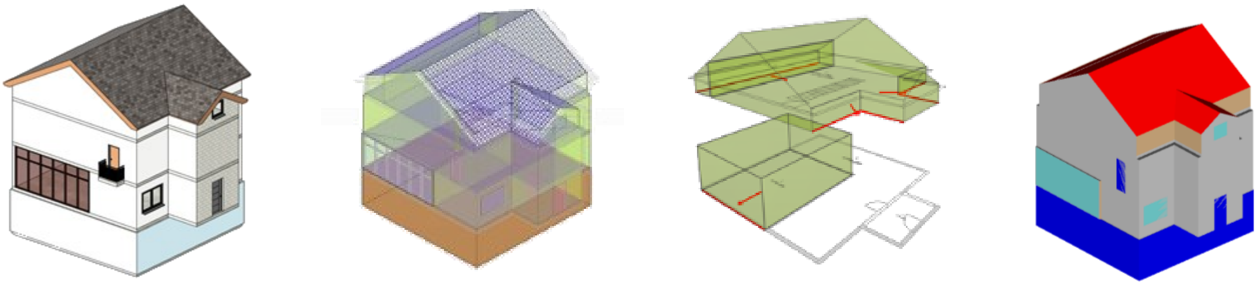

Figure 4: Part of case study showing the process steps for the thermal model generation based on Revit built-in algorithms

Both in ArchiCAD and Revit, it required two to three hours and several iterations of export and testing to obtain a satisfactory output. For an early design stage, this is likely to be discouraging for a designer in a real-world scenario. These shortcomings motivate the scientific solutions to thermal model generation. Unfortunately, only one of the mentioned algorithms is publicly accessed: The space boundary tool [12] is the exception, but did not produce any output for none of both thermal models exported. Errors indicated by the custom Solibri Model Checker test set could not be removed without modifying the model geometry and caused the space boundary tool to stop execution without an error message.

As a third alternative, we tested an implementation of the simplified procedure presented in 2.3. As such, we accessed the solution offered by the commercial software Passivhausplanungspaket (PHPP), based on a concept and algorithms described by Malhotra *et al.* [13]. Additional parameters need to be imported into the BIM-authoring software, used for manual classification of all elements. Skipping the possible specification of constructions and heat bridges, we prepared the export by specifying a thermal categorization of the elements only. In few minutes, the thermal model generated can be visualized and finalized with the support of an IFC-based import wizard. The categorization process and the resulting model are shown in Figure 5.

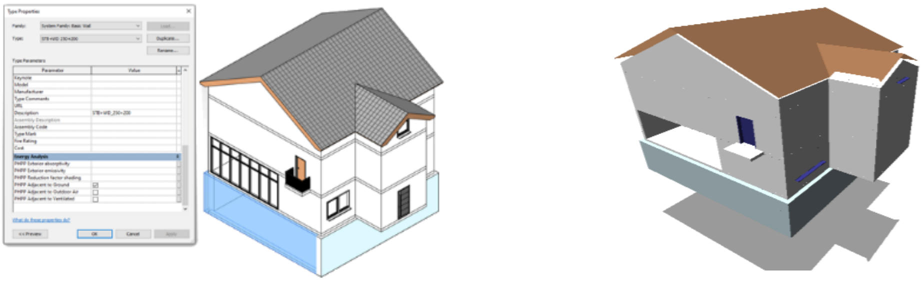

Figure 5: Preprocessing of building elements using imported parameters and IFC-based import wizard of PHPP

Considering the export in figure 5 (right), one can note two major flaws of the result: During parsing, the curtain wall was not detected and had to be added manually. Further, the successful recognition of two of the three windows could not be validated visually. Instead, manual confirmation of the imported data in the spreadsheet format proved these to work. This concluded the case study, while section 3.2 evaluates the suitability of the approaches for the use case.

3.2 Evaluation

The case study confirms that the appropriate generation of a thermal model is a demanding task. Thus, the integration of a thermal analysis method for LCEA in the early stages requires a well-justified choice. As a formalization, we compare the approaches according to three criteria: As a first criterion, the robustness of a solution to inaccurately placed rooms and varying model geometries. Second, closely related, the effort that an applicant of LCEA needs to invest for a qualified prediction. Third, we considered the vendor neutrality as a desirable feature of any BIM-application.

In the case of using built-in functionalities of authoring software, the case study showed that the results were very accurate after several iterations, for all complex geometric situations appearing in the sample model. Still, the effort of placing rooms and iteratively eliminating occurring errors proved to be high. Unfortunately, in the crucial step of 2nd level SB generation, a user relies heavily on authoring software. As a second alternative, scientific contributions may improve the robustness and efficiency of current solutions [8], but are mainly undisclosed and thus do not enable validation of their performance. The only one accessible [12] was very sensitive to unexpected input and could not give meaningful feedback to the user. However, the IFC interface is neutral to authoring software, as in the example of the third approach. The third approach proved to be quick, but showed deficits in the geometric transfer of certain element instances. As a remedy, the effort for the generation of a thermal analysis input was much less due to the omission of a manual zoning and the error-prone geometric conversion of 1st to 2nd level SB. Table 1 gives a summary of this discussion:

Table 1: Evaluation according to three criteria relevant to LCEA in the early design stages ("+": positive, "o": neutral, "-": negative)

Approach	Robustness	Effort for User	Vendor Neutrality
Generation of 2nd level SB using BIM authoring software	O	O	-
Generation of 2nd Level SB in dedicated middleware	-	-	+
Generation of Thermal Model with the simplified procedure	O	+	o

We concluded that only the simplified method can be an appropriate point of departure to integrate LCEA in the crucial early phases of design. Enabling OE and EE demand predictions in a quick and robust way, we propose an enhanced BIM-based exchange procedure for LCEA in the early design stages. As essential steps, a preprocessing of the BIM-model and the automated quantity takeoff are discussed.

4 Enhanced Data Exchange Procedure

4.1 Preprocessing of the architectural BIM-Model

The thermal shell of a building needs to be identified as a basis for the simplified method of a single zone model. Normally, this information is retrieved through the placed rooms. Because the placement of spaces is time-intensive and prone to inaccuracies, we avoid taking this step. Yet without spaces placed in the model, the recognition of the elements constituting the shell is not trivial. Particular situations like the one of a porch or a semi-heated storey pose difficulties when attempting to automate this step. As a reliable alternative, we propose the manual categorization according to parameters imported into the BIM-authoring software.

Following the categorization of the EnEV and the element classification for EE according to [2], we import 26 parameters. Half of these parameters represent categorizations for thermally relevant elements, half for EE-only relevant elements. Divided according to element types, the user must choose a classification among few options. To ensure a consistent and quick preprocessing, view filters color the building elements according to the classification. All EE-only relevant elements are indicated with the same color such that the thermal shell of the building can be easily distinguished. The preprocessing step and the visual feedback through the view filters are shown in the left part of figure 7. As data that is not related to elements, the net area is indirectly derived from the thermally relevant floors. The gross heated volume is approximated subsequently by asking the user for a medium storey height. Given the successful preprocessing, the quantity takeoff described in section 4.2 can take place.

4.2 Quantity Takeoff

We implemented the quantity takeoff for the energy analysis with the .NET API of Revit. Figure 6 shows the class structure implemented to conduct the quantity takeoff, including a transfer of geometric information for validation purposes.

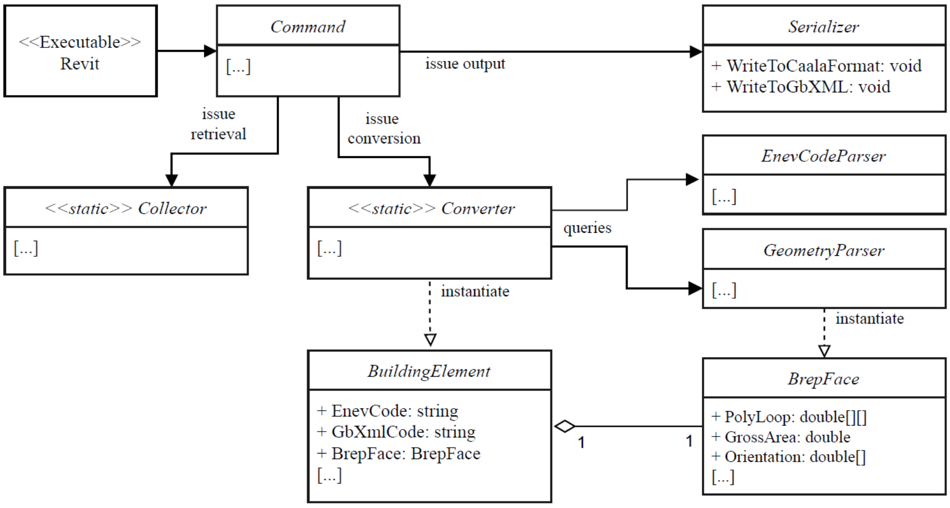

Figure 6: UML class diagram of conversion plugin

The *Command* object orchestrates the retrieval of the objects from a Revit document, distinguishing walls, windows, doors, openings, floors, and roofs. Passing these in collections to the *Converter*-class, the categorization according to EnEV and gbXML is parsed for every element as well as a planar *BrepFace*. The parsing of geometry is simple for walls, floors, and roofs, assuming a correctly modeled orientation. For windows, doors, and curtain walls this is more demanding, as the Brep solid geometry accessible via the API consists out of many granular facets per orientation. As a remedy, we work with bounding boxes, leading to a slight offset of the vertices stored. This geometric and thermal data is serialized from the object-oriented structure to two formats: First, to gbXML as an open and established standard. Second, to the format readable by the software for computer-aided architectural life cycle analysis (CAALA) [2]. The integration with CAALA gives the possibility to validate the workflow and to show the benefits for LCEA in the early design stages.

4.3 Validation

The desired functionality of the workflow is to enable robust and efficient data exchange between BIM authoring and LCEA software. As a functional validation, the sample building from the case study was chosen. It could be preprocessed in few minutes, with clear visual feedback due to the view filters in place. The geometric accuracy of the export was validated with the gbXML-viewer, shown in Figure 7. Two mainly esthetical flaws of the quantity takeoff can be noticed: First, the holes between the axis-oriented building elements. Second, the offset of some geometries retrieved using a bounding box, e.g. the curtain wall face. However, both types of flaws do not affect the correctness of thermal analysis. For esthetic reasons, the surfaces could be translated in the middle axles of the corresponding elements and "stitched" together in a post-processing step.

Figure 7: Preprocessing of building elements using imported parameters and view filters (l.) and visual validation using gbXML (r.)

As an end-to-end test, we let an architect design an architectural BIM-model and perform an LCEA. Without prior knowledge of thermal analysis and LCA, the explanation of the workflow and the preprocessing logic took up 20 minutes. Given this, the architect started to model and categorize a minimalist building with four walls, foundation slab, roof, doors, and windows. Materials and HVAC configuration were assigned in CAALA. A few minutes later, the first LCEA of the sample models could be retrieved. The architect elaborated the sensitivities of design choices by iteratively returning to the authoring software and generating variants of the sample building. For the default material- and HVAC settings in CAALA, the architect found the orientation and the length-width ratio of the building to be relatively negligible. Only for a very efficient HVAC configuration, the optimization of building geometry and the materials started to be sensitive to the life cycle energy of the building. The architect concluded that the workflow supports an educative use of LCEA because it teaches which decisions matter.

5 Conclusion

In the design process, design choices should be influenced by their effects on the operational and the embodied energy demand of a building. Because modifications can be applied in an early design stage with less effort and consequences, we investigated data exchange procedures to encourage a frequent and didactic usage of LCEA. While the data exchange for embodied energy demand calculations is straightforward, the generation of a thermal model from a BIM-model is a complex and error-prone step.

As a means to analyze a suitable data exchange for thermal analysis, we conducted a case study comparing three different approaches. As a first approach, the built-in algorithms of authoring software were tested. As a second approach, we documented scientific solutions available as dedicated middleware. Finally, a simplified procedure with lowered geometric demands was tested. The evaluation of the case study showed that the third approach is the suitable start point for the continuous use of LCEA throughout the entire design process.

Thus, we developed a software prototype based on the simplified procedure. For a robust data transfer with low modeling effort, we introduced a preprocessing phase with imported parameters and visual feedback. The quantity takeoff was implemented using the API of Revit and serializing the extracted data to gbXML, and a proprietary format for the software CAALA. A sample export to gbXML served as functional validation of the prototype, the software CAALA for end-to-end testing with an architect. The test with the architect confirmed that the prototype enables a quick comparison of design variants and the evaluation of design choices according to their sensitivity.

6 References

[1] M. Hegger, M. Fuchs, T. Stark, and M. Zeumer, *Energie Atlas: nachhaltige Architektur*. München/Basel, Berlin, Boston: Birkhäuser, 2007. Accessed: Oct. 10 2020.

[2] A. Hollberg, "A parametric method for building design optimization based on Life Cycle Assessment," Bauhaus-Universität Weimar, 2016.

[3] *DIN EN ISO 14040: Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006); German and English version EN ISO 14040:2006*, Deutsches Institut für Normung, Jun. 2006.

[4] T. Schöndube, *Primärenergiebedarf resultierend aus Herstellungs-, Nutzungs- und Instand-haltungsphase von Gebäuden in Abhängigkeit vom energetischen Gebäudestandard.* [Online]. Available: https://www.bow-ingenieure.de/wp-content/uploads/2020/04/2019_Bauphysiktage_Weiterentwicklung-EnEV.pdf (accessed: Sep. 2 2020).

[5] S. Ebertshäuser, K. Graf, P. von Both, K. Rexroth, R. Di Bari, and R. Horn, "Sustainable building information modeling in the context of model-based integral planning," *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 323, p. 12113, 2019, doi: 10.1088/1755-1315/323/1/012113.

[6] K. Forth, A. Braun, and A. Borrmann, “BIM-integrated LCA - model analysis and implementation for practice,” in *Sustainable Built Environment D-A-CH Conference 2019*, 2019.

[7] V. Bazjanac, “Space Boundary Requirements for modeling of building geometry for energy and other performance simulation,” 2010. [Online]. Available: https://www.academia.edu/32704514/Space_Boundary_Requirements_for_Modeling_of_Building_Geometry_for_Energy_and_Other_Performance_Simulation

[8] H. Ying and S. Lee, “Generating second-level space boundaries from large-scale IFC-compliant building information models using multiple geometry representations,” *Automation in Construction*, vol. 126, p. 103659, 2021, doi: 10.1016/j.autcon.2021.103659.

[9] G. Lilis, “Space Boundary Topology Simplification for Building Energy Performance Simulation Speedup,” 2020. [Online]. Available: http://www.ibpsa.org/proceedings/BS2019/BS2019_210693.pdf

[10] A. Schlueter and F. Thesseling, “Building information model based energy/exergy performance assessment in early design stages,” *Automation in Construction*, vol. 18, no. 2, pp. 153–163, 2009, doi: 10.1016/j.autcon.2008.07.003.

[11] M. Lichtmeß, “Vereinfachungen für die energetische Bewertung von Gebäuden,” D - Architektur, Bergische Universität Wuppertal, Wuppertal, 2010. [Online]. Available: http://elpub.bib.uni-wuppertal.de/servlets/DerivateServlet/Derivate-1797/dd1004.pdf

[12] C. M. Rose and V. Bazjanac, “An algorithm to generate space boundaries for building energy simulation,” *Engineering with Computers*, vol. 31, no. 2, pp. 271–280, 2015, doi: 10.1007/s00366-013-0347-5.

[13] A. Malhotra, J. Frisch, and C. A. van Treeck, “Technical Report: Literature Review concerning IFC, gbXML and CityGML data models for Energy Performance Simulation; 1st,” 2019.