From Physical to Analytical Models: Automated Geometry Interpretations

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Abstract. Building information modelling promises model-based collaboration between stakeholders in the project design stage. However, physical and analytical building models used for architectural design and structural analysis respectively can rarely be interchanged between the stakeholders due to numerous differences in building element representation, especially the representation of geometry. This papers aims to overcome the geometry representation differences by proposing geometry interpretation methods. The interpretation methods, such as linearization, planarization, reconnecting elements and perimeter adjustment, were defined for a use-case building model and implemented using a novel open data exchange framework. The methods facilitate automated conversion between physical and analytical models and provide a base for lacking standardization of interpretations. This work fills the gaps in the existing model-based communication that could eventually help with facilitating a seamless data exchange between physical and analytical models.

1. Introduction

Construction industry, as one of the least digitized, aims to increase productivity by implementing building information modeling (BIM) and achieving digital collaboration (Agarwal et al. 2016). An obstacle still present in achieving a seamless data exchange for digital collaboration is the lack of software interoperability (Grilo and Jardim-Goncalves 2010). They state that the interoperability concept needs to be expanded beyond the information systems towards business processes, employees and culture, and management of external relationships. In our previous research we identified the need to focus on domain-specific data models instead of integrated building models, and interpretations between them as business processes for improving software interoperability and eventually automating the data exchange (Sibenik and Kovacic 2019).

The level of achievement of a seamless data exchange varies between professional domains. Numerous software tools belonging to different professional domains have also differing internal structures, which hinders the full interoperability across the software tools. However, the stakeholders belonging to various domains still aim to exchange the information of interest. One of the greatest challenges is a transfer of a building model between architectural design and structural analysis (Kepplin et al. 2017). The experts exchanging information of interest need to have mutual understanding of each other's domains in order to facilitate the communication (Luyten 2015). We find the collaboration during the developed design (*Einreichsplan* in Austria) stage particularly interesting since both the architectural design plans and structural analysis calculations are required for the building permit (Kovacic et al. 2015). Software tools in both domains allow for the use of building models, however, the model-based data exchange is still burdened with problems (Sibenik 2016).

As in Eastman et al (2018), models used for architectural design are referred to as physical (or architectural (Qin et al. 2011), or BIM models (Ramaji and Memari 2018)), while the structural analysis models are analytical (or structural (Qin et al. 2011)). Representations of building elements have significant differences, especially regarding the geometry representation. While physical models aim to render the elements similarly to their real-world 3d shape, analytical models tend to simplify the geometries and reduce dimensionality of building elements to points, lines and surfaces. We identified the need to further explore these complex geometry interpretations in order to improve the interoperability itself. The interpretations (or transformations (Ramaji and Memari 2018)) have been performed mostly intuitively based on the experience of structural engineers (Kepplin et al. 2017). Therefore, the existing intuitive interpretations represent the process of defining analytical models based on information available in physical models mainly based on the experience of structural engineers.

Several research papers considered model interpretations between physical and analytical models, however not focusing on the geometry interpretation rules. A paper which most thoroughly documents the geometry interpretations is Ramaji and Memari (2018), giving a list of required interpretations for a transformation of an industry foundation classes (IFC) physical model to an IFC analytical model. Their paper emphasizes the importance of interpretations, however it is limited to swept-solid geometry defined with IFC standard (naming physical and analytical representations as swept-solid and topological respectively). In order to further edit the interpretation rules for IFC geometry definitions and contribute to the framework, expert IFC knowledge is required. Authors such as Hu et al. (2016), Qin et al. (2011) or Liu et al. (2010) focus on developing new data exchange frameworks between architectural design and structural analysis. Although geometry interpretations are an unavoidable part of each framework, they are not described in detail, serve the examined case studies, but cannot be validated for the general use or other business processes. The existing intuitive interpretation practices are not documented, nor related to the proposed interpretation methods. The interpretations serve for an "end-to-end" model transformation automation without allowing a detailed insight for end users.

Structural engineers cannot rely on completely automated processes, which are not transparent or comprehensible ("black-box scenario") (Holzer et al. 2007); as they carry the responsibility for the calculation and need to have a completely reliable model as a starting point. Therefore, a framework in our work uses open interpretation rules, which could be tailored for additional workflows and practices. Due to the lack of documented cooperative knowledge of structural engineers and architects, in this paper we will try to map some common rules for establishing an analytical model from a physical model. The research question we aim to answer is: *how to automate existing intuitive interpretations of physical to analytical building model?*

The following Section 2 will present the methodology and explain how the interpretations were defined. Section 3 describes single interpretation methods including linearization, planarization, reconnecting elements and perimeter adjustment. The methods and resulting structural model are discussed in Section 4, and the conclusion belongs to Section 5.

2. Methodology

In our previous work (Sibenik and Kovacic 2019) a novel framework and the corresponding system architecture were developed that incorporate interpretation rules in an open data exchange. The framework consists of three procedures: i) classification, ii) interpretation and iii) automation. In the first procedure, classification, the terminology and domain-specific requirements are defined. Interpretation procedure defines the relations between domain-specific classification systems, predefined terminology and definitions. Finally, the automation procedure implies automatic communication between the domain-specific models on the central database with the proprietary software tools and the belonging proprietary models.

Interpretation procedure consists of several procedural steps such as: validation, filtering, non-geometrical interpretation, geometrical interpretation and enrichment and reasoning. For the exchange between architectural design and structural analysis models the geometrical interpretation is the most challenging procedural step. Possibilities to model analytical geometry are usually numerous and not standardized, and therefore the resulting model depends on the structural engineer's experience. However, numerous similarities between different approaches exist and documenting the existing intuitive interpretations could lead to standardization. Due to the lack of documented practices, in this paper we make a new proposal to interpret geometries based on the use-case building. Additionally, the newly defined interpretations are implemented within the previously described framework.

For the use-case building model, a model of Villa Savoye was chosen. It represents the modernist work of architecture, where concrete columns define the main support system with concrete slabs. Additionally, basement walls and staircase walls on the roof terrace were considered as part of the structural system. The use case building was modelled with Autodesk Revit 2019 and exported to IFC 2x3. The IFC building model is converted to the JSON format with a self-made converter *IFCtoJSON* (Sibenik and Petrinas 2020) in order to store it in the semi-structured database MongoDB.

Further on, a geometry kernel is used to define and edit geometry. Geometry kernels such as 3d ACIS Modeler (ACIS) were already used to overcome the differences between architectural design and structural analysis (Mora et al. 2006, Romberg et al. 2004) and to manage complex geometric interpretation. Xu et al. (2019) use an additional geometry kernel to generate meshes for finite element modeling, focusing on the boundary-representation (BRep) models. This research focuses on the early design stage, and therefore does not use the full potential of architectural BIM models in the developed design stage, where building elements are already defined. Also, in the aforementioned research, the resulting models are not analytical models with reduced dimensionality extracted from the existing architectural models, which is a standard workflow in the developed design stage.

Workflow implemented in this research is depicted in Figure 1. After exporting the IFC model from Revit, the IFC model is converted to JSON format, filtered and the geometry definitions are adapted to Open Cascade geometry classes. There are numerous geometry kernels for handling of geometry on the market, however we chose Open Cascade as a free open source geometry kernel. We created the methods by focusing on the IFC geometry definitions found in the IFC model (swept solid, mapped representation, clipping and BRep) and converting them to Open Cascade classes. All these steps (red dashed box in Figure 1) could be replaced with the direct export from Revit to the desired format, however the IFC approach was chosen in order to be more flexible and allow the use of multiple proprietary software tools.

The geometrical interpretation steps take place with the Open Cascade geometry definitions with the help of available Open Cascade methods. We created redDim (*red*uce *Dim*ensionality) program that contains all the methods implemented for the use-case building. Besides the geometry information, redDim uses information about the element type, load-bearing property, element id and material name for further import to structural analysis software tool. The interpretations depend on building element type and Open Cascade geometry, which will be tested for extensibility in our future work. The resulting geometries are also defined with the Open Cascade kernel. Methods are developed in such a way to overcome the differences between physical and analytical representations of all structural elements of the use case building, and a model as a whole, resulting in a useable structural analysis model. The resulting model is an open structural analysis model, and in the further steps it can be imported by mapping the information to the structural analysis software tool. In that way, the geometry interpretations are not anymore part of the problematic software import (Sibenik 2016).

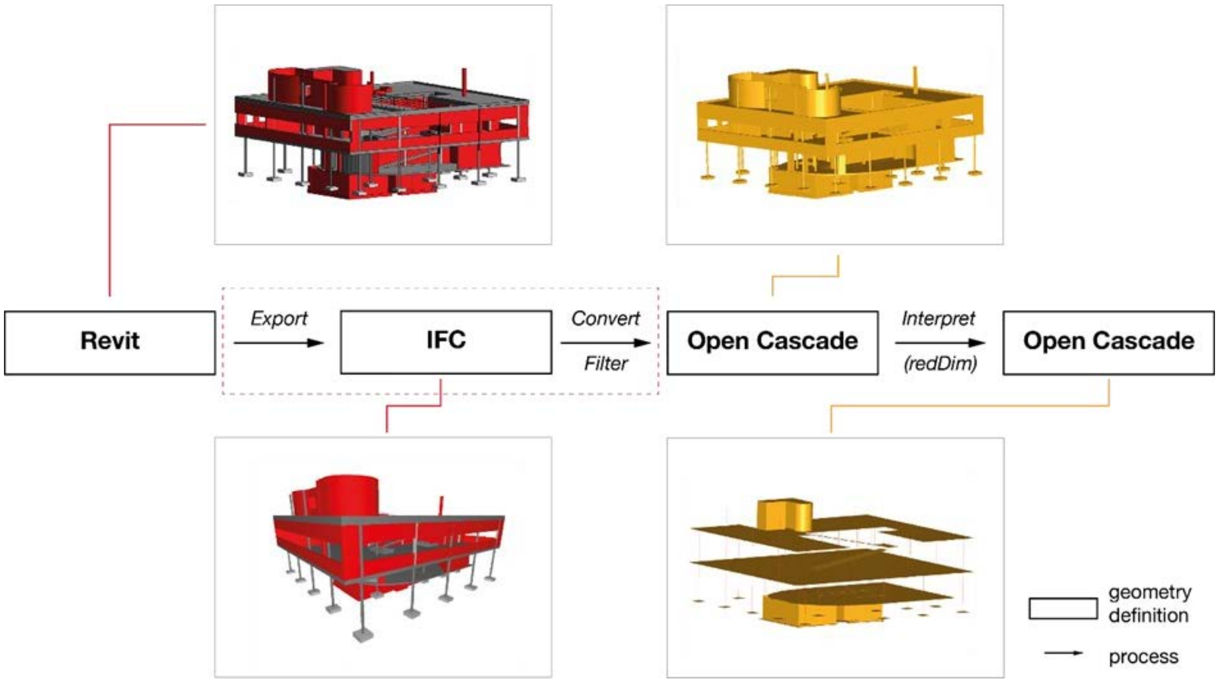

Figure 1: Workflow for the data exchange between native and central physical and analytical building models including geometry definitions and processes

3. Interpretation Methods

The geometry interpretation methods for the data exchange from physical into analytical model, developed and applied within the framework include linearization, planarization, reconnecting elements and perimeter adjustment. The methods are based on the thorough literature review (Ramaji and Memari 2018, Liu et al. 2010), and they were chosen in order to support specific geometries present in the use case building model, such as columns with round and rectangular cross section, straight and curved one-layered walls with uniform thickness, horizontal and tilted uniform-thickness slabs and single foundations.

3.1 Linearization

Linear elements in the use case building model were only columns with round and square cross-sections. The columns are represented as Open Cascade topological shapes: cylinders and boxes. For both topologies a single algorithm was used to convert the shape to edge, consisting of several methods (Figure 2): i) top and bottom faces are identified by analyzing and comparing all the faces constituting the shape; two parallel faces with smallest area could also be identified for linear elements, e.g. in the case of non-vertical linear elements (such as beams); ii) vertices defining the centers of mass of the faces is found; iii) edge is created between the vertices representing the linear element.

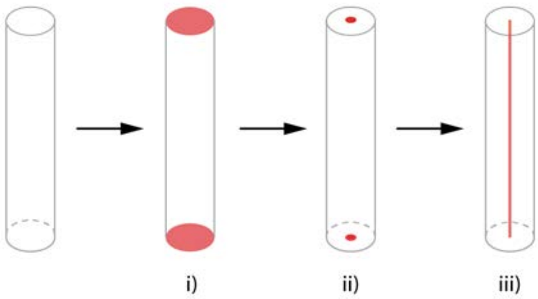

Figure 2: Linearization of building elements

3.2 Planarization

Planar elements of the use case building were walls and slabs (including flat roof), both represented as topological shapes of Open Cascade, some containing openings. As a starting point, a complex topological shape is created consisting of the wall or slab shape and the corresponding openings. The planarization method involved (Figure 3): i) locating the largest face of the shape; ii) finding the element thickness by analyzing distances from the central face vertex to its projection on the neighboring surfaces; iii) offsetting the largest face for half of the thickness to the inner part of the topological element. In that way a planar element axis is created and represented as Open Cascade face.

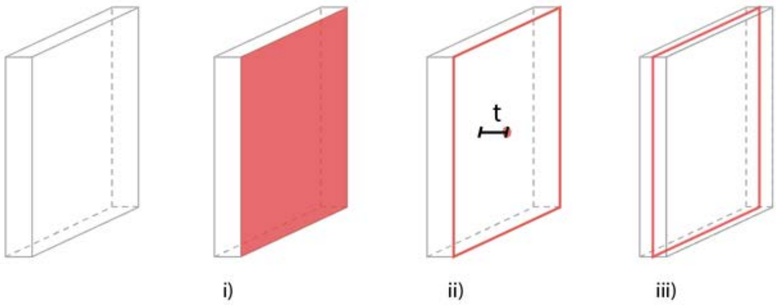

Figure 3: Planarization of building elements

3.3 Reconnecting Elements

Physical and analytical representations of elements are interrelated. Connected physical building elements need to be investigated for the neighboring elements. Based on the results, the analytical elements need to be reconnected. In order to make this, several methods were developed (Figure 4): i) finding neighboring elements in the physical model by checking the minimum distance between elements, and also considering the element type (e.g. columns cannot be reconnected to other columns or walls, but can to slabs) and inclination (tilted slabs); ii) addressing each element in their structural representation and their neighbors, also in the structural representation; further on, depending on whether an element is linear or planar: iii)a) linear elements or edges in Open Cascade are extended until the intersection point with the neighboring planar element; iii)b) the planar elements are extended or trimmed based on the geometry: rectangular geometries are recreated in such a way that the closest edges are projected, adjacent edges extended and the remaining edges unchanged. Vertical planar elements are connected both to horizontal and vertical neighboring planar elements.

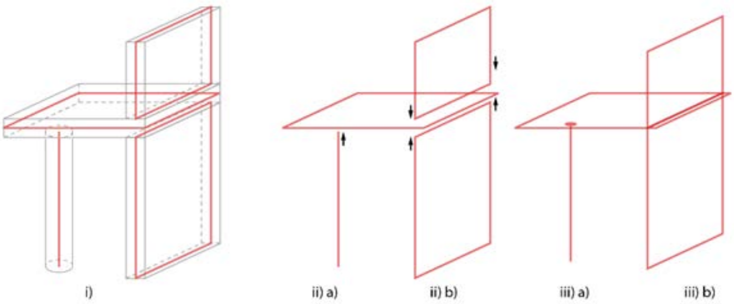

Figure 4: Reconnecting elements in structural representation

3.4 Perimeter Adjustment

Similar as in the previous method, the information about the neighboring building elements is used in order to adjust the perimeter of horizontal planar elements. In the use-case model, the edges of horizontal planar elements were adjusted to the vertical building elements supporting them. Firstly, the list of neighboring building elements is filtered and the elements near the perimeter edges are identified. Additionally, linear vertical elements are connected to two closest vertical load-bearing elements in the same neighbor list and in such way *load-bearing fronts* are created. These *fronts* were used to check if the slab edge should be adjusted to the underlying columns. As an overview, for perimeter adjustment the following method sequence was developed (Figure 5): i) underlying vertical elements close to the perimeter in the analytical model are found; ii) "load-bearing fronts" are created from the vertical linear elements; iii) projections of planar vertical elements and "fronts" are found on the horizontal planar element; iv) the intersection distance to the edge of the slab are checked, those further than tolerance eliminated; parallelism of the edges to the projections is checked; iv) face is extended or trimmed to the edges which fulfill the conditions from iii).

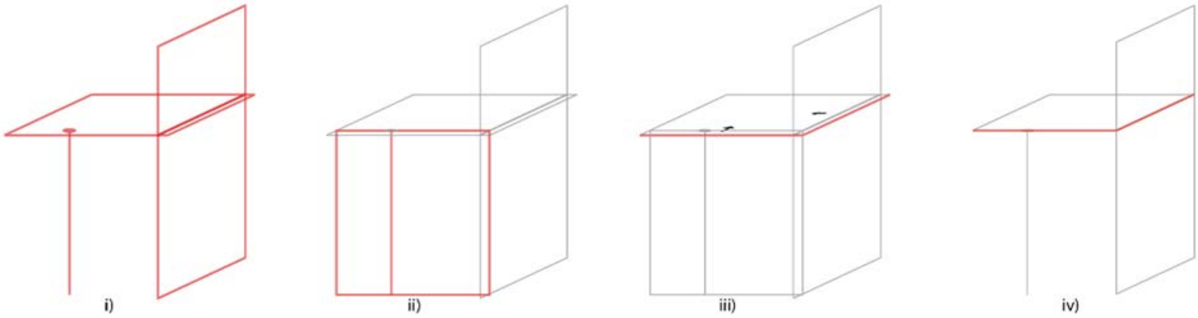

Figure 5: Perimeter adjustment of horizontal structural elements

4. Discussion

The research question "how to automate intuitive processes of interpreting physical to analytical building model?" is answered by proposing four interpretation methods based on the geometrical elements from the use-case building. The four methods cover some common building elements and relatively simple but commonly present geometries such as columns with constant cross-sections and walls and slabs with constant thickness through the use-case model. The interpretations take place during the definition of an analytical model from the physical model. They are not standardized nor documented for the existing workflows, which causes many inconsistencies and problems for the data exchange practices between architectural design and structural analysis domains. The interpretation methods are implemented with a novel framework, described in our previous work (Sibenik and Kovacic 2019).

The main advantage of the novel framework is that it moves the procedural steps for interpretation from single software tools (either architectural design or structural analysis) to the central database. Interpretation methods are facilitated with the open source geometry kernel on the central database. Therefore, the end users (or coordination/BIM managers) have the insight to the methods taking place, understand the model behavior and can adjust it to their workflows if needed. This is in the current practices mostly impossible since the import or export procedures work as "black-boxes" defined in the proprietary software tools.

The innovative aspects of this research lies primarily within documenting of the intuitive interpretations rules in such a way that they could be automated with other software tools or geometry kernels. Secondly, the innovation is the implementation of the interpretations in previously defined open exchange framework.

All building elements in the use-case building have been successfully interpreted, through application of above described methods of linearization, planarization, reconnecting elements and perimeter adjustment. Some interpretations were more elaborate to automate than the others, partly because of the complexity of the traditional intuitive process and partly because of the technical reasons such as geometry kernel suitability and predefined methods. The level of difficulty depended on several factors: a) difficulty to translate IFC to Open Cascade geometry; b) understanding the traditional intuitive process; c) difficulty in translating the traditional intuitive process to a method. Current focus of research was on the usability of technology, in the future research the impact of different factors will be investigated and evaluated more closely.

One of the current limitations of this approach is the lack of options for interpretations on single building elements. The use case is completely automated, which could pose a problem for other practices and building models. Structural engineers need more control over the interoperation process. The methods defined in this research are limited to the use-case model. For wider practical implementation it is necessary to extend them with additional ones and to cover more geometries. The interpretations are based on the IFC building models that depend on the export performance of native software tools and their IFC interface, which are different from the building models in the native software. Therefore, this step could be replaced with the direct connection of the software tool to the central database.

Next steps will include the optimization of the framework together with application of the interpretation steps in order to get the direct open exchange model from Revit. The framework, after being enhanced with additional methods, will be tested on the models from design offices. In that way the scalability of the current approach will be tested. The usefulness and usability of the novel software can be tested only after a user-friendly interface is provided, which is also one of the future steps, where the engineers can tackle a single element and better control the interpretations. Additionally, an exchange in the other direction will be tested, from analytical to physical model.

5. Conclusion

This paper aims to cover a knowledge gap in describing and documenting the intuitive procedural step of geometrical interpretations taking place between physical and analytical models. This knowledge is found to be a requirement in overcoming the discrepancies between architectural design and structural analysis building models and achieving a successful data exchange.

Methods described in the paper are linearization, planarization, reconnecting elements and perimeter adjustment. Although the described geometrical interpretations represent only a small part of numerous possibilities and undocumented knowledge taking place during the information exchange between physical and analytical models, the geometries present in the use case, namely vertical columns with constant cross section, and walls and slabs with constant thickness, can often be found in building models. Hence it is possible to predefine the majority of geometrical interoperations in such a way. Implementing the interpretations in this or other framework might significantly simplify the data exchange process, the most common and repetitive tasks could be automated, leaving a small portion of building elements, geometries and interpretations to structural engineers to manually deal with.

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