Primljen / Received: 5.5.2021.
Ispravljen / Corrected: 25.11.2021.
Prihvaćen / Accepted: 5.12.2021.
Dostupno online / Available online: 10.4.2022.

Automated preprocessing of building models for structural analysis

Authors:

[1]**Goran Šibenik**, M.Sc. CE
goran.sibenik@tuwien.ac.at
Corresponding author

[1]Prof. **Iva Kovačić**, PhD. CE
iva.kovacic@tuwien.ac.at

[1]**Valentinas Petrinas**, B.Sc.
valentinas.petrinas@tuwien.ac.at

[2]**Wendelin Sprenger**, PhD. CE
wendelin.sprenger@zueblin.de

[2]**Dario Bubalo**, MCE
dbubalo1987@gmail.com

[3]**Nikola Ruzičić**, MCE
nikola.ruzicic@atp.ag

[1] Institute of Interdisciplinary Building Process Management, Technische Universität Wien, Austria
[2] Ed. Züblin AG, Stuttgart, Germany
[3] ATP architekten ingenieure, Vienna, Austria

Subject review

Goran Šibenik, Iva Kovačić, Valentinas Petrinas, Wendelin Sprenger, Dario Bubalo, Nikola Ruzičić

Automated preprocessing of building models for structural analysis

BIM workflows still involve time-consuming manual model preprocessing for structural analysis such as assigning new data like structural material properties or loads, which prevents prompt feedback and is error prone. The main objective of this research is to automate the preprocessing of analytical building models so as to accelerate and improve structural analysis. The research is based on literature review and a real use case analysis, followed by formalization of preprocessing methods, their verification via two pilot building models, and evaluation by practitioners through panel discussion. The developed procedures can automatically assign loads, supports and joints floor-wise and reduce the model preparation time, errors and design costs in daily structural analysis practice; however, further adoption and consideration of existing practices is needed to increase the usefulness and usability of the proposed methods.

Key words:

structural analysis, automation, building information modelling, BIM, preprocessing

Pregledni rad

Goran Šibenik, Iva Kovačić, Valentinas Petrinas, Wendelin Sprenger, Dario Bubalo, Nikola Ruzičić

Automatizirana predobrada modela građevine za proračun konstrukcija

Tijek rada prilikom korištenja BIM-a i dalje zahtijeva dugotrajnu ručnu predobradu (preliminarnu analizu) modela za proračun konstrukcija, kao što je dodjeljivanje novih podataka poput svojstava građevnog materijala ili opterećenja, što sprječava slanje brzih povratnih informacija i podložno je pogreškama. Glavni cilj ovog istraživanja jest automatizacija predobrade analitičkih modela građevina radi ubrzanja i poboljšanja proračuna konstrukcija. Istraživanje se temelji na pregledu literature i analizi slučaja, uz formalizaciju metoda preliminarne analize, njihovu verifikaciju kroz dva pilot modela građevina i evaluaciju u panel-raspravi stručnjaka u praksi. Izrađene procedure mogu se automatski dodijeliti opterećenja, oslonce i spojeve za podne konstrukcijske elemente i smanjiti vrijeme pripreme modela, pogreške i troškove projektiranja u svakodnevnoj praksi proračuna konstrukcija. Međutim, potrebna je šira primjena postojeće prakse kako bi se povećala korisnost i primjenjivost predloženih metoda.

Ključne riječi:

proračun konstrukcija, automatizacija, informacijsko modeliranje gradnje, BIM, predobrada

1. Introduction

Building information modelling (BIM) workflows are becoming a wide-spread practice in the design of buildings. However, the studies related to the domain of structural analysis and optimization lag behind other AEC domains [1], and numerous challenges in the BIM-based collaboration with this domain still exist [2]. BIM is defined as the "use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions" [3]. Therefore, in structural analysis, BIM addresses the use of shared digital representation of a built asset to facilitate structural analysis in order to form a reliable basis for decisions. Even though this definition integrates building models and processes, the scope of shared information and affected processes remains unclear. BIM potentials have not as yet been realised in their full scope due to multiple reasons, such as the resistance of stakeholders, lack of know-how, and the need for adaptation of the already existing workflows [4]. These challenges are also encountered in the scope of structural modelling and analysis within BIM environments, resulting in building models that are often not shared between the stakeholders and the processes that are characterized by manual (re)work in the realisation of daily structural analysis tasks. The content of analytical BIM models and related processes remains vague, as the international BIM standards (e.g. [5, 6]), or national ones [7], provide general frameworks and lack detailed specification of digital domain-specific workflows. BIM software tools should allow seamless information flow between project stakeholders [8], but the differences in data classification systems, levels of development, and standards have still not been overcome [2, 9].

This paper addresses development of more efficient processes for the structural analysis of buildings in BIM environment, with the objective of automating preprocessing of structural analysis building models (Figure 1).

Interpretations from physical to analytical models are described in the existing work. Physical building models are defined by other stakeholders in the design process. [9]. In the preceding work, the automated procedures, like geometry interpretations, redefining building element types or materials, deal with interpretations of the already defined information. A resulting building model is still not ready for structural analysis. Preprocessing of a building model involves procedures of assigning new information like loads or supports to create an analysis-ready model. These procedures interrelate structural design and analysis, and automating them could provide prompt feedback and reduce time, errors, and costs needed for structural analysis. The automated preprocessing and modelling of structural components constitutes a research gap that is addressed in this research [1].

The aim of this research is to develop and verify an automated solution for preprocessing procedures within a structural BIM-authoring software, as these procedures are currently carried out manually by structural engineers (Figure 1). They are not standardized within existing heterogeneous workflows in the building design process. The primal beneficiary of the automation are structural engineers, since the time-consuming, erroneous, and costly manual work is partly automated. Additionally, the automation of preprocessing procedures allows for improvement of the design process and delivery of better results due to prompt feedback, enabling more iterations and thus resulting in an optimized building design, and in safer and better performing buildings.

2. Literature review

2.1. BIM in the AEC

The AEC (Architectural Engineering and Construction) industry lags behind other industries regarding its gain on productivity and disruption across the value chain; digital technologies are recognized as part of the solution to improve collaboration, control of the value chain and data-driven decision making [10]. BIM covers several industry's digitalization goals and should bring multiple advantages in the design phase like earlier collaboration of domains and provide a possibility to link building models to various analysis tools [11]. However, implementation of BIM is facing multiple difficulties like stakeholders' resistance

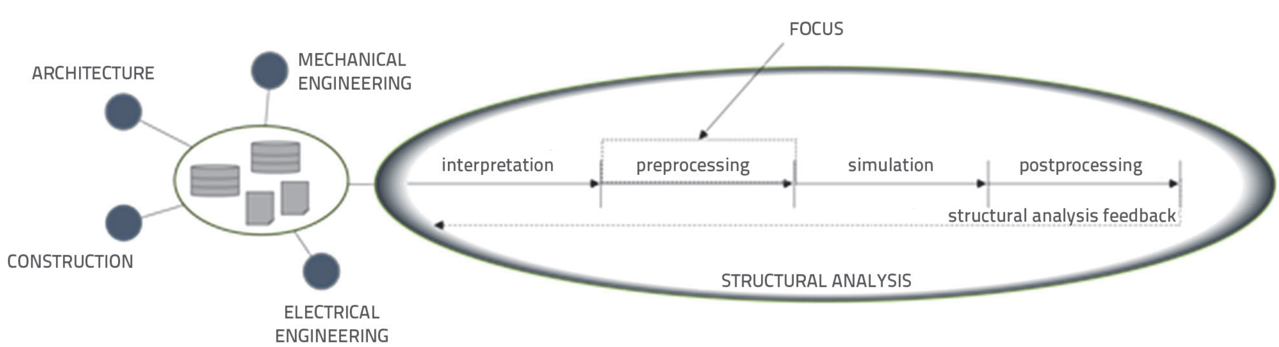


Figure 1. Focus of research within BIM environment

to change, problems in adapting existing workflows, proper understanding and use of tools, or lack of required collaboration [4]. Multiple national and international standards aim to speed up the implementation of BIM in the industry. A set of international standards ISO 19650 deals with the organization and digitization of information about buildings and civil engineering works including BIM. To reach true collaboration a higher level of standardized processes is required [3]. The standard emphasizes the importance of information delivery planning and responsibility matrix [3]. Transfer of information is achieved via common data environment (CDE) throughout the whole life cycle of buildings and civil engineering works. The delivery phase of the assets, which encompasses the design phase is addressed [5]. These standards represent an important step towards facilitating automated information management by providing a framework which can be used for developing information management systems. This research aims to further investigate the possibilities recommended by the standard in the case of information management for structural analysis of building construction. The industry is characterized by loosely-coupled one-time organizations consisting of multiple small and medium enterprises cooperating on delivering a unique building project. This type of cooperative work results with heterogeneous workflows, and the standardized workflows and information flows are still not available. Therefore, we investigate domain-specific workflows relevant for structural analysis.

2.2. BIM tools for structural analysis

The emergence of BIM in the AEC industry has yielded BIM-authoring tools for structural analysis, but the concept of BIM for structural analysis still needs to be clarified. Digital tools using the finite element method (FEM) have been used to simulate structural performance for many decades now. More recently, BIM tools for structural analysis have become available. The most commonly used method for performing structural analysis is the FEM, where building elements are defined in their analytical representation [9, 12]. The FEM can be applied on various scales, from a single connection detail to an entire building, but in practice it is usually found on a building element scale, e.g., a slab or a part of the structural system; the use of this scale has roots in traditional analysis methods in which it was unfeasible to simulate an entire building. The current literature offers a variety of features distinguishing software tools facilitating FEM simulations from BIM structural analysis tools. Features of BIM authoring tools for structural analysis are described in the literature as follows:

- BIM authoring tools allow communication with other stakeholders via standardized formats, such as industry foundation classes (IFC), or provide additional methods that can import and edit models originating from other software tools [13].
- The use of intelligent objects and support of object-oriented design in structural analysis models is the core feature of BIM software [14], although traditional FEM software tools are mostly realized as object-oriented.
- The core feature of BIM is the workflow in which the design, analysis and documentation are interrelated processes, meaning that their interdependencies are at least partly automatically resolved [15].
- A workflow in which the data is digitally transferred to structural analysis is considered a BIM workflow in [16], compared to the traditional one where the data is remodelled.
- The greatest potential of BIM is recognized in workflow automation [16], as the tasks like remodelling or assigning new information performed manually by engineers increase the likelihood of errors and inconsistencies.

Review of the state of the AEC industry reveals that the next step in BIM development is to improve the internal BIM workflows, where the existing data will be used in a more efficient way to create structural models [17]. Vilutiene et al. [1] offer an exhaustive review of BIM implementation in structural analysis. They argue that technical issues relevant for structural engineers have been neglected in the research community. In order to efficiently interrelate the design and analysis, and eventually the documentation process, the interpretation of information coming from other stakeholders, and assignment of new information for structural analysis, need to be automated as much as possible. Although different views on BIM in structural analysis exist, the literature reveals that procedures executed by structural engineers are more automated in BIM workflows compared to traditional approaches, such as allowing import of external models and enhancing connections between the design, analysis, and documentation processes.

2.3. BIM advancements in structural analysis

Experts from various domains contribute to the design of buildings. An increase in research on the topic of BIM implementation in structural design and analysis visibly points to its rising significance [1]. A slow pace of BIM application in civil engineering, and especially in structural engineering has been recognized, and it can be concluded that promises coming with BIM workflows and software tools need to be investigated to solve technical issues for structural engineering [1]. Similarly, a literature review on the automation of structural analysis underlines its gain in importance in recent years [18]. In this review, a survey is described, and it is noted that structural design automation and interoperability with other domains, which are also the topics of this research, are of highest importance for improving the design process. The authors state that the automatic preprocessing of the model would enable more iterations and therefore a more optimized design; it would save time and money needed for model preprocessing, while also avoiding human errors that occur due to repetitive manual rework. Time dependent structural analysis would become feasible, and the safety of construction sites would be improved. A proposal for an automated preprocessing is described in [18], albeit only for an early phase of the design. New work procedures that will improve the effectiveness and efficiency of current design processes are recognized as the most popular BIM-related topic for structural analysis [19].

A common structural analysis workflow during building design is described in [14], where it is stated how a significant amount of manual work can be avoided by relating structural analysis and architectural design models. The authors present a fairly simple case study and describe how loads like self-weight and uniform design load are manually created for the analysis. In a traditional planning workflow, architectural design model is generally imported to FEM tools from schematic design through design development [20]. A workflow supporting data analysis during building design is proposed in [20], but here the focus is on structural design rather than on structural analysis. A plug-in tool for structural analysis called Robot can assist structural engineers in performing optimization of a building structure [21]. Some steps provided with the plug-in are the cross-section, supports and load cases definition. Supports can be roller, pinned or fixed connections to the foundations, and the load cases include self-weight, live load, and wind loads. However, most of the inputs are assigned manually in the model.

Another form of the automation of structural analysis is provided as a support tool for architectural design, by introducing structural knowledge to architectural design tools. The members and connections design can be realized in such a way [22]. However, this approach can hardly replace established structural analysis practices which rely on structural analysis software tools having a large market share. An additional tool in Matlab can help architects in the early design stages to receive feedback for the renovation projects based on floor plans [23]. The motivation for the tool are iterative requests on design feedback, which structural engineers usually provide only for a decided design, which is also the case in the developed design stage. The research [23] focuses on the floor plans and walls as structural elements, which does not entirely correspond to the BIM approach in the developed design stage of architectural design.

The validation of models before assignment of new information can be considered a part of the preprocessing for structural analysis, and is especially required if the models originate from an external practice. This is a broad topic that is developing in multiple directions. Since the standards available for structural analysis are not yet digitalization-ready [9], an extensive reconsideration of building element definitions, properties and the corresponding boundary conditions, is required. The validation can focus on two types of information: geometrical information [24], e.g. if a certain building element having a certain geometrical shape is valid, or semantical information [25], e.g. if the objects and their properties correspond to a certain schema. In our work, the validation is not extensively researched, but it is recognized as a step preceding the assignment of new information for structural analysis.

2.4. Preprocessing in various AEC domains

A data management approach with the focus on energy and structural optimization is described in [26]. The authors of that paper emphasize the need for vagueness in the architectural model at the early stage of the design process. Structural optimization during the early stage of design is characterized by the lack of information for structural analysis. Thus, BIM models with different LODs are used to capture and implement expert knowledge to perform the analysis [26], which was developed with a fuzzy logic inference system in [27]. The authors of [26] do not discuss interoperability with diverse software tools and data transfers, but rather they keep the proposed multi-LOD meta-model compliant with the IFC standard. However, the transfer of data complying with the IFC standard could engender multiple problems and reduce the practicability of the approach [2]. Keough et al. [28] develop CatBot that directly connects parametric design in Catia and structural analysis in Robot, which generates new designs considering also the structural performance. The structural information is assigned in Catia so that it can perform a multi-objective optimization of design at an early stage of design. A tool that automatically provides multiple design variants of tall buildings, which are of significant importance in an early phase of design, is presented in [29]. There is a lack of automated approaches for performing structural analysis, especially if BIM models are involved [29]. Automation attempts similar to those relating to early stages of design have not been found for the developed design stage. Building models and structural analysis in the developed design stage are characterized by more detailed information and different type of uncertainties compared to the early design stage, which is why a different expert knowledge needs to be captured in order to automate the model preprocessing.

The need for automatic preprocessing of FEM models from the available models is recognized in other domains of civil engineering beyond building design and construction. The tunnel information modelling, as a parallel to BIM, is used to automatically prepare the FEM calculation [13]. The boundary conditions and material properties, besides the geometry, are automatically established in the "BIM-to-FEM" approach, and not described to detail [13]. A framework for calculating wind effects on buildings is developed in [30], where the need for automatic geometry interpretation and calculation for such a repetitive and error-prone analysis is recognized. Although research conducted in other domains has similar motives, the workflows and stakeholder involvement in other civil engineering domains differ from those encountered in building design and construction.

2.5. Structural analysis workflows

The review presented in this subsection focuses on the research details describing structural analysis workflows on a building element scale. The structural analysis workflow represents all processes and information leading to

Table 1. Information origin from the review of digital workflows exchanging architectural design and structural analysis models

	Architectural design	Structural analysis
[20]	Geometry	Section properties, boundary conditions, loads
[21]	Geometry (option 1)	Geometry (option 2), sections, supports, load cases
[32]	Drawings, initial dimensions, section sizes	Analytical models, structural properties, loads
[35]	Geometry, location of the members, types of materials and properties	Load types and cases, boundary conditions
[36]	Appearance – art, geometrical and spatial aspect	Simplified model, loading component and joint connections
[37], [38]	Geometric locations, member section profiles, material data, structural members that are provided by the architects as a vertical and lateral load transferring system	New structural members, load cases and their combinations, geometric boundary conditions
[39]	Geometry (physical model)	Loads and supports
[40]	Elevation, grids, geometry	Analytical model, material properties, section properties, boundary conditions, load information
[41]	Geometry, element connectivity, cross-sectional dimensions, mechanical properties of materials	Geometry and support creation, material definition, load assignment

structural analysis. It involves data exchange and definition of new information. Structural engineers do not define their model from scratch. The model geometry results from the data exchange between architectural design and structural analysis. The workflow first involves creation of geometry by an architect, mutual consent on the structural system, and extraction of the structural model from the architectural model. The information resulting from these tasks is neither standardized nor defined in detail.

Structural analysis workflows and the data flow within them are described in multiple papers dealing with BIM workflows and structural analysis. A set of modelling guidelines, aimed at improving data exchange between physical and analytical models focusing on model geometry, is defined in [32]. A framework involving the interpretation of physical model with regard to a corresponding analytical model, both in the IFC format, is proposed, but the models are not preprocessed for structural analysis [33]. They interpret existing information [33], such as geometry and material, and do not enrich it in order to make it ready for simulation. Several practical cases using 3D structural analysis are reported, and the advantages of 3D analysis such as better understanding of the structure and more cost-effective results, are listed in [34]. There is no consensus about information origin in the research describing data exchange workflows (Table 1).

2.6. Literature review summary

BIM for structural analysis does not imply a certain scale or type of analysis, but it does imply more automated processes, greater amount of information sharing and less manual work. Proposals for the automation of current structural engineering practices address primarily an early phase of design (e.g., [26]), which still lacks significant amount of information about a building design compared to the developed design; therefore, it directs towards generative design. Other civil engineering practices, such as tunnel design, have a partly automated model preprocessing, but different workflows and involvement of stakeholders. Structural analysis workflows in the developed building design are heterogeneous and have not been sufficiently explored in the existing literature. From the literature review of digital workflows presented in Table 1, it can be concluded that the geometry of all building elements enclosing a space, and materials of building elements with visual properties and types of building elements, are delivered from architectural design to structural analysis. In some cases, after consultation with structural engineers, architects define the information about the load-bearing property of building elements, foundations, and grids. The following information is usually not explicitly defined during architectural design: analytical geometry of structural building elements, loads, structural properties of materials, supports, and structural connections of building elements. Architectural software tools generally do not provide ways to define that information. The automated preprocessing methods, as part of structural analysis workflows, are missing in the standards or literature, except for the methods provided by software tools that overcome software-specific problems in the form of workarounds. We aim to advance the existing structural analysis practices by providing an automated model preprocessing, thereby reducing costs, errors and time, and providing better feedback to other domains. Problems arise due to lack of documentation describing workflows for structural analysis, and lack of methods that are needed for automation and, finally, automated procedures. Therefore, this research aims to close the gap of the missing preprocessing by identifying and automating potentially standard preprocessing procedures for the developed design stage during building design.

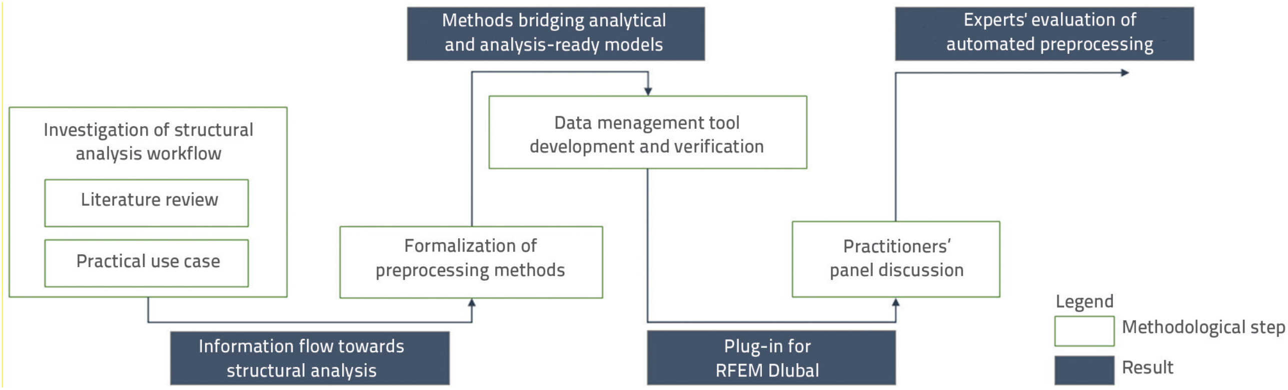


Figure 2. Methodological steps and corresponding deliverables

3. Methodology

The automation of the preprocessing steps preceding structural analysis in the building design phase, which are currently conducted manually, is the focus of this paper, which rounds up the implementation of data exchange between the architectural design and structural analysis. A framework that facilitates data exchange between the architectural design and structural analysis building models was developed, implemented, and verified in the previously published research [9, 31]. The framework allows for an open classification and interpretation at the central storage, and finally automates the data exchange with the proprietary software tools. Objects are defined on the building element scale, where semantic information is defined using IFC terminology, and geometrical information using the Open Cascade geometry kernel. The Open Cascade provides predefined methods that are used for the interpretation of geometry. The automation of preprocessing procedures that create an analysis-ready model is realized through several methodological steps that are described below and in Figure 2:

- Identification of preprocessing methods is based on a thorough literature review (Subsection 2.5) as well as on the real use case analysis of a modelling and data exchange process of a German structural engineering company (Section 4). The real use case reflects the everyday procedures conducted with BIM authoring tools for structural analysis.
- Formalization of the preprocessing methods in an automatable form is required so that they can be realized as a data management tool (Section 5). The tool accesses analytical model at the central storage, after interpretation of geometrical and non-geometrical information from a physical building model provided by an architect [9, 31]. Such a model is considered a starting point for preprocessing methods that enrich it to an analysis-ready model. Similar models can be manually recreated from the information provided in architectural design. Analytical models that were used for model preprocessing contain analytical geometry of building elements, building element types, and materials. The preprocessing methods are derived from the previously conducted analysis. The methods are developed by comparing the initial and expected building models, and by identifying and describing processes that provide a desired result.
- The developed data management tool maintains communication with the central data storage (realized with MongoDB) and facilitates conversion to a particular structural engineering finite element calculation tool (RFEM Dlubal). The data in MongoDB and RFEM Dlubal can be accessed via the application programming interface (API). The APIs are used with ..Net framework to create a software tool that is available as a plug-in in RFEM Dlubal. The RFEM graphical user interface (GUI) also serves as a GUI for the plug-in and allows the end user to gain insight into the automation methods. The developed preprocessing methods were implemented and verified via two pilot building models originating from the above-mentioned structural engineering company. The two models were preprocessed with the developed tool and their structural performance was calculated. The results were evaluated by the authors and compared to the results of a traditional structural analysis. In this step of the research, the two pilot buildings were used to verify the approach and sufficiency of the identified procedures and information (Section 6).
- Finally, the feedback and evaluation of generalization potential of implemented automation methods was realised through the practitioners' panel discussion (Section 7). The practitioners' expertise is needed to identify optimization potentials as preprocessing rules are bound to individual or interfirm conventions.

4. Identification of preprocessing steps: analysis of structural analysis workflows

4.1. Workflow procedures

The objective of the presented research is to automatically establish a model that is sufficient for structural analysis by enriching model information originating from other domains. In order to achieve this, a significant amount of novel structural-analysis-specific information is required. Each information is

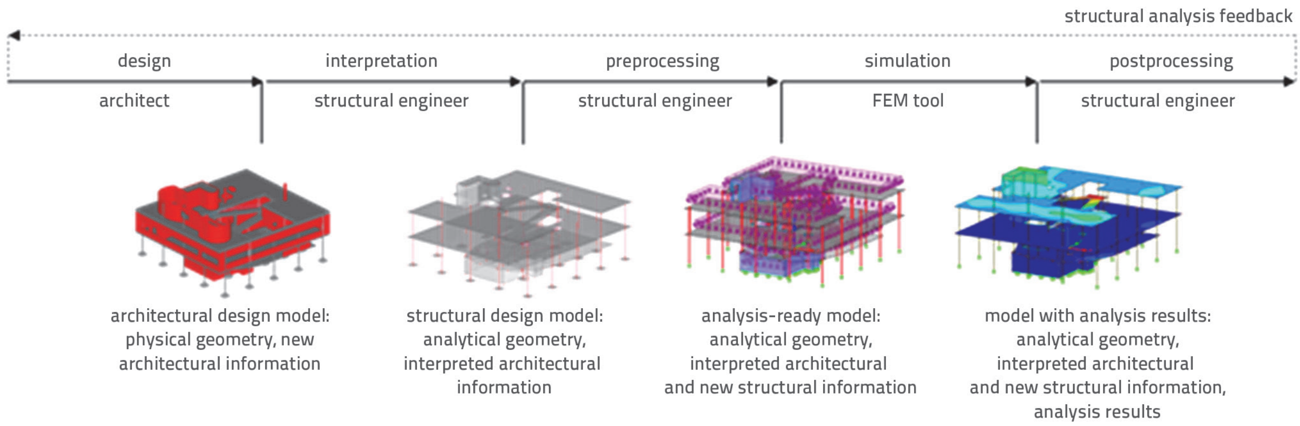


Figure 3. Procedures leading to structural analysis feedback

generated or edited at a specific point in the workflow (Figure 3); the automation methods are replacing manually performed procedures and generate or edit the same information. The information origin is investigated in this section. Multiple procedures that lead to feedback from structural engineers are displayed in Figure 3. The procedures where information is defined by structural engineers solely belong to preprocessing, while redefining information originating from the architectural model, centrally stored as a non-proprietary architectural design building model, belong to interpretation; an interpreted model is also centrally stored as a non-proprietary structural analysis model.

Multiple information, such as loads, load combinations or additional structural building elements, is defined solely by structural engineers. The identification of such information, its separation from the information originating from an architectural model, and procedures that define such information, require a detailed investigation of the structural engineers' workflow, practices, and processes. Therefore, the workflow is investigated through the literature review (Subsection 2.5) and the real use case, the purpose being to capture existing modelling and analysis processes.

4.2. Real use case

Within the real use case (involving a German construction company), the process analysis including the design, interpretation and preprocessing procedures, was conducted during the period of eight months (from April 2020) through multiple interviews, observation of processes and continuous feedback from a team of company experts. The team was composed of multiple BIM experts and structural engineers, working in the company on the implementation and improvement of building design workflows across domains, as well as conducting various day-to-day structural analysis tasks. Therefore, they were able to identify challenges and opportunities within the existing workflows, and to describe standard workflows leading to structural analysis feedback. Engineers use RFEM Dlubal to conduct structural analysis; architectural design is not always created within the company, i.e., it might also be external. The real use case serves primarily to validate the findings made during literature review (Subsection 2.5); the details that were inexistent or insufficiently described in the literature for automation purposes regarding the modelling and reasoning processes for creating an analysis-ready building model were documented. Exact information assigned during the procedures was obtained and, if necessary, discussed with competent experts.

Process analysis of the company specific practice revealed that an architectural model is generated in Revit, which needs to be filtered, leaving the definition of load-bearing elements to structural engineers. The filtered model is not imported as such in the RFEM Dlubal analysis tool. It is remodelled for the so called "2,5D structural analysis". This analysis involves modelling of individual slabs and the underlying building elements are represented as punctual or linear supports, depending on the underlying element. The calculations are individually performed for each slab. If the slab is not the top slab, all overlying elements are represented as punctual or linear loads, depending on the building element type, with the values resulting from the previous simulation. The first slab being calculated is the top slab, and the lower slabs are assessed sequentially. Slab geometry is redrawn from the existing filtered model.

Multiple loads need to be assigned: dead loads and live loads for each slab, and additionally environmental loads on the roof slab. A standard analysis does not include calculation of environmental loads for vertical elements, although this calculation can be required. The loads calculated on the upper slab supports, which are actually the underlying building elements, are transferred to the lower slab at the place where the same building elements are in contact with the lower slab. These can be linear or punctual loads, depending on the building element type. Joints between the supports and slabs are modelled so that they do not transfer rotation, but here the exception are the joints supporting the console. The real use case delivers results similar to the literature review of the structural analysis workflow: geometry originates from

Table 2. Information origin from the process analysis

Information origin	Information
Architectural model	Geometry, building element types – architectural semantics, materials with visual properties, space uses (not always defined)
Mutual consent on architectural model (structural model)	Geometry of structural system, load bearing properties
Structural analysis model	Analytical geometry, building element types – structural analysis semantics, materials with structural properties, load types and cases, supports, joints

the architectural model, the structural concept is generated by mutual consent of an architect and structural engineer, which results in the structural analysis model. The model consists of multiple horizontal building elements and vertical elements converted to supports and loads. The material and interpretation of building elements follow the architect's input. The following completely new information is assigned by the structural engineers: loads, load combinations and supports. In the 2,5D simulation, the supports are defined under each slab for the underlying elements, not only the foundations. In the 3D analysis, the connections between building elements and slabs are modelled as joints, rather than as supports. An overview of information origin is provided in Table 2.

The analysed 2,5D workflow is realized with multiple RFEM files and the information is assigned manually. Figure 4 depicts the 2,5D workflow: a) loads are assigned to the top slab; b) underlying building elements are defined as supports and the reactions are calculated; c) the reactions are assigned to the next slab as additional loads. A significant part of the workflow can be automated in its current state. However, in our paper we address the fully developed BIM workflows, based on 3D building models. For this reason, our preprocessing methods partly differ from the analysed workflow.

5. Formalization of preprocessing methods for automated preprocessing

5.1. Novel workflow overview

The information defined in the architectural building model is enriched with additional information to prepare the model for structural analysis. Some information can be interpreted and depends on the architectural input, while some is new. We will focus on the new information required for structural analysis, and define the automation methods based on the type of information. While the way to interpret geometric and non-geometric information about building elements with load-bearing properties based on the information defined by the architect has been previously developed in detail [9, 31], the way to generate new information recognized as crucial for structural analysis will be presented here.

The preprocessing methods developed based on the results of workflow analysis are presented in this section. The input and output information remains the same in the traditional and automated procedures, while the developed methods reflect the practices of structural engineers. The aim is to achieve the same result as with traditional preprocessing, i.e., an analysis-ready model, but without repetitive and error-prone manual work. The results of the process analysis imply that the structural building elements are filtered and interpreted in the interpretation part from the architectural building model. Based on the analysed process, the following information is available after the interpretation part: analytical geometry of building elements, materials, element types and their load-bearing properties. The additional required information concerns: loads, supports, and joints. In the traditional approach, the validation step is conducted by visual inspection of the model, and possibly by assigning new or editing the information in problematic spots. The validation is of crucial importance for the preprocessing methods. Once the validation is over, methods are proposed for defining the following information: floor levels, foundations, loads, and joints. The novel workflow encompassing the transfer of data from architectural design to structural analysis is presented on Figure 5.

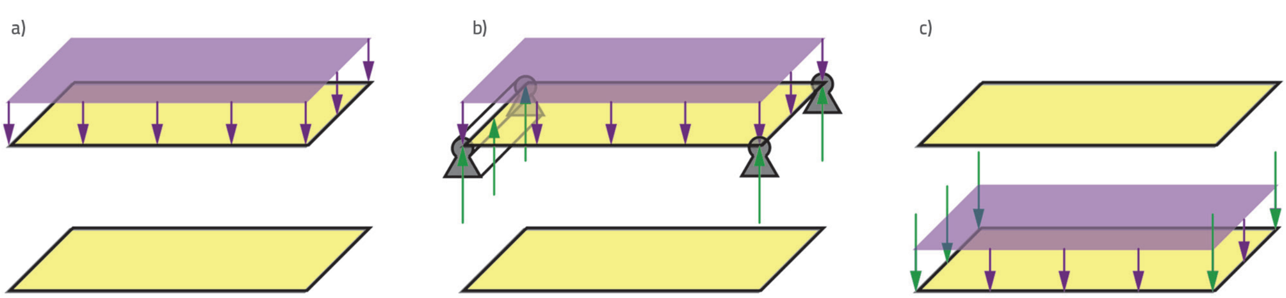


Figure 4. Workflow in 2,5D analysis

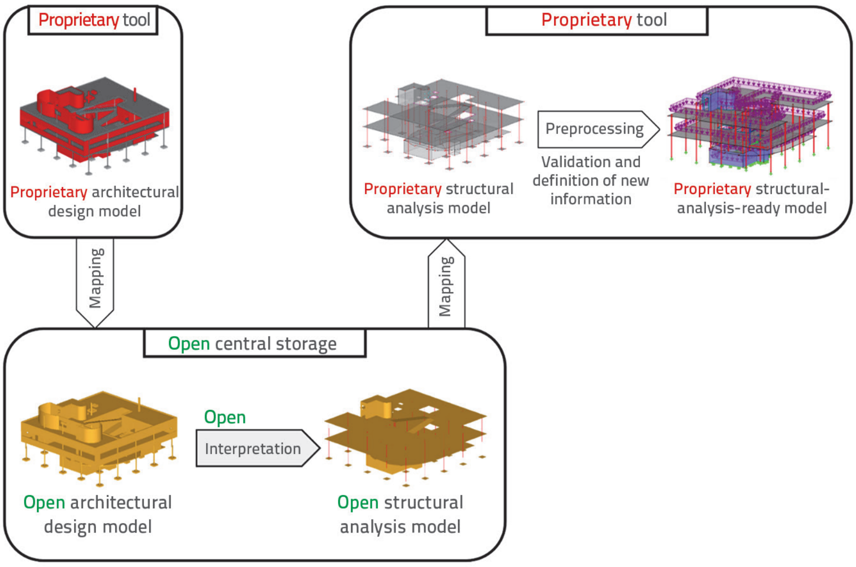


Figure 5. Overview of novel workflow

5.2. Model validation

Model validation is the initial step that comes before assignment of new information. Some exemplary problems that can occur during the import include inadequate or absent definition of material, and incorrect rendering of complex geometry. We took into account some of these problems and treated them before the import. Model validation represents a broad set of topics that have to be considered before the new information is assigned. We recognize the importance of validation before the preprocessing steps, but treat it exemplarily in our work due to the fact that we realize the preprocessing methods on a single workflow. For a wider implementation, the validation would need extensive development.

In this paper, the information about material is considered as an example. The element lacking the material information during import is identified, and the request for appropriate action is initiated, as this information is expected to originate from the architect. The example is shown in Figure 6. Such approaches overcome the discrepancies between the expected and available amount of information. The additional information may be needed due to lack of information on the central storage or performance of software tool. The exhaustiveness of validation methods improves the quality and effectiveness of preprocessing methods.

5.3. Preprocessing methods: new information

Ppreprocessing methods will be presented based on the building information they address: floor levels, foundations, loads, joints.

Floor levels

A preprocessing method aimed at determining floor levels is needed as the current practice in the use case analysis focuses on the floor-wise calculation. The floor levels are often defined in the architectural software tool, but these levels do not necessarily comply with the needs of structural engineers, or with the way they are defined in the structural analysis tool. Generally, the floor levels are defined in structural engineering as the axial plane of the floor slabs, which is the information that is already available after the interpretation step. The purpose of the preprocessing method is to discover relevant floor slabs, assign to them the correct placement or z coordinate, and set a structure for the rest of preprocessing steps. The floor slabs are first filtered, and only horizontal slab elements are considered relevant. They can also be validated if there are multiple slabs within a certain tolerance value; the alignment of neighbouring slabs is already considered in the interpretation step [9]. The method defining the floor levels does not generate new knowledge. It is nevertheless considered to be a preprocessing method as it creates a structure for the rest of preprocessing.

Foundations

It is not clearly defined within the building design process whether foundations are modelled during the architectural design or structural analysis. Even if foundations are defined in the architectural model, structural engineers are responsible for their dimensioning. We concluded from the process analysis that foundations are generally defined by structural engineers, and proposed an automatic creation of foundations during preprocessing of the structural analysis model.

Three types of foundations need to be automatically generated: individual foundations, strip foundations, or mat foundations, depending on the geometrical element where they are placed: point, line, or surface. The foundations are placed at the bottom of each structural element that transfers loads to the ground, and so the point represents the bottom of a column, a line the bottom of a wall, and a surface the slab used as the mat foundation. In the case foundations are modelled during architectural design, building elements defining the foundations should be defined as points, lines, or surfaces already during the interpretation. The foundations are generally placed at the lowest level in the floor-wise calculation, but the positioning might be more complex and involve multiple levels. The position of the ground or outside space determined by enclosed space uses could be considered for more complex validation steps.

Loads

Imported structural analysis models do not contain information about loads since loads are normally not defined during architectural design. Loads are a requirement for any structural analysis. There are several types of loads that are assigned before the analysis takes place. Additionally, load combinations need to be defined to analyse structural performance in more complex conditions, and the way they are defined is standardized [42]. Four types of loads are common: dead load, live load, impact load, and environmental load [43]. Dead load is the constant load imposed on the structure, and it is typically the self-weight of building elements. The self-weight is dependent on materials and is applied on each structural element. The self-weight can be assigned automatically for the whole building as the information about the material comes from the architectural model, while material properties, such as specific weight, are available in RFEM.

Live loads are applied to all slabs in the building models. They can be temporary loads like those imposed by furniture or occupancy and are calculated using standard values [44, 45]. They can also be the loads imposed by the non-load-bearing structure of the building element, and their calculation is also standardized [46]. A precondition for automating the live loads based on the interpreted models is that an architect adequately defines the room uses. However, this is not often the case, and, therefore, the aim is to assign the uses for the entire floor.

Besides the dead and live loads the environmental loads remain required in the standard calculation. Environmental loads depend on two factors: geographical location of the building, which determines specific values for environmental loads, and whether a building element borders the external space. If the rooms are defined in the model, the building element bordering external space can be identified easily. Otherwise, a more complex reasoning algorithm needs to be developed. If the room uses are missing, and if the floor-wise calculation takes place, a simplified approach is to assign the environmental snow load only to the slabs on the top level, using the coefficients available in standards for specific locations [46]. In RFEM, these values can be assigned based on the altitude and snow zone. The geographical location is a known input from the start of the project and should be present in the central database. Impact loads are usually assigned in special cases only.

Joints

During structural analysis of slabs without modelling of vertical elements, there are no joints between vertical and horizontal elements as the vertical elements are represented as supports or loads. Joints define in which way the building elements are connected to each other. For the 3D analysis, they have a significant effect on the final analysis results. The joints are primarily modelled as pin-connected, and the rotation is not transferred in both directions in the case of punctual joints, while the rotation can be transferred in the direction of the line defining the joint in the case of linear joints. Fixed-connected joints are modelled for the case of cantilevers, when the rotation transfer is necessary. The information about cantilevers is not directly defined by the architect. Nevertheless, this knowledge can be automated, either by analysing the room functions (e.g., balcony), or by using a more complex algorithm that can identify cantilevers based on geometry. We assign pinned-connected joints as a default, but this can be readjusted in the follow-up. The joints between individual elements are a topic that requires further research for obtaining realistic results and for investigation of their automation potential.

6. Implementation and verification: pilot building models

The proposed preprocessing methods are implemented and verified on two pilot building models provided by the construction company. The preprocessing methods are implemented on 3D models, developed in the previous work including interpretation of building models [9, 31]. The models in the preceding study are created with IFC exports from Autodesk Revit, and automatically interpreted to analytical building models. The context of these studies conforms to the scope of information of the architectural design models described in the workflow analysis. The interpreted models provide a starting point for the preprocessing methods, and these models

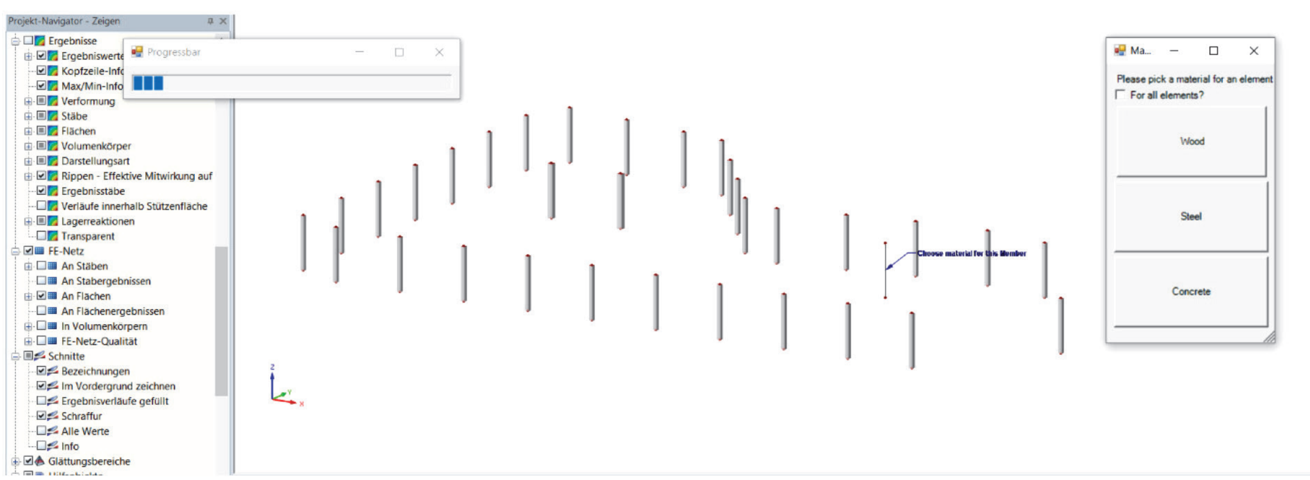
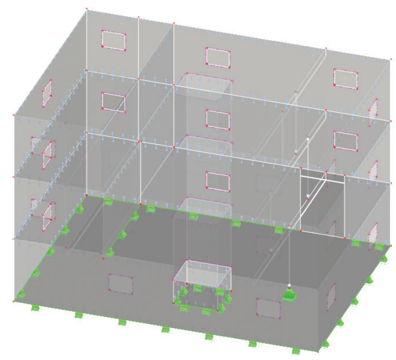
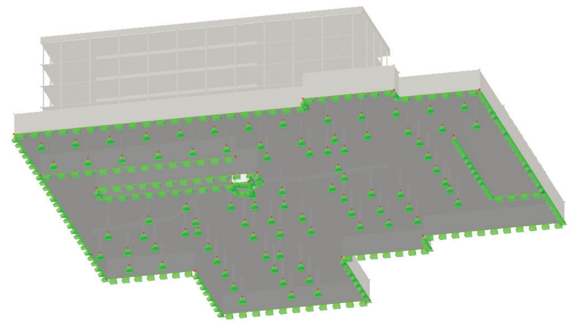
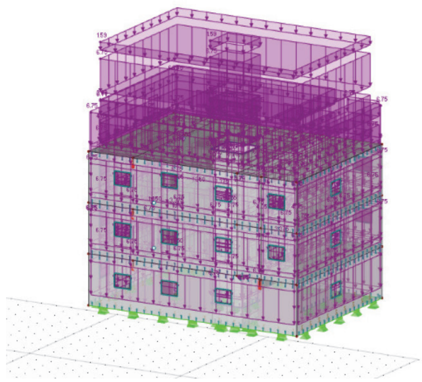
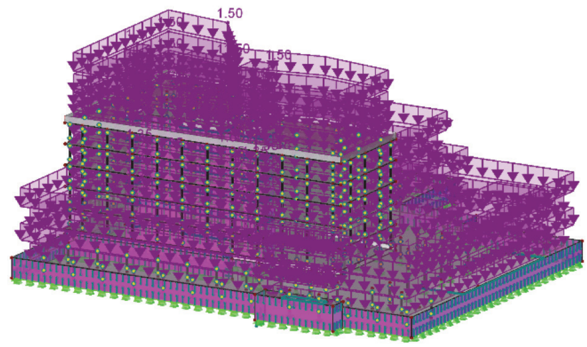
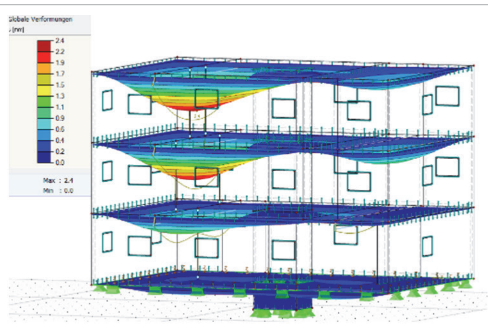
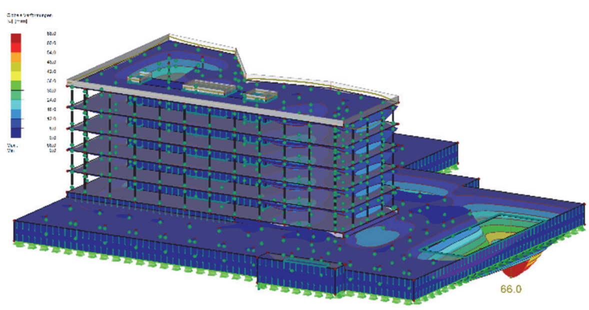


Figure 6. Material assignment after validation

Table 3. Screenshots of results of preprocessing methods and analysis

	Pilot model 1	Pilot model 2
Foundations		
Loads		
Simulation results		

contain analytical geometry of structural building elements with assigned building element types and materials. However, the same or similar models can also be manually generated using structural analysis tools, after redefining the information provided in the architectural design.

The proposed automation of preprocessing methods requires transitioning from 2.5D to 3D models. The implementation involved a way to validate the models through validation of materials (Figure 6), and preprocessing of the validated model. The preprocessing methods included definition of floor level, foundations, loads, load combinations, and joints. Finally, the results of the structural analysis were compared with the results assessed by the company, from which the models originate.

The preprocessing was implemented using the centrally stored structural models and the available proprietary RFEM model, where the RFEM Dlubal API was used with the data available at the central storage. This facilitated the use of the Open Cascade geometry kernel with the .Net framework system architecture to realize the communication and preprocessing methods.

The preprocessing tool is realized as the RFEM plug-in. The approach is developed as a semi-automatic process. However, the default values or additional information such as space use can lead to a fully automated approach. Analytical models that are addressed with the plug-in need to have sufficient and accurate information: analytical building element geometries, building element types and materials assigned. The plug-in first detects the building floors that represent the main structure for further automation steps (Figure 7).

It is possible to automate creation of supports or loads on a particular floor. In Table 3, the results are demonstrated on two pilot models. The joints are defined without the user interaction. However, they can be further edited if required. The created foundations, loads and the results of the analysis are displayed.

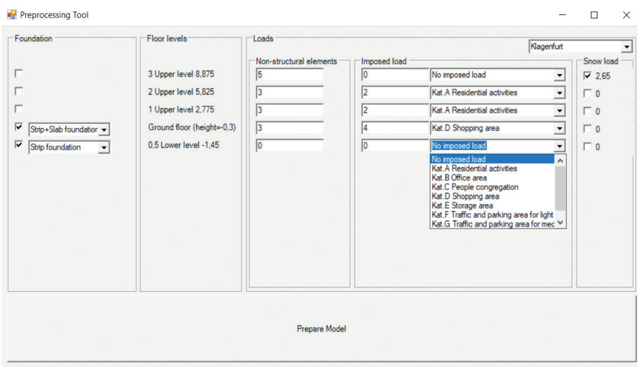


Figure 7. Plug-in screenshot

Additionally, the verification was performed by comparing simulation results obtained with the proposed methods with simulation results from the 2.5D analysis. A schematic view of 2.5D and 3D analyses are given in Figure 8. The 2.5D analysis is performed step-wise, floor by floor, with multiple files and models, while 3D involves a single analysis. RFEM Dlubal supports 2.5D analysis by allowing transfer of the calculated reactions as loads between multiple files.

The resulting reactions in foundations, obtained with 2.5D and 3D analyses, were compared. Although the loads assigned to the slabs are equivalent in both analyses, the resulting reactions differ. The difference is measured as percentage of the 2.5D results. The 3D analysis generally results in similar reactions in foundations. However, the results are sometimes significantly different, and sometimes they even change direction of the reaction. Single results are compared in Table 4, and the difference between 2.5D and 3D results is summarized in Table 5. The difference points to the unreliability of the 3D analysis for the engineers who are familiar with 2.5D, as the results differ by more than 15 % in 18.2 % of foundations of the first pilot model, and 29.9 % of foundations of the second pilot model. Even if the relative difference is significant, the absolute difference does not point to unrealistic values. The results were validated with a structural engineer.

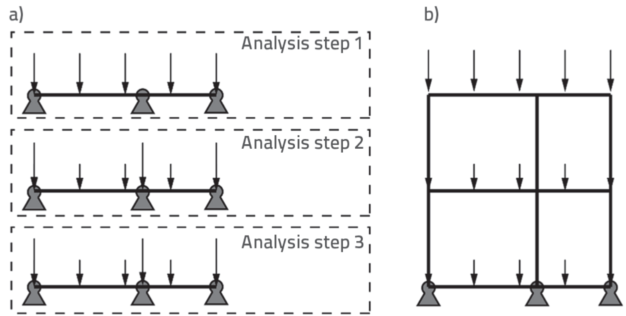


Figure 8. Schematic comparison of a) 2,5D analysis and b) 3D analysis

7. Evaluation through practitioners' panel discussion

Panel discussion is chosen as a method for receiving feedback from a small group of experts, and as a means to evaluate the proposed approach. The panel discussion was held as an online workshop and involved three structural engineers from two different construction companies, and two BIM experts. The discussion time was 108 minutes, and was moderated by the first author of the paper. The general workflow with interpretations and preprocessing methods for the analytical model was presented, followed by semi-open discussion. The discussion included a predefined open-ended questionnaire assessing the usefulness and usability of the developed plug-

Table 4. Comparison of 2,5D and 3D analysis results

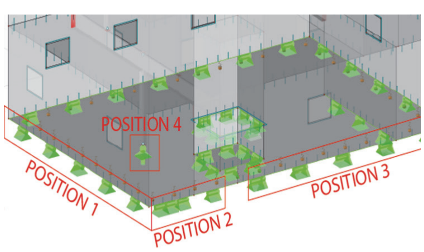
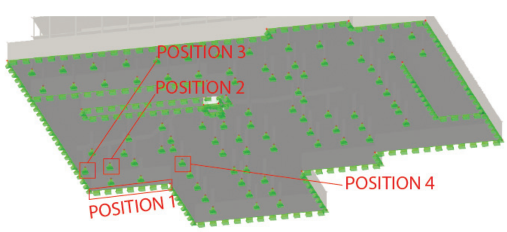
	Screenshot with foundation positions	Position	2.5D	3D	Diff. [kN]	Diff. [%]
Pilot model 1		1	185.71 kN/m	170.21 kN/m	15.5	8.35
		2	117.38 kN/m	134.40 kN/m	-17.0	14.50
		3	170.84 kN/m	179.51 kN/m	-8.7	5.07
		4	876.49 kN	657.25 kN	219.2	25.01
Pilot model 2		1	3.16 kN/m	3.58 kN/m	-0.42	13.29
		2	83.73 kN	179.31 kN	-95.58	114.15
		3	55.81 kN	38.40 kN	17.41	31.20
		4	100.52 kN	97.47 kN	3.05	3.03

Table 5. Overview of reaction differences in foundations between corresponding 2,5D and 3D analysis results

Difference	0-5 %	5-15 %	15-25 %	25-50%	>50%
Pilot model 1	1 (9.1%)	8 (72.7%)	1 (9.1%)	1 (9.1%)	0 (0%)
Pilot model 2	55 (51.4%)	20 (18.7%)	9 (8.4%)	11 (10.3%)	12 (11.2%)

in. The focus of the discussion and questionnaire was set on the applicability of the preprocessing methods in daily practice. As all participating engineers have been using RFEM Dlubal in their work, RFEM Dlubal plug-in provides a possibility to examine the procedures in a familiar environment.

The feedback provided by the participants in the discussion addressed general issues regarding the preprocessing automation, as well as the specific preprocessing methods. General remarks include:

- Both companies use architectural models originating from Revit and RFEM Dlubal for structural analysis
- 2.5D is preferred to 3D structural analysis primarily due to traceability and clarity of calculation; however, the calculated cross sections of building elements may be greater than in the case of 3D.
- 3D analysis delivers results that are difficult to verify due to complexity of the system.
- Traceability of simulation is needed for the inspection engineers, which is not available in 3D analysis.
- Automation of preprocessing methods is regarded as useful and usable, but needs some adaptation.
- Practices do not significantly differ between companies.
- Structural engineers are generally part of the project before the developed design and specific information can be defined in advance.
- Significant amount of experience-based knowledge is used in the identification and analysis of the model.

Feedback received from the participants shows that they recognize the standardization potential of the proposed preprocessing methods:

- A similar approach is performed to identify the floor levels; however, an important point is the detection of the ground floor, which is usually placed close to ±0,00 elevation.
- Foundations can be defined in two ways, based on the results of the geotechnical analysis:
  - as the proposed solution, under each element separately;
  - by excluding the support capabilities of a ground plate due to poor characteristics of the soil.
- Loads are highly dependent on the building use and special building requirements. The proposed loads can be regarded as standard input. It is necessary to include multiple building codes.
- Joints can be modelled in two ways, depending on whether the
  - prefabricated, which indicates that the rotation is not transferred, or
  - cast in place, meaning that the rotation can also be transferred.

The preprocessing methods require some adaptation, but a similar plug-in that could automate the existing practices or some preprocessing steps is recognized as a great help for a day-to-day business.

8. Discussion

This research answers the question "How to facilitate automated building model preprocessing within a structural analysis software tool". The proposed preprocessing methods automate assignment of additional information traditionally performed manually, and round-up the information flow before structural analysis. Manual preprocessing, suboptimal exploitation of software tools in the existing BIM-based workflows, lack of technical solutions for structural analysis, and inadequate support for the existing practices, are the issues that are answered with the novel proposal. These problems are identified in the literature [1, 17] and, although some automated preprocessing exists at other design stages [26] or in other domains [13], the structural analysis preprocessing is still lacking in the developed building design. The proposed solution is in accordance with general tendencies of BIM for structural analysis, to automate workflows within and beyond the AEC domains [15, 16]. An automated preprocessing provides speedier feedback and reduces errors, cost, and time needed for structural analysis.

Standard workflow for structural analysis involves data generation during architectural design, interpretation of existing data for structural analysis, and assignment of new data through preprocessing. The flow of information within the workflow, including the responsible stakeholder, position within the workflow, and the way it is generated, are all recognized as crucial for digitalization in standards [3]. Structural analysis workflows are analysed in this research as they are currently not sufficiently documented. Interpretations use already defined information and create non-proprietary structural models [9]. On the other hand, the presented preprocessing methods assign new information to the analytical models interpreted from architectural design and are software tool specific.

The feedback discussion points to the existing discrepancy between the practice and the theoretical hypothesis behind the BIM-based structural analysis concept, the gap which is addressed through this research. While BIM promotes the use of shared digital representation of a building, and BIM-authoring tools for structural analysis provide ways for the creation and analysis of 3D models, a hybrid solution is implemented in practice: 3D analysis is conducted by simplifying it to the scale of a single floor level, commonly only a single slab, the so called

2,5D analysis. The 2,5D analysis is especially appreciated for the transparency of calculation, which is required by inspection engineers. When the analysis is performed with a complete 3D model, the proprietary tools do not offer clear explanation of simulation steps, nor do they take responsibility for the analysis results, which is not acceptable for the engineers holding responsibility for the stability of buildings. 2,5D can be seen as a sub-set of analysis based on a 3D model, where the preprocessing method is applied on a smaller scale of a building floor or only a building element, such as a floor slab. Additional tool for decomposition of a 3D model and achievement of communication between partial models is needed for full automation of preprocessing with the 2,5D analysis. The participants, structural engineers, expressed their concerns regarding the results and reliability of 3D analyses, as a rigid model often delivers unsatisfactory results. The 3D model with exhaustive validation and automatic preprocessing methods is regarded as a feasible solution, but 2,5D provides better and faster results if the preprocessing steps are performed manually. An exemplary comparison of 2,5D and 3D analysis is provided within the research, demonstrating the reliability of the 3D analysis.

The proposed preprocessing methods are regarded as a possible way towards a reliable 3D analysis, albeit with some adaptations, like choosing the construction type (prefabricated or cast in place) or defining the foundation capabilities of the bottom plate based on the ground. The 3D analysis is performed for earthquake simulation, usually with a decided design. Therefore, constant feedback by structural engineers through a simulated structural behaviour is not anticipated, especially for the demanding and long-lasting simulations like behaviour during a seismic event. By automating preprocessing, workflows could eventually achieve a real-time feedback and optimize the design of buildings.

Model updating and change tracking still constitute a challenge, and require consideration within the new framework. In the existing practice, the changes are performed manually and transferred to the affected floors, except in cases when the changes require a completely new simulation.

The workshop participants acknowledged the potential of the proposed automated preprocessing methods and further automation of model preparation. An automatic recognition of floor levels, and definition of foundations, loads and joints, are considered a significant aid, which could allow for faster and less error-prone model editing, eventually leading to real-time feedback. The real-time feedback would open new possibilities for model optimization, and would consequently deliver more higher-quality buildings.

9. Conclusion

In this paper, the model preprocessing for structural analysis during building design is identified and formalized, and then automation methods are proposed. The automated methods create analysis-ready building models by assigning structural information. The interpretation procedure, which precedes preprocessing, is based on the previously developed data exchange framework characterized by multiple domain-specific classifications and open interpretations [9]. As the building models originating from architectural BIM models do not provide sufficient information for the analysis, the processes of assigning new structural information are herewith captured and automated. The novelty of this research is the proposal for the automation of preprocessing methods, which may serve as a basis for future development and standardisation of methods. Additionally, the presented work provides a detailed workflow analysis including the information flow, documented preprocessing methods, realisation of a plug-in, and experts' feedback. Further on, a comparison of 2,5D and 3D is provided to answer concerns of structural engineers. The automation of workflows is anticipated with the development of BIM tools, and is recognized as a knowledge gap in the literature.

The building model preparation for analysis rounds up the data exchange framework in one direction, from architectural design to structural analysis, and can provide first analysis results by introducing some assumptions with less effort. Our approach does not automate further structural optimizations like reinforcement placement or material change (postprocessing); these tasks are topics for future research. However, as confirmed during panel discussion, the automation of preprocessing steps is at this point crucial for realizing BIM benefits and speeding up digitalization in the domain of structural design and analysis. The proposed preprocessing methods are at this stage based on the literature review and intra-firm data-exchange practices, and include definition of floor levels, foundations, loads, and joints. The methods depend on the architectural building model as well. The external models, from another software tool, or different structural engineering practices, would require exhaustive validation procedures and might require edited or new preprocessing methods. A system architecture that can adequately support such a heterogeneous set of services is required. Our approach needs to be verified with additional software tools; some tools might not provide interfaces to achieve similar results. Following the consideration of other software tools, the positioning of methods within the framework is of crucial importance. The limitations of RFEM API are recognized as lying in the sphere of geometry modifications. Therefore, the Open Cascade kernel and the centrally edited geometry, which provides greater flexibility, is needed for some preprocessing steps.

The future research will involve provision of similar services with additional structural analysis tools, building models, and practices. Similar plug-ins are required for other structural analysis software tools, and the presented proposal may serve as a basis for such development. The authors intend to investigate the possibility of providing such services with microservice architecture, so as to be able to satisfy heterogeneous workflows.

Acknowledgements

We would like to express our gratitude to Strabag SE, Vienna, and their subsidiary Züblin, Stuttgart, for supporting this research through the DATAFILTER project. We would also like to thank ATP architekten ingenieure, Vienna, for taking part in the panel discussion. We express our gratitude especially to Konstantinos Kessoudis, Richard Schaffranek, Maximilian Knoll and Dr. Georg Hochreiner for providing their support in the realisation of this research.

REFERENCES

[1] Vilutiene, T., Kalibatiene, D., Hosseini, M.R., Pellicer, E., Zavadskas, E.K.: Building Information Modeling (BIM) for Structural Engineering: A Bibliometric Analysis of the Literature, Advances in Civil Engineering, (2019), https://doi.org/10.1155/2019/5290690.

[2] Sibenik, G., Kovacic, I.: Assessment of model-based data exchange between architectural design and structural analysis, Journal of Building Engineering, 32 (2020), https://doi.org/10.1016/j.jobe.2020.101589.

[3] ISO: ISO 19650-1:2018 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) - Information management using building information modelling - Part 1: Concepts and principles. Geneva, Switzerland: ISO, 2018.

[4] Arayici, Y., Coates, P., Koskela, L., Kagioglou, M., Usher, C., O'Reilly, K.: Technology adoption in the BIM implementation for lean architectural practice, Automation in Construction, 20 (2011) 2, pp. 189-195, https://doi.org/10.1016/j.autcon.2010.09.016.

[5] ISO: ISO 19650-2:2018 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling — Part 2: Delivery phase of the assets. Geneva, Switzerland: ISO, 2018.

[6] ISO: ISO 29481-1:2016 Building information models - Information delivery manual - Part 1: Methodology and format. Geneva, Switzerland: ISO, 2016.

[7] LM.VM.: Leistungsmodelle Objektplanung – Architektur [LM.OA.BIM], eds. Lechner, H., Heck, D., Graz, Austria: Verlag der Technischen Universität Graz, 2014. https://www.arching.at/fileadmin/user_upload/redakteure/LM_VM_2014/LM_Objektplanung_Arch_BIM_.pdf

[8] Miettinen, R., Paavola, S.: Beyond the BIM utopia: Approaches to the development and implementation of building information modelling, Automation in Construction, 43 (2014), pp. 84-91, https://doi.org/10.1016/j.autcon.2014.03.009.

[9] Sibenik, G., Kovacic, I.: Interpreted open data exchange between architectural design and structural analysis models, Journal of Information Technology in Construction (ITcon), 26 (2021), Special issue CIB World Building Congress 2019: Information technology of smart city development,. pp. 39-57, https://doi.org/10.36680/j.itcon.2021.004.

[10] McKinsey & Company: The next normal in construction, https://www.mckinsey.com/business-functions/operations/our-insights/the-next-normal-in-construction-how-disruption-is-reshaping-the-worlds-largest-ecosystem, 2020.

[11] Sacks, R., Ghang, L., Eastman, C., Teicholz, P.: BIM Handbook: a Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors. Wiley-Blackwell, 2018.

[12] Hasan, A.M.M., Torky, A.A., Rashed, Y.F.: Geometrically accurate structural analysis models in BIM-centered software, Automation in Construction, 104 (2019), pp. 299-321, https://doi.org/10.1016/j.autcon.2019.04.022.

[13] Alsahly, A., Hegemann, F., König, M., Meschke, G.: Integrated BIM to FEM approach in mechanised tunneling, Geomechanics and Tunnelling, 13 (2020), pp. 212-220, https://doi.org/10.1002/geot.202000002.

[14] Bhusar, A.A., Akhare, A.R.: Application of BIM in Structural Engineering, SSRG International Journal of Civil Engineering (SSRG-IJCE), 1 (2014) 5, pp. 11-17.

[15] Strafaci, A.: What does BIM mean for strucutral engineers?, CE News, 20 (2008) 9, pp. 62-65, https://images.autodesk.com/adsk/files/what_does_bim_mean_for_civil_engineers_ce_news_1008.pdf.

[16] Sampaio, A.Z., Azevedo, V.: BIM in structural analyses of buildings, Proceedings of the 6th International Conference on Mechanics and Materials in Design, eds. Silva Gomes, J.F., Meguid, S.A., pp. 349-358, Ponta Delgada, Portugal, 2015.

[17] Mackey D.: BIM and Structural Engineering. Structure, 2017 (2017) January, pp. 46-49, https://www.structuremag.org/wp-content/uploads/2016/12/D-Business-Issues-Mackey-Jan17-1.pdf.

[18] Hamidavi, T., Abrishami, S., Hosseini, M.R.: Towards intelligent structural design of buildings: A BIM-based solution, Journal of Building Engineering, 32 (2020), https://doi.org/10.1016/j.jobe.2020.101685.

[19] Ciotta, V., Asprone, D., Manfredi, G., Cosenza, E.: Building Information Modelling in Structural Engineering: A Qualitative Literature Review, CivilEng, 2 (2021), pp. 765-793. https://doi.org/10.3390/civileng2030042

[20] Boechat, L.C., Correa, F.R.: Augmented BIM Workflow for Structural Design Through Data Visualization, Proceedings of the 18th International Conference on Computing in Civil and Building Engineering (ICCCBE) 2020, eds. Toledo Santos, E., Scheer, S., Cham, Switzerland, Springer, 2021, https://doi.org/10.1007/978-3-030-51295-8_15.

[21] Eleftheriadis, S., Mumovic, D., Greening, P., Chronis, A.: BIM Enabled Optimisation Framework for Environmentally Responsible and Structurally Efficient Design Systems, Proceedings of the 32nd ISARC, pp. aa1-9, Oulu, Finland, 2015, https://doi.org/10.22260/ISARC2015/0096.

[22] Patlakas, P., Livingstone, A., Hairstans, R., Neighbour, G.: Automatic code compliance with multi-dimensional data fitting in a BIM context, Advanced Engineering Informatics, 38 (2018), pp. 216-231, https://doi.org/10.1016/j.aei.2018.07.002.

[23] Kim, S., Ryu, H., Kim, J.: Automated and qualitative structural evaluation of floor plans for remodeling of apartment housing, Journal of Computational Design and Engineering, 8 (2021) 1, pp. 376–391, https://doi.org/10.1093/jcde/qwaa085.

[24] Wu, J., Zhang, J.: New Automated BIM Object Classification Method to Support BIM Interoperability, Journal of Computing in Civil Engineering, 33 (2019) 5, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000858.

[25] Lee, Y.-C., Eastman, C.M., Solihin, W.: Rules and validation processes for interoperable BIM data exchange, Journal of Computational Design and Engineering, 8 (2021) 1, pp. 97–114, https://doi.org/10.1093/jcde/qwaa064.

[26] Abualdenien, J., Schneider-Marin, P., Zahedi, A., Harter, H., Exner, H., Steiner, D., Singh, M.M., Borrmann, A., Lang, W., Petzold, F., König, M., Geyer, P., Schnellenbach-Held, M.: Consistent management and evaluation of building models in the early design stages. Journal of Information Technology in Construction (ITcon), 25 (2020), pp. 212-232, https://doi.org/10.36680/j.itcon.2020.013.

[27] Steiner, D.: Formulierung und Generierung von Expertenwissen zur Entwicklung intelligenter Ersatzmodelle für die Tragwerksplanung in frühen Entwurfsphasen (in German), Tagungsband 30. Forum Bauinformatik, eds. Steiner, M., Theiler, M., & Mirboland, M., Weimar, Germany, Bauhaus-Universität Weimar, 2018.

[28] Keough, I., Benjamin, D.: Multi-objective optimization in architectural design, SpringSim '10: Proceedings of the 2010 Spring Simulation Multiconference, San Diego, California, USA, Society for Computer Simulation International, 2010, https://doi.org/10.1145/1878537.1878736.

[29] Hamidavi, T., Abrishami, S., Ponterosso, P., Begg, D., Nanos, N.: OSD: A framework for the early stage parametric optimisation of the structural design in BIM-based platform, Construction Innovation, 20 (2020) 2, pp. 149-169, https://doi.org/10.1108/CI-11-2019-0126.

[30] Delavar, M., Bitsuamlak, G.T., Dickinson, J. K., Costa, L.M.F.: Automated BIM-based process for wind engineering design collaboration, Building Simulation, 13 (2020), pp. 457–474, https://doi.org/10.1007/s12273-019-0589-2.

[31] Sibenik, G., Kovacic, I., Petrinas, V., Sprenger, W.: Implementation of Open Data Exchange between Architectural Design and Structural Analysis Models, Buildings, 11 (2021) 12, pp. 605, https://doi.org/10.3390/buildings11120605.

[32] Birkemo, A.S., Hjortland, S.C., Samindi, S.M., Samarakoon, M.K.: Improvements for the workflow interoperability between BIM and FEM tools, Building Information Modelling (BIM) in Design, Construction and Operations III, eds. De Wilde, P., Mahdjoubi, L., & Garrigos, A., pp. 317 – 327. Southampton, UK: WITpress, 2019.

[33] Ramaji, I.J., Memari, A.M.: Interpreted information exchange: implementation point of view. Journal of Information Technology in Construction (ITcon), 25 (2020), pp. 123-139, https://doi.org/10.36680/j.itcon.2020.008.

[34] Haefner, L.: Nowadays Structural Engineering with the Use of BIM Technology—From 3D Modeling, Structural Analysis, and Design to Structural System Evolution: Practitioner Report, Structures Congress 2017: Business, Professional Practice, Education, Research, and Disaster Management, ed. Soules J.G., pp. 24 – 34, Reston, Virginia, USA, ASCE, 2017, https://doi.org/10.1061/9780784480427.003

[35] Aldegeily, M., Zhang, J.: From architectural design to structural analysis: a data-driven approach to study Building Information Modeling (BIM) interoperability, Proc., 54th ASC Annual International Conference, ed. Sulbaran, T., pp. 537-545, Fort Collings, Colorado, ASC Associated Schools of Construction, 2018, http://ascpro0.ascweb.org/archives/cd/2018/paper/CPRT152002018.pdf.

[36] Chi, H.L., Wang, X., Jiao, Y.: BIM-Enabled Structural Design: Impacts and Future Developments in Structural Modelling, Analysis and Optimisation Processes, Archives of Computational Methods in Engineering, 22 (2015), pp. 135–151, https://doi.org/10.1007/s11831-014-9127-7.

[37] Deng, X.Y., Chang, T.Y.P.: Creating structural model from IFC-based architectural model, Joint International Conference on Computing and Decision Making in Civil and Building Engineering, pp. 3687-3695, Montreal, Canada, 2006, https://itc.scix.net/pdfs/w78-2006-tf577.pdf.

[38] Qin, L., Deng, X.Y., Liu, X.L.: Industry foundation classes based integration of architectural design and structural analysis, Journal of Shanghai Jiaotong University (Science), 16 (2011) 1, pp. 83-90, https://doi.org/10.1007/s12204-011-1099-2.

[39] Papadopoulos, N.A., Sotelino, E.D., Martha, L.F., Nascimento, D.L.M., Faria, P.S.: Evaluation of integration between a BIM platform and a tool for structural analysis, Systems & Management, 12 (2017), pp 108-116, https://doi.org/10.20985/1980-5160.2017.v12n1.1203.

[40] Ren, R., Zhang, J.: A new framework to address BIM interoperability in the AEC domain from technical and process dimensions, Advances in Civil Engineering, (2021), https://doi.org/10.1155/2021/8824613.

[41] Wu, J., Sadraddin, H.L., Ren, R., Zhang, J., Shao, X.: Invariant signatures of architecture, engineering, and construction objects to support BIM interoperability between architectural design and structural analysis, Journal of Construction Engineering and Management, 147 (2021) 1, https://ascelibrary.org/doi/abs/10.1061/%28ASCE%29CO.1943-7862.0001943.

[42] ÖNORM: ÖNORM EN 1990:2013 03 15 Eurocode - Basis of structural design (consolidated version), Vienna, Austria, Austrian Standards, 2013.

[43] Udoeyo, F.: Structural Analysis, Philadelphia, Pennsylvania, U.S., Temple University Press, 2019.

[44] ÖNORM: ÖNORM EN 1991-1-1:2011 09 01 Actions on structures - Part 1-1: General actions - Densities, self-weight and imposed loads for buildings (consolidated version), Vienna, Austria, Austrian Standards, 2011.

[45] ÖNORM: ÖNORM B 1991-1-1:2020 12 01: Eurocode 1 - Actions on structures - Part 1-1: General actions - Densities, self-weight and imposed loads for buildings - National specifications concerning ÖNORM EN 1991-1-1 and national supplements, Vienna, Austria, Austrian Standards, 2020.

[46] ÖNORM: ÖNORM B 1991-1-3:2018 12 01 Eurocode 1: Actions on structures – Part 1-3: General actions - Snow loads, Vienna, Austria, Austrian Standards.