Automated Model Preprocessing for Structural Analysis

G. Sibenik[a], I. Kovacic[a] and V. Petrinas[a]

[a]Institute of Interdisciplinary Building Process Management, Technische Universität Wien, Austria
E-mail: goran.sibenik@tuwien.ac.at

Abstract

Numerous modelling and structural analysis workflows reflect the heterogeneity and vague standardization in the construction industry; hence their automation is not straightforward. Procedures like redefining geometry from scratch or assigning loads one-by-one, are mostly performed manually, are time-consuming and error-prone, reflecting traditional workflows in digital BIM environments. BIM tools for structural analysis, compared to finite element method tools, aim to automate and interrelate structural design, analysis and documentation. This paper investigates the potential and obstacles for automation of structural analysis workflows. We focus on automation of model preprocessing, the procedures which interrelate structural design and analysis.

Through literature review and a practical use case analysis, automatable procedures were identified and formalized. They were further verified in the experts' panel discussion. The results indicate that defining floor levels, loads and load combinations, supports and joints are standard model preprocessing procedures. In special cases, e.g. special grounding conditions or heavy machinery, manual overriding of automatically assigned values might be required. Lack of clarity and traceability in the structural analysis of a complete building model, and the lack of confidence in background processes in BIM analysis tools, are identified as the main obstacles for automation.

Finally, we deliver a prototype of the automated procedures with structural analysis software RFEM Dlubal, which exemplifies implementation. The automation of preprocessing is especially important for design optimization and time-dependent structural analysis during construction or demolition. This research contributes with an improvement proposal of BIM-based structural analysis thus enhancing the overall digitalization level of the building design process.

Keywords –
Preprocessing; BIM; Automation; Structural analysis

1 Introduction

The use of digital tools to perform structural analysis increased in the last decades; currently the tools are present in most structural analysis practices, although some analyses are still performed manually [1]. The building information modelling (BIM) paradigm gained on popularity among structural engineers, but the finite element method (FEM) tools, which have been used for a longer time, are not clearly distinct from the ones referred to as BIM structural tools. Automatic relations between structural design, analysis and documentation is found to be the main feature of BIM software tools [2]. These relations have not yet been fully realized, and significant manual work is necessary for the design tasks leading to structural analysis [1]. It is necessary to address the technical issues which will provide structural engineers with benefits promised by BIM [3].

Preprocessing of a building model involves data management procedures of assigning new information like loads or supports to create an analysis-ready model. In this paper, the procedures are called preprocessing methods if they are automatically performed. The procedures interrelate structural design and analysis, and automating them could reduce time, errors and cost needed for structural analysis. Achieving an automated relation between the design, analysis and documentation is the way to fully enable the BIM ideas in structural analysis software tools – therefore defining the preprocessing methods is unavoidable. Besides achieving the full BIM potential, the preprocessing methods allow for real-time feedback in the form of a quick preliminary structural analysis of the interpreted and imported physical building model originating from architectural design, as the manually performed time-consuming tasks are automated and the information necessary for the analysis is promptly assigned. Automated preprocessing of building models is a research gap addressed in this research

In our preceding research we developed a software tool which interprets building models for structural engineers [4]. The model which can be used for the analysis is prepared on the non-proprietary central storage and can be imported to any structural analysis tool which offers a way to access and manage its internal structure and data (e.g. via application programming interface (API)). A building model imported in such a way is not ready for structural analysis and assigning additional information is required. However, the information origin and the way it is defined remains in the gray area, and needs to be further investigated. Some design management literature exists which roughly indicates services provided by project stakeholders (e.g. [5]). The description of services does not reach the building element information level (such are objects and their properties); therefore the information assignment procedures within the workflow need to be investigated. Information origin provides the base for automation – focus is on the information assigned after the architectural model is interpreted and imported (analytical model with geometry and element types), and before the structural analysis takes place (analysis-ready model with supports and loads).

The next section presents a review of existing research regarding the automation of preprocessing procedures. Section 3 describes the research methodology, followed by the proposal of automation methods in section 4. Section 5 provides the example of implementation and section 6 the verification of the proposed methods via an experts' panel discussion. The results are discussed in section 7.

2 Literature review

The topic of automatic preprocessing of structural analysis models has not been widely addressed in the light of the existing design practices. Literature review performed in [6] shows how automation of structural analysis is becoming a more popular topic over the years, since the structural design automation and interoperability with other domains is of highest importance for the design process. In the academic community, new forms of design workflows are often proposed without consideration of the traditional approaches, especially in the early design phase. Reconsideration of traditional workflows is desired, however a complete paradigm shift has not received a positive feedback in practice [1]. The aim of this work is to provide a solution to automatically perform preprocessing steps existing in practice. Such tools have not been found for the developed design phase – however implementation of preprocessing in the early design phase or other domains such as tunnel engineering is addressed in the literature. The automatic preprocessing promises more design variants due to prompt structural analysis feedback, resulting with more optimal design, less errors and finally less time and money required for the whole project.

A design cycle lasts longer than a month for a single design alternative, the main limitation being unsuitable representation for analysis, whereby the engineers spend more than half of their time in managing information [7]. Automation of analysis of design alternatives is viewed as a solution to this problem. Focus of their work [7] is a multidisciplinary optimisation with numerous design variants, existing in the early design stage. Energy and structural optimisation in the early design stage is investigated in [8]. Compared to developed design, the early design lacks information for a detailed analysis, therefore tools used for performing energy and structural performance need to consider some uncertainties. Accordingly, models with varying amount of information, as required during the evolving designs, are proposed [8]. In our work, the focus is on developed design where a sufficient amount of data is usually available for structural analysis. However, a required data scope is hardly ever formalized on the level of building elements and belonging properties so it could be correspondingly validated.

Automating preprocessing steps for structural analysis is more common in infrastructural projects such as tunnel design than in the building projects. Similarly to BIM, [9] propose tunnel information modelling (TIM) which is able to unify multiple models relevant for tunnel design in an object-oriented manner. In their "BIM-to-FEM", tunnel design information is extracted and preprocessed for the FEM analysis, whereby the boundary conditions are automatically assigned based on the design data. A framework calculating wind effects on the building is developed in [10], recognizing the need for automatic geometry interpretation and analysis for such a repetitive and error-prone task.

A workflow common for structural analysis shows how significant amount of manual work could be avoided by relating it to the architectural model [11]. They present a fairly simple case study and describe how loads like self-weight and uniform design load are manually created for the analysis. A traditional design workflow is presented in [12], describing that from schematic design through design development the architectural design is generally imported to FEM tools. They propose a workflow supporting data analysis during the design, but focus on structural design and not structural analysis. A plug-in for structural analysis tool Robot developed in [13] supports structural engineers in performing optimization of a building structure. Most of the inputs are however assigned manually in the model.

Another form of automation of structural analysis is provided as a support tool for architectural design, by introducing structural knowledge to architectural design tools. Members and connections design can be realized in such a way [14]. However, this approach can hardly replace established structural analysis practices which rely on structural analysis software tools having a large market share. Additional tool in Matlab which helps architects in the early design stages to receive feedback for the renovation projects based on the floor plans is described in [15]. Their motivation are iterative requests on design feedback, which structural engineers usually provide only at the decided design, similarly to the developed design stage. Researchers [15] focus on the floor plans and walls as structural elements, which does not entirely correspond to the BIM approach in the developed design stage. Specialized knowledge regarding seismic performance of buildings is automated and described in [16]. They propose a platform that automates iterative steps usually performed by structural engineers to find optimal and satisfying structural design. Structural analysis practices for buildings during developed design are heterogeneous and have not been sufficiently explored. The automated preprocessing methods are not available except for methods provided by software tools which overcome software-specific problems in the form of workarounds. Research describing the structural analysis workflows and data requirements can be found, and will be considered in section 4. As the structural analysis practices differ, so do the ways to automate the model preprocessing procedures. Besides international standards, numerous project-, company- or country-specific standards exist defining the workflows leading to structural analysis. These standards have suited well the traditional practices, but leave plenty space for intuitive experience-based decision making which is not suitable for automation in such form [17]. The standards do not address objects used in the software tools.

Lack of technical solutions for structural analysis is evident from the literature review, especially for the developed design stage [3]; automated preprocessing and modelling of structural components is a research gap addressed in this research. The research question we address with this work is: “How to automatically preprocess a building model for structural analysis?”

3 Methodology

This paper is part of a larger project investigating data exchange between architectural design and structural analysis. In the preceding research, a tool interpreting an architectural building model was developed and implemented with multiple building models [4]. Building models containing geometry and information about element types created by architects are interpreted to representation suitable for structural engineers. The interpretations focused on geometric information and result with an analytical building model. This tool, although being a useful aid for structural engineers and saving significant amount of time needed for redefining information available in another form, does not provide structural engineers with an analysis-ready model. Additional information which is not available in architectural design model is required before the structural analysis can take place. The heterogeneity of design workflows makes automation of certain procedures difficult or even impossible. Hereby, the question of automating preprocessing procedures for structural analysis is addressed through several methodological steps:

- Pareprocessing methods are identified through literature review describing workflows to structural analysis on building element level and a real use case analysis of a modelling and data exchange process of a German structural engineering company. This analysis delivers information origin which is a base for formalizing preprocessing methods.
- Preprocessing methods are formalized so they could be automated with a data mangement tool. 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 which provide a desired result.
- Data management tool is developed as a prototype and the formalized methods are implemented. The tool maintains communication with the central data storage (realized with MongoDB) and facilitates the conversion to the particular structural engineering finite element calculation tool (RFEM Dlubal). The developed preprocessing methods are implemented and verified with a test building model originating from the above-mentioned structural engineering company.
- Finally, the feedback and evaluation of generalization-potential of implemented automation methods was assessed through practitioners’ panel discussion. Practitioners’ expertise is needed to identify optimization potentials as preprocessing rules are bound to individual or interfirm conventions.

4 Automatable procedures

The literature review and the use case analysis revealed information stemming from the architectural design as well as the information defined by structural engineers. Barely any information originates from the cooperative work between architects and structural engineers in a standard workflow, but a significant amount of information is of interest to both stakeholders. This analysis was used to propose the preprocessing methods.

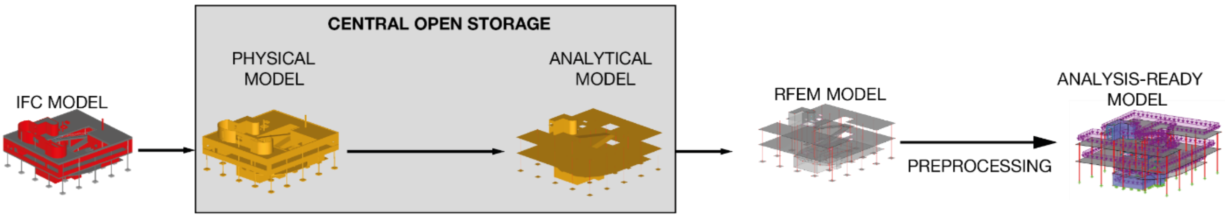


Figure 1 Overview of the workflow leading to structural analysis

4.1 Information origin

The information origin investigation is necessary to determine which preprocessing procedures are performed in the existing workflows in academia and practice - which information is assigned in the preprocessing part of the workflow. The preprocessing methods are depicted within the workflow (Figure 1), which also implies the software tools which will be used for their realization.

From the literature review of workflows presented in Table 1 it can be concluded that: geometry of all building elements enclosing a space, materials of building elements with visual properties and types of building elements, is delivered by an architect to a structural engineer. Occasionally, after the consultation with structural engineers, architects define the information about the load-bearing property of building elements, foundations and raster. The information which is usually not explicitly defined by the architect are the analytical geometry of structural building elements, loads, structural properties of materials, supports and structural connections of building elements. The architectural software tools generally do not provide ways to define that information.

Table 2 Information origin according to use case 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

Following the literature review, a use case analysis of the workflow leading to structural analysis has been performed. A use case analysis is performed with a German construction company, including the procedures of design, interpretation and preprocessing. It was conducted in a period of time of eight months through multiple interviews, observation of processes and continuous feedback through a team of company experts. The use case analysis delivered similar results to the literature review and they are summarized in Table 2. Analysis of processes showed that the engineers use 2,5d analysis characterized by multiple models based on slabs. They do not use a complete building model to perform the analysis, but divide the model into multiple models,

Table 1 Information origin according to literature review

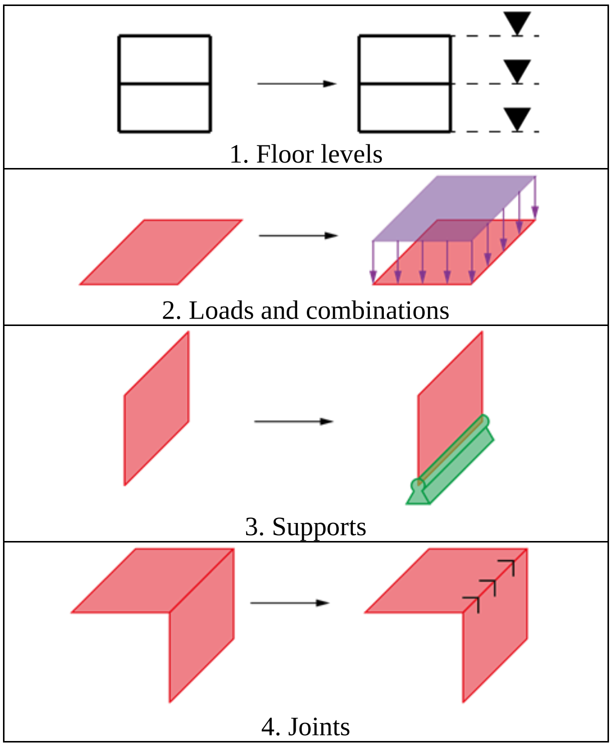
	Architect	**Structural engineer**
[18]	Geometry, location of the members, types of materials and properties	Load types and cases, boundary conditions
[19]	Drawings, initial dimensions, section sizes	Analytical models, structural properties, loads
[12]	Geometry	Section properties, boundary conditions, loads
[20]	Appearance – art, geometrical and spatial aspect	Simplified model, loading component and joint connections
[21]; [22]	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
[13]	Geometry (option 1)	Geometry (option 2), sections, supports, load cases
[23]	Geometry (physical model)	Loads and supports
[24]	Elevation, grids, geometry	Analytical model, material properties, section properties, boundary conditions, load information
[25]	Geometry, element connectivity, cross-sectional dimensions, material mechanical properties	Geometry and support creation, material definition, load assignment

according to the floor levels. While the horizontal load-bearing elements are represented as building elements, vertical ones are represented as loads or supports. Therefore, we account 2,5d approaches in the proposal of preprocessing methods.

4.2 Preprocessing methods

Based on the literature review and the use case analysis, it was concluded that four types of information are assigned after the data from architects is interpreted and recreated. Interpretation of information coming from the architects is addressed in more detail in our previous work [4]. New information realized through preprocessing methods involve the creation of floor levels characteristic for 2,5d analysis, load and load combination assignment, definition of supports and joints between the building elements. Table 3 depicts schematically the recognized methods, which are enumerated and described in the follow-up. This additional information is assigned to the analytical model directly within the structural analysis software tool.

Table 3 Proposal of preprocessing procedures



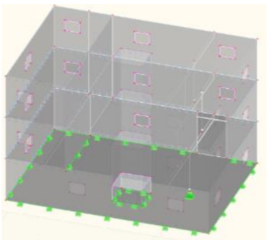
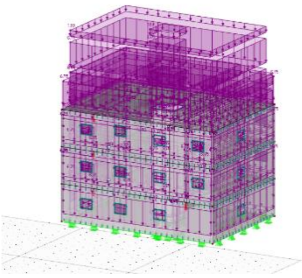
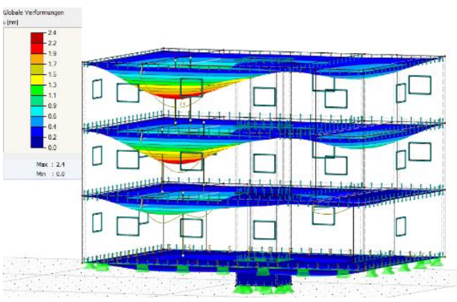
1. Based on the performed analysis, structural engineers do not rely on the analysis of a complete 3d building model, but rather perform 2,5d analysis. 2,5d analysis means identifying floor levels and modelling only slabs as building elements. Upper vertical elements are modelled as loads, while the lower vertical elements are modelled as supports. In our research we proceed with a 3d analysis as we consider it the future of assessing structural building performance; still, we identified the need to define floor levels in order to support the established practices. After the definition of floor levels further methods can be implemented.
2. Loads and load combinations need to be defined for structural analysis. Four types of loads can be assigned: dead, live, impact and environmental loads. Out of these four types, only impact-loads are not standard for each structural analysis. We identified that self-weight is a requirement for each building element as a dead load. Live loads are dependent on the use of space which is sometimes provided within a model by an architect, but on other times needs to be assigned by a structural engineer. Environmental loads affect the external elements of the building and are based on the environmental conditions of the geographic location. In the case of 2,5d analysis they are assigned to the top slab. Other loads are assigned floor-wise to each slab in the model.
3. Supports can sometimes be found in architectural models, but they are usually defined by structural engineers as they do not affect a building appearance. They are placed on the bottom of building elements and can be defined as points, lines or surfaces. We assign them to the lowest floor depending on the vertical elements above the slab.
4. Detailed descriptions of the way to define joints in the developed design phase was not found in the examined literature nor in the use case analysis since they were not present in the 2,5d approach (as only slabs are represented as building elements). Vertical elements represented as supports in 2,5d analysis partly indicate the joint behaviour, since supports have similar properties. In our work, joints are defined as pin-connected, not transferring the rotation in the case of column-slab connection, and the wall-slab connection can transfer rotation in the direction of a connection line. Joint definition is a complex topic highly influencing 3d analysis which has not been sufficiently investigated for all possible cases.

5 Prototype implementation

A prototype for RFEM plug-in has been developed that is able to preprocess a test building model. The plug-in is developed with RFEM Dlubal API and .NET Framework. It uses the Open Cascade geometry kernel to handle the geometrical information. The plug-in is linked to a central storage where information is stored in a non-proprietary format, and at the same time it is linked to

RFEM Dlubal internal storage and proprietary model. The preprocessing methods are therefore specific for a proprietary software tool, unlike the model interpretations taking place on the central open storage. It was possible to realize all methods with the prototype plug-in, and to perform a satisfying structural analysis in the follow-up. Table 4 shows screenshots of a test model with the results of preprocessing methods and analysis.
The methods are fully automated with default values, but allow some interventions, e.g. changing the use of space influencing the live loads, or the floor level where the environmental loads or supports are placed. These methods do not represent the exhaustive possibilities for structural analysis, however they represent most common procedures and aid structural engineers not to start from a blank model with their work. Additional enhancement are available in the further step directly within the RFEM Dlubal, these may however be integrated within the plug-in if recognized as standard for certain workflows.

Table 4 Test model after preprocessing and analysis

 Test model with assigned supports
 Test model with assigned loads and combinations
 Analysis results

6 Panel discussion

The panel discussion involved structural engineers from two companies. The feedback provided by the participants in the discussion addressed general issues regarding the preprocessing automation, as well as the specific preprocessing methods. The remarks were:

- 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 analysis, however the analyzed cross sections of building elements may be larger than in the case of 3d.
- 3d analysis delivers results which are difficult to verify due to lack of clarity of calculation in a structural analysis software tool. Traceability of analysis is demanded by inspection engineers, which is not provided 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 for identifying and analyzing the model.
- Feedback received from the participants recognizes the standardization potential in 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: i) as the proposed solution, under each element separately; ii) by excluding the support capabilities of a ground plate due to bad ground characteristics.
- 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 country-specific building codes.
- Joints can be modelled in two ways, depending on whether the i) prefabricated or ii) cast in place building system is used; the i) indicates that the rotation is not transferred; while ii) can transfer also rotation.

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.

7 Discussion & conclusion

Many manual time-consuming procedures are performed for each project from scratch, whereby these tasks are not only similar between the projects, but often across multiple practices. The amount of similarity across practices and a unique solution is hard to define due to lacking documentation and standards. This paper proposes preprocessing methods based on the existing research and practice, which have not been formalized for automation purposes. The new proposal is based on the literature review and use case analysis and is implemented as a prototype tool with a test building model. The tool was received with appreciation and is regarded as a benefit for structural engineering. Further investigation of heterogeneous practices is needed for providing a tool which would satisfy practices beyond the scope of this research.

The BIM paradigm regarding structural analysis tools is still unclear. This paper emphasizes the need for automation of preprocessing, and relating structural design and analysis in a digital and automated way in order to provide prompt feedback about structural building performance, save time and money and reduce errors during building design. The greatest problem in the proposed approach is found in the readiness of structural engineers to fully rely on the analysis with 3d geometry. However, an approach with automated preprocessing methods in a similar way, is recognized as beneficiary and required to improve structural analysis work.

One of the limitations of the provided solution is that it does not consider special cases of structural analysis, like special grounding conditions or heavy machinery. Numerous workflows and projects need to be analyzed in order to determine which workflows and procedures have automation potential. In order to generalize this proposal and the implemented prototype, certain adaptations and extensions based on the results of exhaustive studies might be needed. Unique problems might and will occur for certain building projects, but still, generalized solution needs to be able to cover standard procedures, while the special ones can be manually overridden. Supporting various practices might potentially be realized by using service-oriented system architecture like microservices [26].

Therefore, next steps regarding the software tool is to test the provided methods with additional building models. The methods will be tested with other structural analysis software tools and additional practices. Similar plug-ins are required for other tools, and the proposed prototype may serve as a base. A process analysis is required for each procedure which is to be automated. The proposals changing entirely the existing design workflows, have not been successfully accepted in the AEC community.

8 Acknowledgements

The authors would like to thank Strabag SE, Vienna, and their subsidiary Züblin, Stuttgart, for supporting this research through the project DATAFILTER. We would also like to thank ATP architekten ingenieure, Vienna, for taking part in the panel discussion.

9 References

[1] Stracke J. and Kepplin R. Der BIM-Prozess in der Tragwerksplanung. *Beton- und Stahlbetonbau*, 115: 324-331. 2020. https://doi.org/10.1002/best.201900097

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

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

[4] Sibenik G., Kovacic I., Petrinas V. From Physical to Analytical Models. Automated Geometry Interpretations, In Ungureanu L.C. and Hartmann T. (eds.), *EG-ICE 2020 Workshop on Intelligent Computng in Engineering*, Berlin, Germany, 2020.

[5] PMI - Project Management Institute *A guide to the Project Management Body of Knowledge (PMBOK guide) (6th ed.)*. Project Management Institute, Pennsylvania, USA, 2017.

[6] 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.

[7] Flager F., Welle B., Bansal P., Soremekun G. and Haymaker J. Multidisciplinary process integration and design optimization of a classroom building. *Journal of Information Technology in Construction (ITcon)*, 14: 595-612, 2009. http://www.itcon.org/2009/38

[8] 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. and Schnellenbach-Held M. Consistent management and evaluation of building models in the early design stages. *Journal of Information Technology in Construction (ITcon)*, 25: 212-232, 2020. https://doi.org/10.36680/j.itcon.2020.013.

[9] Alsahly A., Hegemann F., König M. and Meschke G. Integrated BIM to FEM approach in mechanised tunneling. *Geomechanics and Tunnelling*, 13: 212-

220, 2020. https://doi.org/10.1002/geot.202000002.
[10] Delavar M., Bitsuamlak G.T., Dickinson J. K. and Costa, L.M.F. Automated BIM-based process for wind engineering design collaboration, *Building Simulation*, 13: 457–474, 2020. https://doi.org/10.1007/s12273-019-0589-2.
[11] Bhusar A.A. and Akhare A.R. Application of BIM in Structural Engineering, *SSRG International Journal of Civil Engineering (SSRG-IJCE)*, 1:11-17, 2014.
[12] Boechat L.C. and Correa F.R. Augmented BIM Workflow for Structural Design Through Data Visualization. In Toledo Santos E. and Scheer S. (eds.) *Proceedings of the 18th International Conference on Computing in Civil and Building Engineering (ICCCBE) 2020*, Springer, Cham, Switzerland, 2021. https://doi.org/10.1007/978-3-030-51295-8_15.
[13] Eleftheriadis S., Mumovic D., Greening P. and Chronis A. BIM Enabled Optimisation Framework for Environmentally Responsible and Structurally Efficient Design Systems. In *Proceedings of the 32nd ISARC*, pages 1-9, Oulu, Finland, 2015. https://doi.org/10.22260/ISARC2015/0096.
[14] Patlakas P., Livingstone A., Hairstans R. and Neighbour G. Automatic code compliance with multi-dimensional data fitting in a BIM context, *Advanced Engineering Informatics*, 38: 216-231, 2018.. https://doi.org/10.1016/j.aei.2018.07.002.
[15] Kim S., Ryu H. and Kim J. Automated and qualitative structural evaluation of floor plans for remodeling of apartment housing, *Journal of Computational Design and Engineering*, 8: 376–391, 2021. https://doi.org/10.1093/jcde/qwaa085.
[16] Guan X., Burton H. and Sabol T. Python-based computational platform to automate seismic design, nonlinear structural model construction and analysis of steel moment resisting frames. *Engineering Structures*, 224, 2020. https://doi.org/10.1016/j.engstruct.2020.111199.
[17] Sibenik, G. and Kovacic, I. Interpreted open data exchange between architectural design and structural analysis models. *Journal of Information Technology in Construction (ITcon)*, 26, Special issue CIB World Building Congress 2019: Information technology of smart city development: 39-57, 2021. https://doi.org/10.36680/j.itcon.2021.004.
[18] Aldegeily M. and Zhang J. From architectural design to structural analysis: a data-driven approach to study Building Information Modeling (BIM) interoperability. In Sulbaran T. (ed.), *Proceedings of 54th ASC Annual International Conference*, pages 537-545, ASC Associated Schools of Construction, Fort Collings, Colorado, 2018. http://ascpro0.ascweb.org/archives/cd/2018/paper/CPRT152002018.pdf.
[19] Birkemo A.S., Hjortland S.C., Samindi S.M. and Samarakoon M.K. Improvements for the workflow interoperability between BIM and FEM tools. In De Wilde P., Mahdjoubi L. and Garrigos A. (eds.), *Building Information Modelling (BIM) in Design, Construction and Operations III*, pages 317 – 327. WITpress, Southampton, UK, 2019.
[20] Chi H.L., Wang X. and Jiao Y. BIM-Enabled Structural Design: Impacts and Future Developments in Structural Modelling, Analysis and Optimisation Processes. *Archives of Computational Methods in Engineering*, 22: 135–151, 2015. https://doi.org/10.1007/s11831-014-9127-7.
[21] Deng X.Y. and Chang T.-Y.P. Creating structural model from IFC-based architectural model. In *Joint International Conference on Computing and Decision Making in Civil and Building Engineering*, pages 3687-3695, Montreal, Canada, 2006. https://itc.scix.net/pdfs/w78-2006-tf577.pdf.
[22] Qin L., Deng X.Y. and Liu X.-L. Industry foundation classes based integration of architectural design and structural analysis. *Journal of Shanghai Jiaotong University (Science)*, 16: 83-90, 2011. https://doi.org/10.1007/s12204-011-1099-2.
[23] 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: 108-116, 2017. https://doi.org/10.20985/1980-5160.2017.v12n1.1203.
[24] Ren R. and Zhang J. A new framework to address BIM interoperability in the AEC domain from technical and process dimensions. *Advances in Civil Engineering*, 2021, 2021. https://doi.org/10.1155/2021/8824613.
[25] Wu J., Sadraddin H.L., Ren R., Zhang J. and 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. https://ascelibrary.org/doi/abs/10.1061/%28ASCE%29CO.1943-7862.0001943.
[26] Sibenik G., Kovacic I., Huyeng T.-J., Thiele C.-D. and Sprenger W. Microservice system architecture for data exchange in the AEC industry. In Semenov V. and Scherer R.J. (eds.) *ECPPM 2021 – eWork and eBusiness in Architecture, Engineering and Construction: Proceedings of the 13th European Conference on Product & Process Modelling* (1st ed.), CRC Press, London, UK, 2021. https://doi.org/10.1201/9781003191476