Doctoral Thesis

DATA EXCHANGE BETWEEN ARCHITECTURAL DESIGN AND STRUCTURAL ANALYSIS MODELS

submitted in satisfaction of the requirements for the degree of
Doctor of Science
of the TU Wien, Faculty of Civil Engineering

Dissertation

DATENAUSTAUSCH ZWISCHEN ARCHITEKTUR UND TRAGWERKSPLANUNG MODELLE

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines
Doktors der technischen Wissenschaften
eingereicht an der Technischen Universität Wien, Fakultät für Bauingenieurwesen
von

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Vienna, June 2022 _____

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Acknowledgements

This doctoral thesis was conducted as part of the Doctoral College Computational Design (DC:{CD}), supported by TU Wien, and projects Datafilter and AEContologies, supported and in cooperation with Strabag SE, Vienna. The work was carried out on the Institute for Interdisciplinary Building Process Management, Department of Integrated Planning and Industrial Building.

I would like to thank my supervisor Prof. Dr. Iva Kovacic for providing constant support during the duration of the research projects, and for the motivating and indispensable insights on each topic that came across. I am grateful for the given opportunity to pursue the doctoral thesis on the department.

I would also like to thank my second supervisor Prof. Dr. Georg Suter for the constructive criticism and for his valuable contribution to the doctoral thesis.

Research conducted with Strabag SE created an inspiring environment due to excellent cooperation with the team, where I would especially like to thank to Dr. Wendelin Sprenger for his time and effort in sharing his know-how and thoughts that helped keeping the projects on the right track.

Department of Integrated Planning and Industrial Building was a great environment to carry out the work, and I am grateful to all the colleagues that kept positive atmosphere and team spirit on both office and home-office days.

I would like to thank my family and friends, first of all my parents and my sister, for keeping up with the thesis topics which might be sliding out of their scopes of interest, sometimes providing valuable feedback and always providing more valuable support. This thesis would not be possible without them.

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Abstract

The AEC industry lags behind other industries when it comes to digitalization process. The concept of building information modelling (BIM) promises improved productivity, quality and efficiency of business by increasing the digitalization, primarily in the building design phase. In BIM workflows, multiple design phase stakeholders create, edit and exchange building models, but these activities still face multiple human, procedural and technological problems. Workflows are in practice heterogeneous, which makes it difficult to provide a single solution across the industry. One of the processes regularly facing difficulties is a data exchange between architectural design and structural analysis models. This data exchange is required from the early design phase, followed by multiple iterations in order to find an optimal building design. In case that BIM-authoring tools are used by architects and structural engineers, a model-based exchange is still not a common practice; structural engineers recreate a model, which is an error-prone, redundant and inefficient process. How to achieve a seamless data exchange between architectural design and structural analysis models is the main question of this work.

This doctoral thesis addresses several methodological steps that finally lead to a solution which facilitates a seamless data exchange between architectural design and structural analysis. The thesis is cumulative, based on four peer reviewed journal papers.

Initially, the obstacles within the existing technologies were identified through literature review and a comparative study. A framework based on software-independent data management that overcomes the identified obstacles is conceptualized and implemented after examining multiple data management solutions. The framework implementation was realized with a pilot use case building model; the verification tests the framework with additional two use case building models, originating from an external design office. Finally, the framework is extended with automatic preprocessing steps, required before the structural analysis, and validated through an expert panel discussion. The framework and resulting technological solution demonstrate a way to automate the data exchange process and support the existing BIM-based modelling practices and end-user requirements. It displays reduction of manually performed tasks and delivers valid structural analysis models with an open exchange process, which can be further extended to satisfy heterogeneous practices.

The innovative contribution of this thesis is that, rather than the existing academic and industrial solutions often focusing on single practices or proprietary software tool combinations, it recognizes the heterogeneity in the AEC industry. The proposed solution is based on the open data exchange approach and considers varying data management procedures between multiple domains and practices besides the varying data requirements. It can be linked to additional software tools (via APIs) and provide support for varying workflows (e.g. microservices). The novel framework integrates open inter-model procedures, which have been either counted out or taken as granted until now, although they are the main obstacle in the exchange between architectural design and structural analysis practices. This work emphasizes the need to document, standardize and automate the intuitive knowledge in the design workflows in order to realize the BIM promises. The digitalization in the industry needs to focus on the dynamical solutions within the design process, instead of focusing solely on the data-related issues.

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Zusammmenfassung

Die AEC-Branche ist im Vergleich zu anderen Branchen noch wenig digitalisiert. Das Konzept der Gebäudedatenmodellierung (Building Information Modeling - BIM) verspricht verbesserte Produktivität, Qualität und Effizienz der Geschäftsprozesse durch zunehmende Digitalisierung, vor allem in der Planungsphase. Planungsbeteiligte erstellen, bearbeiten und tauschen Gebäudedatenmodelle in BIM-Workflows aus, aber diese Aktivitäten sind immer noch mit zahlreichen menschlichen, prozeduralen und technologischen Problemen verbunden. Die Workflows sind in der Praxis heterogen, was eine einheitliche Lösung für die gesamte Branche erschwert. Einer der Prozesse, der regelmäßig auf Schwierigkeiten stößt, ist der Datenaustausch zwischen Architektur- und Tragwerksplanungsmodellen. Der domänenspezifische Datenaustausch zwischen Architektur- und Tragwerksplanung ist jedoch bereits in der frühen Entwurfsphase erforderlich, gefolgt von mehreren Iterationen, um einen optimalen Entwurf zu liefern. Ein modellbasierter Austausch ist immer noch keine gängige Praxis, wenn Architekten und Tragwerksplaner BIM-Authoring-Tools verwenden. In der Praxis erstellen Tragwerksplaner meist das Modell neu, was ein fehleranfälliger, redundanter und ineffizienter Prozess ist. Die Forschungsfrage, welche in dieser Dissertation verfolgt wird, lautet daher: Wie kann ein nahtloser Datenaustausch zwischen Architektur- und Tragwerksplanungsmodellen erreicht werden?

Diese Dissertation befasst sich mit den erforderlichen methodischen Schritten die einen nahtlosen Datenaustausch zwischen Architektur und Tragwerksplanung ermöglichen. Die Arbeit ist kumulativ aufgebaut und basiert auf vier Peer Review unterzogenen Zeitschriftenartikeln.

Zunächst wurden die Hindernisse der bestehenden Technologien durch eine Literaturrecherche und eine Vergleichsstudie identifiziert. Nachdem mehrere Datenverwaltungslösungen untersucht wurden, wurde ein Framework konzipiert und implementiert, welcher auf einer softwareunabhängigen Datenverwaltung basiert und derzeit identifizierte vorherrschende Hindernisse überwindet. Das Framework wurde anhand eines Pilotstudien-Gebäudemodells implementiert. Die Verifizierung des Frameworks wurde durch zwei weitere Gebäudemodelle, welche von einem externen Planungsbüro stammen, durchgeführt. Abschließend wurde der entwickelte Datenaustausch-Framework durch automatische Vorverarbeitungsschritte, die für eine statische Berechnung erforderlich sind, erweitert, und durch eine Paneldiskussion mit Experten validiert. Das präsentierte Framework und die daraus resultierende technologische Ausführung zeigen wie der Datenaustauschprozess zwischen Architektur-, und Tragwerksmodellen automatisiert werden kann. Weiters können dadurch bereits bestehende BIM-basierte Modellierungspraktiken erweitert, sowie Anforderungen der Endnutzer in der Praxis unterstützt werden. Die Ergebnisse zeigen, dass das Framework unterstützt manuell ausgeführte Aufgaben im Prozess zu verhindern. Durch den offenen Austauschprozess entstehen korrekt modellierte Tragwerksmodelle, welche in Zukunft weiter ausgebaut werden können um die heterogenen Praxen zu ermöglichen.

Der innovative Beitrag dieser Dissertation besteht in der Anerkennung der Heterogenität in der AEC-Branche, im Gegensatz zu den bestehenden akademischen und industriellen Lösungen, die sich oft auf einzelne Praktiken oder Kombinationen proprietärer Software-Tools konzentrieren. Die vorgeschlagene Lösung basiert auf dem offenen Datenaustausch und berücksichtigt neben den verschiedenen Datenanforderungen auch die verschiedenen Datenverwaltungsprozeduren zwischen den Domänen und Praktiken. Die entwickelte Technologie kann mit zusätzlichen Software-Tools (über APIs) verbunden werden und unterschiedliche domänenspezifische Arbeitsabläufe unterstützen (z.B. Microservices). Das neuartige Framework integriert offene Prozeduren zwischen Modellen, die bisher entweder ausgeklammert oder als selbstverständlich angenommen wurden,

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obwohl sie das Haupthindernis für den Austausch zwischen Architektur und Tragwerksplanung darstellen. Diese Arbeit unterstreicht die Notwendigkeit, intuitives Wissen in den Planungsprozessen zu dokumentieren, zu standardisieren und zu automatisieren und dadurch derzeitige BIM-Potentiale tatsächlich zu realisieren. Die Digitalisierung in der AEC-Industrie muss sich auf die dynamischen Lösungen innerhalb des Planungsprozess konzentrieren, anstatt ausschließlich die datenbezogenen Probleme zu lösen.

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Abbreviations

AEC – Architecture Engineering Construction

AECO – Architecture Engineering Construction and Operation

AP – Application Protocol

API – Application Programming Interface

BIM – Building Information Modelling

BRep - Boundary Representation

CAD – Computer Aided Design

CSG - Constructive Solid Geometry

CV V2.0 – Coordination View Version 2.0

FEM – Finite Element Method

GUI – Graphical User Interface

IDM – Information Delivery Manual

IFC – Industry Foundation Classes

ISO – International Organization for Standardization

JS – JavaScript

JSON – JavaScript Object Notation

KM – Knowledge Management

MVD – Model View Definition

OC – Open Cascade

OSEP - Open Source EXPRESS Parser

OWL - Web Ontology Language

RDF - Resource Description Framework

ROI – Return of Investment

RQ – Research Question

SME – Small and Medium-size Enterprises

STEP – STandard for Exchange of Product model data

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Glossary

BIM

A joint digital knowledge domain supporting activities of all stakeholders in AEC; based on various data models with geometrical and/or non-geometrical information; allowing data generation, exchange and processing within the lifecycle of built structures.

Workflow

All the steps from the project inception until the demolition in the AEC industry.

BIM workflow

All the steps from the project inception until the demolition supported with BIM technologies.

Data exchange

A process of restructuring and translating data structured under one schema (source schema) into an instance of a different schema (target schema). Data exchange is used in many tasks that require data to be transferred between existing, independently created applications. (Fagin et al, 2005)

Proprietary

Owned and legally controlled by a particular company.

Open

Accessible without proprietary software tools.

Closed

Accessible with proprietary software tools.

Open BIM

A workflow that involves BIM-authoring software tools where a non-proprietary format accessible by a third party is used for data exchange purposes.

Closed BIM

A workflow that involves BIM-authoring software tools and does not allow information access to a third party during a data exchange process without a proprietary software tool.

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Interfaces

A point where two systems meet and can communicate; in the case of data exchange: a point where data is transformed from one to another schema.

Data exchange framework

A basic structure used for a data exchange process, or the way how a communication is achieved. That could be a non-digital communication like handover of printed plans, or a digital data exchange based on e.g. direct communication between software tools, communication through single or multiple files, communication through a server or similar digital tools.

Classification

Systematic arrangement of data in groups or categories according to established criteria. (Merriam-Webster 2022)

Taxonomy

A hierarchical structure to classify information (van Rees 2003)

Ontology

A specification of conceptualization (Gruber 1993)

Formal, explicit specification of shared conceptualization (Studer et al 1998)

Interpretation

Deriving data in the form required by a certain application from existing available data in another form (Bazjanac and Kiviniemi 2007). Can also be referred to as data transformation.

Declarative knowledge

“Knowing-that” or systemic information of one system related to information about another system at an instant of time (de Giorgio 2020).

“Concepts, terms and taxonomy for articulating, classifying and structuring things and phenomena in a logical mental representation” (Lee 2022).

Procedural knowledge

“Knowing-how” or a variation of information about another system between two instants of time (de Giorgio 2020).

“Skills for efficiently and effectively solving problems” (Lee 2022).

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Structure

This thesis is conducted and presented as a cumulative dissertation. The first part of the dissertation introduces the problematics of a model-based data exchange between architectural design and structural analysis. It includes problem statement, research question and research scope; it is followed by the analysis of the existing research, industry and technology. The objectives of the dissertation are described next. The research design is presented together with the methodology used in each step of the research. The methodological steps are reflected in four research papers, each of them answering a specific research question. The introductory section concludes with a summary of dissertation contributions, limitations and future research.

The second part of the dissertation are the publications, which describe the developed methods in detail.

Publication 1:

"Assessment of model-based data exchange between architectural design and structural analysis", *Journal of Building Engineering*, Volume 32, Goran Sibenik and Iva Kovacic (2020)

This paper unveils the existing challenges in the data exchange process between architectural design and structural analysis models. The data exchange process between architectural design and structural analysis models can be realized in multiple ways, however, it is generally not realized as a model-based data exchange in current practices. The model-based exchange still requires a significant effort to be achieved compared to a manual remodelling. Multiple approaches to data exchange, such as direct, software-specific exchange, and open data exchange were considered. The limited number of proprietary solutions facilitating data exchange excludes numerous combinations of software tools. As the AEC industry is characterized by small and medium-sized enterprises (SME) individually choosing software tools, it is not realistic to expect that the software-specific solutions will manage to cover all possible combinations in the future. On the other hand, open data exchange solutions provide a way to deal with data exchange issues between numerous combinations, and reduce the number of required software-specific implementations. Hence, the open data exchange solutions are the focus of this paper, and the open solutions were considered in the rest of this dissertation.

The most common solution for the data exchange between architectural design and structural analysis is industry foundation classes (IFC) standard. Therefore the objective of the paper is narrowed to the identification of obstacles in the IFC-based data exchange. By closely investigating the existing problems, the issue of missing interpretations between domain-specific models is identified as the most crucial one.

Publication 2:

"Interpreted open data exchange between architectural design and structural analysis models", Journal of Information Technology in Construction, Volume 26, Goran Sibenik and Iva Kovacic (2021)

In this paper a novel data-exchange framework is proposed and described. Proposal of a novel framework is closely related to the identified obstacles in the existing technologies. The main feature of the framework is to facilitate the interpretations between domain-specific models. Problematic aspects of the existing data exchange framework are tackled with the features of the novel proposal. The first feature of the novel proposal is to allow for domain-specific classification, since the existing classifications used in the IFC-based open exchange does not represent requirements of any

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particular domain. Domain-specific classification is required in order to realize the interpretations between the domains. The interpretations reflect currently intuitive knowledge-based interpretations, which have not been widely documented until now. Finally, the domain specific models still need to be linked with the proprietary software tools. The framework consisting of classification, interpretation and automation is proposed to solve the issues in the existing data exchange practices.

Publication 3:

"Implementation of open data exchange between architectural design and structural analysis models", Buildings, Volume 11(12), Goran Sibenik, Iva Kovacic, Valentinas Petrinas and Wendelin Sprenger (2021)

System architecture supporting the novel framework was realized by considering the standards, software tools and practices in the AEC industry for the data exchange between architectural design and structural analysis, as well as the existing data management solutions in other domains and industries having higher digitalization level. System architecture reflects all three parts of the novel framework: classification, interpretation and automation. Multiple software tools are newly developed and combined with the existing ones in order to realize a suitable system architecture solution. Autodesk Revit is chosen as the software tool providing the architectural design model, and RFEM Dlubal as the importing structural analysis tool; resulting system architecture is defined for the data exchange between these two software tools. Out of the numerous possibilities to realize the desired framework, a combination of self-made software tools was developed primarily based on MongoDB semi-structured database, .Net framework with C# for the data management with Open Cascade (OC) libraries, RFEM Dlubal API, and a hybrid definition of IFC and OC classes for building model classification. The system architecture is realized with a single pilot building model, and verified with two additional external models.

Publication 4:

"Automated preprocessing of building models for structural analysis", Gradjevinar, Volume 74(3), Goran Sibenik, Iva Kovacic, Valentinas Petrinas, Wendelin Sprenger, Dario Bubalo and Nikola Ruzicic (2022)

The novel framework was optimized by extending it with additional functionalities. The extension is a support for preprocessing steps before the structural analysis takes place. It allows for automatic setup of an imported analytical model for structural analysis. Automated assignment of levels, loads, joints and foundation was realized with the newly developed RFEM plug-in. This extension questions the possibility of an automatic and prompt structural analysis feedback by rounding-up a one-directional data exchange process, from the architectural design model to structural analysis. The extension is verified through a panel discussion, where its use in differing workflows is considered.

Figure 1 depicts the research papers and the addressed topics.

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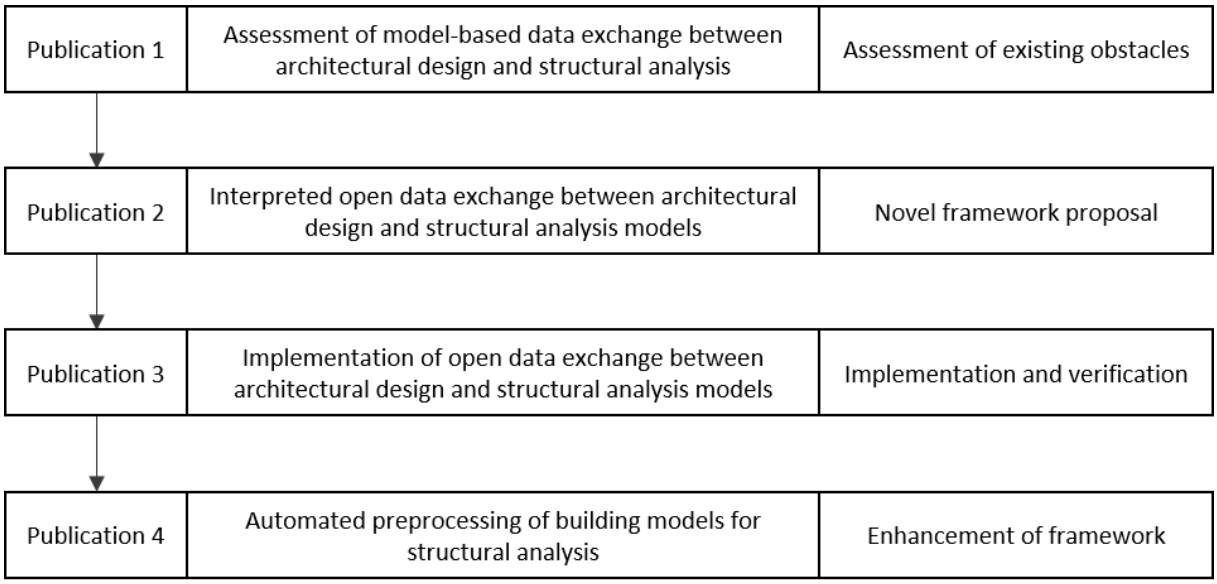

Figure 1 Research papers overview

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PART I

OVERVIEW

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1. Introduction

1.1. Problem statement

The increasing digitalization, in particular implementation of BIM bears a promise to reduce building project cost and time thus increasing quality (Sacks et al 2018). However the implementation of BIM is burdened with numerous challenges; most of all with the lack of software interoperability and data exchange problems (Grilo and Jardim-Goncalves 2010). Further on, there is no single definition of BIM (Succar 2009, Bolpagni 2022), as diverse opinions and perspectives on the topic exist. BIM is considered a planning tool as well as a method; it is considered an information modelling process, as well as an information management; it is considered a modelling process and a model.

Through software developers and regulative bodies the terms of closed BIM and open BIM have been established in the practice. Thereby closed BIM is defined as a BIM process where data exchange is achieved using an interface between software tools – a data exchange format remains proprietary between the two software tools. The open BIM standardizes the data exchange process with an open standard as a data exchange format. However, the original data remains proprietary. The original data is still not accessible, and remains embedded in the authoring software tool. The AEC industry is characterized by stakeholders in the form of SME, which perform domain-specific tasks and independently choose out of numerous software tools. Open BIM requires a single interface for each software tool in the collaborative design ecosystem, and therefore shows greater potential in achieving a seamless data exchange across the industry since closed BIM needs an interface for each combination of communicating software tools.

Based on Bazjac and Kiviniemi (2007), a seamless exchange and/or sharing means “direct data exchange and/or sharing among software applications in the AEC industry”, where “direct” means without end-user intervention. They claim that rules of data transformation need to be coded in software tools and provide unambiguous interpretations. They use the term interpretation for the case when the data is not provided in the form needed by end users, but can be derived from the existing data through interpretation. This process is called data parsing or transformation as well. A single and unambiguous interpretation of data without human intervention would not be able to satisfy the heterogeneity of existing workflows. At the moment, there is no consensus on some interpretations, multiple correct solutions exist and therefore an end-user input is required. Nevertheless, by automating repetitive tasks in the process through interpretation rules, the need for human interventions and errors and omissions caused by manual data transformation would be reduced. In this dissertation, a seamless data exchange is perceived as an exchange without errors and omissions, where manual data transformation is not excluded but minimized.

The main requirement for a data exchange with open BIM between architectural design and structural analysis would be providing a sufficient set of original data in the form of open data, which is relevant for structural analysis, and transfer it in a correct form to a receiving software tool. This data needs to be modified to correspond the requirements of structural engineers. Thereby, one problem regarding the implementation of open BIM concept and digitalizing the data exchange process in the AEC industry is the insufficiency of original data (data remains accessible only within the software platform), while the second one is erroneous representation of the existing data in the receiving software tools; which prevents a seamless data exchange between architectural design and structural analysis models. This dissertation aims to solve a **problem of a seamless data exchange** between architectural design and structural analysis with the concept of open BIM, which would be able to satisfy the ecosystem of heterogeneous workflows and software tools during a building design process. The main motivation comes from a typical data exchange scenario during the spatial coordination phase, previously called developed design phase. In this phase, engineering

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requirements are incorporated into the architectural concept, typically respecting building regulations and resulting with an application for a building permit. In the spatial coordination phase sufficient information is provided for structural analysis during the architectural design, however, only in exceptional tailor-made workflows this information is also exchanged and redundant, costly and time-consuming manual tasks avoided. The dissertation focuses on a one-way exchange, from architectural design to structural analysis, using commonly found building models as described in Section 1.3.

1.2. Research question

In the AEC practices multifold digital models exist to support design, analysis and simulation tasks. Each model is used for a specific task or for a specific set of tasks. The prerequisite to perform a task is that a model contains a sufficient amount of information. Tasks that need to be performed vary domain-, company-, software- or even end-user-wise. The required model information needs to satisfy the specific needs of the task that is performed. There are partial overlaps between various models / sets of information. Digital data exchange can be used to transfer the shared sets of information between the models used by various stakeholders. In that way, the error-prone redefining of information by an end user would be avoided. The seamless data exchange between the actors in the process would reduce communication-based errors and planning time, and it is a requirement for achieving a full potential of BIM.

Architectural design and structural analysis models differ in several aspects. The required amount of information in the models is standardized for the particular planning phases, but these standards can differ between the countries; this dissertation focuses on Austrian and German standards and practices. The scope of information needed for a definition of a building element differs not only between the domains, but also between software tools within one domain. However, a significant share of information can be found in both models; structural engineers develop structural analysis models based on the information in architectural design models. In order to achieve a seamless transfer of data from one to the other model the missing links in the existing digital solutions need to be identified. Therefore, the existing links in traditional data exchange practices, which are still mostly used in their digitized form, as well as the obstacles in the BIM-based exchange must be investigated. Current regulations do not define the communication between various domains to the level where they could be automated; therefore the data exchange process is often defined by software developers. Due to the lack of standards and ambiguous interpretations, transfers between software tools result in inconsistent models where different inconsistencies can be found in each software tool combination. With this dissertation the aim is to explore and improve the data transfer between architectural design and structural analysis. The aim is to reduce the inconsistencies and direct the exchange process towards the seamless exchange, contributing to the body of knowledge in BIM research with the concept of a successful exchange between the architectural design and structural analysis model, regardless of the software tool.

The main research question addressed in this dissertation is:

How to achieve a seamless data exchange between architectural design and structural analysis models?

Model-based data exchange processes are generally achieved between two software tools, with or without an intermediate data exchange format. The exchange processes between the sets of information are not seamless, although the term seamless considers the exchange being errorless and not necessarily completely automated. The software to software data exchange interfaces do not provide sufficient flexibility for the various end users / domains involved in the process of

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exchange in the AEC industry. Through software to software data exchange, the use of data is limited for the end user. Software to user interfaces provide the possibility for the end user to manipulate the data stored in the central storage. Open central storage means that the end users can access and modify the schema and the schema-based data. The open data storage allows for the data generation, transfer and processing independent of the used software tools. An open software to user data exchange is flexible because it allows end users to define and modify the exchange process. Data unavailability excludes multiple tasks in the AEC workflow, and limits the planning process to the processes provided by software developers. The lack of open software to user data exchange approaches causes various problems, e.g. loss of parameters that define the geometry, missing elements required for a domain-specific data exchange, schema not corresponding to software tool requirements or user concepts. In order to provide for a successful data storage, handling and analysis, independent of software vendor/platform new approaches and technologies supporting and enabling the BIM concept will be examined. Therefore, the analysis of the problems will be followed by a novel framework proposal, based on the open exchange, and its implementation, verification and enhancement. Additionally to the main research question, several questions will be addressed through four research papers:

Which drawbacks in the existing technologies hinder seamless data exchange between architectural design and structural analysis models?

Which framework concept satisfies requirements for seamless data exchange between architectural design and structural analysis?

How can the novel framework proposal for a data exchange between architectural design and structural analysis be implemented?

Can the proposed framework be optimized with additional functionalities?

1.3. Research scope

Building design in the AEC industry is a broad concept consisting of numerous workflows, phases, domains, stakeholders. Data exchange between architectural design and structural analysis alone can be performed during multiple planning phases, involve numerous structural systems and building elements, having various geometries and materials. The focus of this dissertation is a spatial coordination phase, structural system with bearing columns and walls, with typical geometries and materials. Limited scope of some of the most commonly occurring building elements and geometries is investigated in this research. Innovative materials, geometries and structural systems are constantly occurring in the building construction, and predefining rules for all possible combinations represents a cumbersome, possibly impossible task. However, predefined rules for the most commonly occurring data transformation would significantly reduce modelling time and errors, and in some cases even provide a fully automated data exchange. Exhaustive set of interpretation rules is not necessary to improve the data exchange process for most of building designs.

1.3.1. Planning phase

The analysis of an AEC workflow shows that the architectural and structural models are created during three planning phases (RIBA 2020): from the concept design, through the spatial coordination to the technical design. It has not yet been clearly defined how the models are handled, when are they created and which amount of information they contain throughout the phases, but the idea behind BIM is that the models are used during the entire building life-cycle. The first exchange of information between architectural design and structural analysis takes place in the concept design phase. However, most commonly, the structural engineers serve as consultants at this phase, by

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identifying and calculating only the potentially critical spots in the design. The information scope defined during the concept design phase varies depending on the project. It may not contain enough information about the structural concept, excluding the data exchange to the structural analysis. Therefore the usefulness of the BIM-based data exchange varies between the phases, and might not take place in the concept design.

Information exchange between the architectural design and structural analysis takes place regularly during the spatial coordination. In this phase, the architects already define sufficient amount of information for a detailed analysis of the structural system. Because of that, the spatial coordination phase is the focus of this thesis. Iterative exchanges are required to support the frequent changes during the design process in order to deliver an optimal solution. Although the information is bidirectionally exchanged between architectural design and structural analysis, in this work only the direction towards the structural analysis model is considered, because the aim is to support the initial data transfer. The exchange in the opposite direction, as well as the additional model changes face new problems such as data change authorizations and require additional research. However, the extension of the framework with model updates will be required in the future to support continuous seamless data exchange in the design process.

Data exchange between architectural design and structural analysis is important in the technical design phase as well. The concepts exchanged during the technical design phase are similar to the concepts in the spatial coordination. Therefore, by addressing the problems occurring in the spatial coordination, same solutions can be tested for the technical design phase. Manufacturing and construction, handover and close out and use phases are not part of this work, although a seamless data exchange would provide some great benefits in those phases as well, such as time-dependent structural analysis during construction.

1.3.2. Structural system

The focus is on structural systems that are the most common in the construction industry, the systems with bearing walls and columns which transfer loads vertically to the ground, and slabs and beams which receive the loads and transfer them to the bearing walls and columns. Besides the commonly implemented structural system, the scope of this dissertation is limited to commonly used building elements, corresponding geometries and materials. Automating a data exchange of seldomly occurring structural systems requires additional cost-benefit analysis, as manual interpretation could be faster and cheaper compared to the automation of interpretation rules.

1.3.3. Building elements

Architectural models in the spatial coordination phase consist of all building elements described to the specific level of detail required for the building permit. The scope of this dissertation limits the data exchange requirements to some common building elements: floors, walls, columns, beams, roofs and openings. Other types of building elements that may result from architectural design will not be part of this dissertation. The listed elements with the properties required for the data exchange were sufficient for the implementation and verification of system architecture that is hereby realized. Additional building elements or concepts specific for structural engineers will be considered for the preprocessing procedures such are foundations or joints.

1.3.4. Geometry

Regarding the geometries of building elements, this dissertation is limited to the building elements with constant cross section and thickness. Columns with rectangular and circular cross-sections, beams with rectangular cross-sections, straight and rounded walls, and flat and tilted slabs will be

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considered. Such shapes will be addressed based on their representation in the native software tool, although there are multiple ways to define same shapes, only the ones identified in the models will be considered. Other and more complex geometries in the construction projects will not be investigated in this dissertation. The complexity of geometry found in architectural design models can significantly differ between building projects and practices. The scope of investigated geometries is limited to the standard shapes as they make the majority of building elements used in practice, due to lower complexity of construction and cost, and less modelling issues. This dissertation will be conducted by keeping in mind the future extensibility of the framework and system architecture towards more complex shapes. Complex geometries would require more complex interpretation rules, and the benefit of having predefined interpretations remains the greatest with the standard geometries due to their prevalence in building models.

1.3.5. Materials

The researched geometries are with the constant cross sections and thicknesses, and concrete, brick, and wood are common materials that are used in practice for elements with these geometries. The most used materials in the construction industry are concrete, wood and steel. Steel is used primarily for linear elements such as columns and beams, but rarely has constant rectangular cross sections. Therefore, the materials addressed in the dissertation will be concrete and wood, and the rules for material transfer and interpretation between the two disciplines will also be investigated. The scope of materials used for building construction is constantly expanding, but the most commonly used ones like concrete, wood and steel still cover the majority of load-bearing building elements.

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2. Background

2.1. Digitalisation of AEC planning process

A great development potential regarding the digitalization of processes in the construction industry is far from exhausted. From the statistics provided by Roland Berger (2016), the actors in the process agree that the digitalization will affect every process in the industry. At the same time less than 6% are making the full use of the digital planning tools (Roland Berger 2016). The construction industry has to face the digitalization trends, where each company has to find its own place in the process. By neglecting the development of processes through digitalization, the companies are risking to be overtaken by the competitors. The EU laws are already imposing the use of BIM in the governmental projects. It is the matter of time when the actors which stay with the old technologies will not be able to follow the development. Roland Berger (2016) identifies four key aspects of digital transformation: digital data, automation, connectivity and digital access. When talking about the planning process, it is mostly about BIM as a standard of digitalization of the planning processes. In the following graph (Figure 2) a relation between using the 2d, 3d, BIM 3d and BIM 4d models is described. These planning methods can be seen as digitalization level as BIM 4d incorporates BIM 3d, BIM 3d incorporates 3d models, and 3d models 2d drawings.

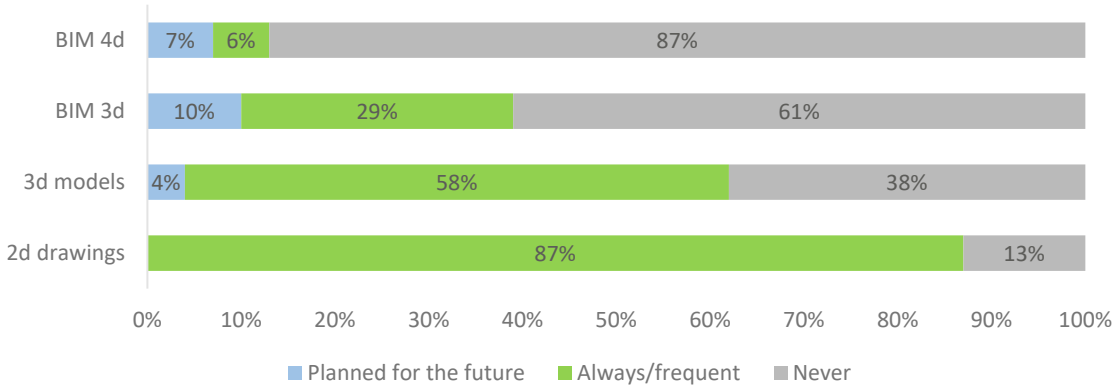

Figure 2 Use of different planning methods in the AEC industry in 2015 in Germany (redrawn from Roland Berger 2016)

Besides achieving a greater productivity, the digitalization of the AEC industry has the potential to solve various problems that still affect the industry: reduction of waste, improving energy efficiency, deficiencies detection, automatic monitoring of equipment, etc. The digitalization would introduce added value that induces innovation reflected in new methods and processes for the industry. Focus is on the particular aspect of the data exchange, which aims to be digital and seamless within BIM workflows. However, the term BIM has different definitions across the industry.

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2.1.1. BIM definitions

There are numerus definitions of BIM in practice and academic research, most likely due to varying professional languages of the partaking domains and highly fragmented industry. As architects' primary focus is on the modelling process and getting in grip of spaces and geometries, so is the data exchange and data accessibility a primary focus of project managers and quantity surveyors. BIM was first mentioned in the early 90s as building information model, and later the term building information modelling was used more frequently (Deng et al 2021). The term "building description system" as in Eastman (1976) had been used with a similar meaning before BIM.

Common definitions reflect various needs and mindsets of numerous professional domains in the heterogeneous AEC industry; such as e.g. focus on 3d modelling, or on data exchange process. The problem of poor lexical literacy when speaking of BIM has already been recognized in the academic community (Succar 2009, Bolpagni 2022). Table 1 lists various considerations under the term BIM.

Table 1 BIM definitions in academia and industry

Autodesk 2021	The holistic process of creating and managing information for a built asset. Based on an intelligent model and enabled by a cloud platform, BIM integrates structured, multi-disciplinary data to produce a digital representation of an asset across its lifecycle, from planning and design to construction and operations.
Borrmann et al 2015	Idea of a consistent use of a digital building model across the life-cycle of a building - from the concept, through planning and construction, to the use of the building.
Eastman 1976	A building description system can be viewed as a large information system encompassing database, routines for entering and editing the database contents, and report generating facilities. (building description system precedes BIM term)
GSA 2007	Development and use of a multi-faceted computer software data model to not only document a building design, but to simulate the construction and operation of a new capital facility or a recapitalized (modernized) facility.
ISO 2015	Construction of a model that contains the information about a building from all phases of the building life-cycle.
ISO 2018	Use of a shared digital representation of a built asset (includes, but not limited to: buildings, bridges, roads, process plants) to facilitate design, construction and operation processes to form a reliable basis for decisions.
NBS 2016	Process for creating and managing information on a construction project across the project life-cycle. One of the key outputs of this process is the building information model, the digital description of every aspect of the built asset. This model draws on information assembled collaboratively and updated at key stages of a project. Creating a digital building information model enables those who interact with the building to optimize their actions, resulting in a greater whole life value for the asset.
NIBS buildingSMART alliance 2015	Business process for generating and leveraging building data to design, construct and operate the building during its life-cycle. BIM allows all stakeholders to have access to the same information at the same time through interoperability between technology platforms / digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life-cycle from inception onwards / organization and control of the business process by utilizing the information in the digital prototype to effect the sharing of information over the entire life-cycle of an asset. The benefits include centralized and visual communication, early exploration of options, sustainability, efficient design,

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	integration of disciplines, site control, as built documentation, etc. – effectively developing an asset life-cycle process and model from conception to final retirement.
Penttilä 2006	Set of interacting policies, processes and technologies generating a methodology to manage the essential building design and project data in digital format throughout the building's life-cycle / methodology to manage the essential building design and project data in digital format throughout the building's life-cycle.
RIBA 2012	Digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it forming a reliable basis for decisions during its life-cycle, from earliest conception to demolition.
Sacks et al 2018	A modeling technology and associated set of processes to produce, communicate, and analyze building models.
Succar 2009	Expansive knowledge domain within the Architecture, Engineering, Construction and Operations (AECO) industry / emerging technological and procedural shift within the AECO – a new CAD paradigm / catalyst for change poised to reduce industry's fragmentation, improve its efficiency, effectiveness and lower the high costs of inadequate interoperability.

For the purpose of this dissertation, a BIM definition is constructed that encompasses the previously described definitions of BIM. In that way, a concept of BIM is defined that should be reached in order to have a complete BIM implementation in the industry:

BIM is a joint digital knowledge domain supporting activities of all stakeholders in AEC; based on various data models with geometrical and/or non-geometrical information; allowing data generation, exchange and processing within the life-cycle of built structures.

Stakeholders that are part of AEC industry worldwide benefit in various ways from BIM workflows. However, the benefits can be significantly different for several reasons: BIM design processes reflect varying national practices; level of detail of a BIM model; level of development of BIM workflow called BIM level; design phase; domain that uses BIM; internal company practices; even because of a specific software tool and a single person involved. The mentioned factors are on different scales, but can be understood as an insight to the complexity of a BIM workflow. Detailed BIM workflow descriptions are usually not provided nor standardized. Therefore, it is very hard to develop a universal metrics that will reliably measure the advantages of using a BIM workflow (Poirier et al 2015). The results are not positive in every tested case compared to the traditional planning workflows, and not in every measured aspect. However, by overcoming still significant people, process and technology problems, BIM benefits will also increase.

In the McGraw Hill Construction (2014), the most common benefit of BIM workflow was the reduction of errors and omissions, which also impacts the cost, duration and rework. In the McGraw Hill Construction (2014) survey, contractors' experiences are analyzed. Length of time using BIM, current BIM implementation level, BIM expertise level and BIM engagement level differ between the countries and affect the benefits the contractors have of using BIM. Return of Investment (ROI), a measurement of BIM benefits, has the highest value where the users have the deepest engagement. Deepest engagement is represented by their skills, years of experience and level of BIM implementation. In the BIM Handbook (Sacks et al 2018) the benefits are primarily categorized based on the phase of the project: preconstruction, design, construction and fabrication, and post construction benefits. The primary interest of this dissertation is the design phase, especially the collaboration between the architects and structural engineers. Based on the BIM Handbook (Sacks et al 2018), the main benefit from the use of BIM models in this phase is the earlier collaboration of multiple domains. Earlier collaboration would reduce errors and omissions and shorten the

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modelling time. Some problems could be discovered earlier, which would result in a more cost-effective design.

Although BIM promises are tempting, not all of them are realized in practice. Many procedural and technical problems still exist, and BIM workflows are not overall present in the AEC industry. However, the implementation of BIM in the practice is increasing. The next section explains different types of BIM practices.

2.1.2. Open and closed BIM, little and big BIM, BIM levels

Based on the BIM definition conceived for the purpose of this dissertation, the full potential of BIM can only be achieved on BIM level 3 that uses a network-based model, as it is perceived that BIM is a joint digital knowledge domain supporting activities of all stakeholders in AEC; based on various data models with geometrical and/or non-geometrical information; allowing data generation, exchange and processing along the life-cycle of built structures. Data model technology should allow integration of e.g. a single shared building data model, multiple domain- or software-specific models or other data structures.

The technology that should be used to achieve BIM is not specified. Workflow in the AEC industry signifies all the steps from the project inception until the demolition. Under BIM workflow are considered all the steps from the project inception until the demolition supported with BIM technologies. Since the BIM technologies did not yet reach their full potential, it is impossible to achieve a workflow fully supported by BIM. BIM workflow promises a seamless digital flow of information, meaning that the errors and omissions are avoided and manual work minimized at the given circumstances, to perform various design, calculation and analysis tasks in the AEC industry. For structural engineers it is particularly valuable since the significant part of their analysis information originate from the architectural design.

The conventional approach to the data exchange process in the AEC industry has been based on the graphical planning documentation as paper documents or alpha-numerical documentation. Each exchange involves the input information, actors that take part in the exchange and in the follow up contribute with additional information to the process.

Nowadays most of the stakeholders are using digital technologies to create and manage the information.

As already mentioned in the problem statement (section 1.1), the data exchange process in BIM workflows is based on two approaches: closed BIM and open BIM. The terms can be conceptual or descriptive, however the precise definition for these approaches cannot be found in the literature. Presented here are the descriptions of these terms as found in Borrmann et al (2015).

i. Closed BIM: is often referred to as a workflow where software tools from one software producer are used and the data exchange takes place with software to software interfaces (Borrmann et al 2015). This approach is not able to cover the whole AEC industry since there is no software producer that encompasses all domains. Therefore, multiple domains are excluded from the process. In this work is proposed that the closed BIM approach does not exclusively involve tools of a single software producer, but also the software to software data exchange between software tools of different producers. Finally, closed BIM is a workflow involving BIM authoring software that does not allow information access to an end user during data exchange process without a proprietary software tool.

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ii. Open BIM: the open BIM approach is a workflow where an open non-proprietary format is used for the data exchange purposes. Open means that end-users can access and modify the schema and the schema-based data. Non-proprietary means that none of the partaking software producer is responsible for the intermediate schema content. Software tools provide specific data from the original model through an interface to a standardized format, where part of the exported data can be used in other software tools. The standardized format is predefined and focused on the exchange process. The use of open format only for the exchange purposes limits the possibilities for user to manage data in the exchange format, since many relevant information are not part of the exchange.

Based on the proposed BIM definition, a framework for data exchange workflow that will be used for the dissertation is proposed. It is compared to already introduced closed and open BIM frameworks: Closed BIM is a data exchange from software tool A to software tool B using proprietary formats; Open BIM is a data exchange from software tool A to software tool B using a standard (e.g. IFC), where the original data remains in native software-platform. Following those concepts, BIM makes a data exchange from software tool A to a non-proprietary storage using a standard; the data from a native software-platform is coupled with the non-proprietary storage.

BIM approach is a joint digital knowledge domain that supports activities of all stakeholders within AEC. It is based on **open non-proprietary data storage**, which allows coupling of various non-proprietary and proprietary models with geometrical and/or non-geometrical information; allowing data generation, exchange and processing in the non-proprietary storage environment. The requirement is that the proprietary software tools support the exchange with the storage within the life-cycle of built structures.

BIM workflows as defined from the stakeholder-perspective, based on the number of stakeholders involved in the workflow, are popularly described as little and big BIM (Jernigan 2008, Borrmann et al 2015). They can be perceived as the second dimension compared to the open and closed BIM. In that way all four combinations are described as possible: little closed BIM, big closed BIM, little open BIM and big open BIM.

i. Little BIM, also addressed as lonely BIM, is an approach where "a BIM software tool is used by a single user for the purposes of its domain-specific tasks" (Borrmann et al 2015). The exchange between the stakeholders does not take place, and the model is only used for the specific domain for which it is created. This definition excludes also the use of multiple software tools within a single company. An isolated use of a single BIM authoring software cannot therefore be put in the relation with terms closed and open BIM, since they define ways of data exchange.

ii. Big BIM is an approach where "a consistent model-based communication is achieved between all stakeholders across all life-cycle phases of a building. Data exchange is achieved through internet platforms and database solutions." Big BIM definition conforms to the BIM definition in this dissertation regarding the involvement of all stakeholders across the building life-cycle, which is still not achieved in practice. Big BIM is perceived as the extension of the existing terms open and closed BIM. In the closed big BIM the tendency is to encompass all the stakeholders and software tools across the life-cycle using proprietary solutions, and in the open big BIM using the web-based intermediate standardized format. In both cases, the central data is limited to either software developer standards or open standards.

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The advantages of BIM workflows are visible already in the approach with little BIM, even if the data exchange does not take place. For instance, the BIM-authoring tools for structural analysis are often distinct from the traditionally used FEM tools by the ability to automatically interrelate design, analysis and documentation processes within a single structural tool. The available technology is still not able to support the use of big BIM. Each workflow that involves any sort of data exchange between various software tools ceases to be little BIM. The AEC workflows that are not limited to little BIM are trying to make use of various BIM models, but not achieving a seamless exchange. That is why the current state of the art is neither little nor big BIM, but the workflows are trying to get closer to the big BIM. Although little BIM workflows can be found in practice, the majority of BIM workflows are in the zone between little and big BIM. The concepts of little and big BIM are related in the literature to open and closed BIM.

Hereby is argued that the concept of little closed BIM vs. little open BIM is obsolete, as the little BIM includes only one stakeholder and does not involve a data exchange. Thereby, the type of the interface used for the data exchange is irrelevant. The only relevance of the terms little closed and little open BIM would be in the maturity process, when evolving from little BIM towards big BIM. The use of open BIM would allow for easier inclusion of software tools supporting open exchange format in the process. Closed BIM would mean that the data exchange is achieved through specific interfaces for each pair of software tools. The poor lexical literacy when talking about BIM already recognized in Succar (2009) and Bolpagni (2022), the definitions of these terms are not sufficient to provide for strong implementation framework, nor to relate them to the BIM maturity model.

Besides the open and closed BIM, and little and big BIM, BIM workflow can be classified based on its maturity stage. Term maturity level is also common. The following description of BIM levels originate from the work of Succar (2009): BIM level 1 is characterized by the use of object-based parametric modelling tools to achieve automatic generation and coordination of documentation and visualization. On this level, the model-based collaboration between the stakeholders does not take place. BIM level 1 corresponds to the little BIM. BIM workflow on the second stage, called BIM level 2, is achieved with a model-based collaboration. In order to reach the second level and facilitate collaboration, seamless data exchange between the domains must be achieved. That is also the ultimate goal of software interoperability, which is a goal of buildingSMART International and open BIM (buildingSMART 2021a). BIM Level 3 workflow manifests through the use of network-based model. The network-based model can be proprietary, belong to a software developer and serve as a platform for exchanging information between the software tools. In this case it cannot be accessed by the end user and the processes are dependent exclusively on the software developers. Open network-based models can be accessed by the end user, and the end users can define the processes and the information exchange. Big BIM is achieved on the level 3, when the BIM workflow is used for the whole life-cycle of a building. BIM, based on the BIM definition in this dissertation, can also be achieved on BIM level 3, depending on the framework. Most of the existing BIM regulations are designed to impose the use of BIM level 1 and BIM level 2. Figure 3 shows the graphical description of BIM levels, and the crucial differences between them, regarding the data and process digitalization, the cooperation between the domains and where little and big BIM are identified. The current technology state is difficult to define as workflows on BIM level 0 still exist, while at the same time there are attempts to introduce external databases and web-based collaboration, corresponding to BIM level 3.

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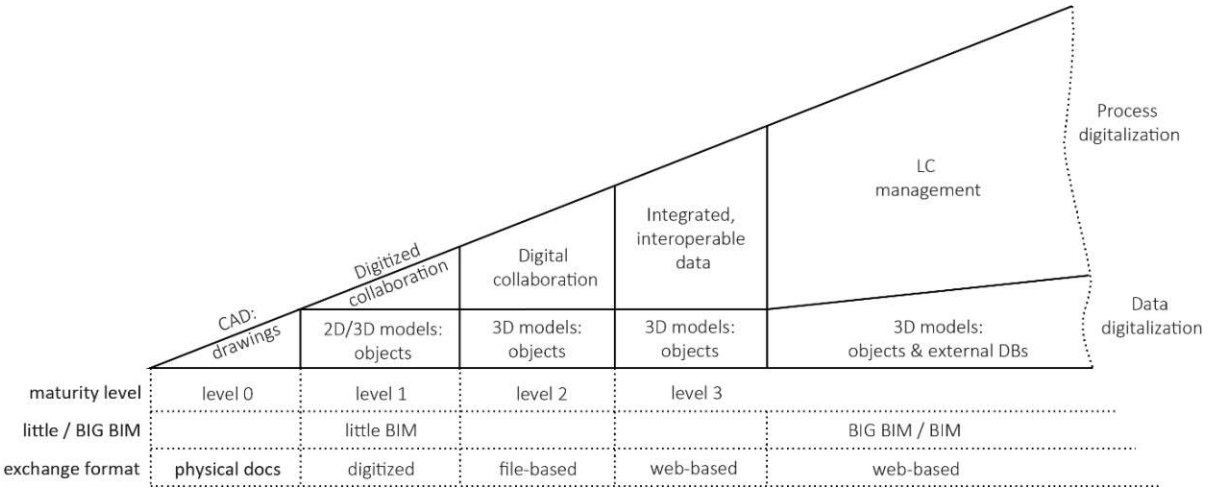

Figure 3 BIM roadmap (adapted from RIBA 2012)

2.2. Digital Building Modelling

Modelling of digital building is a process of generating geometrical and non-geometrical data which represent an existing or virtual building with a specialized software tool. In that way a digital building model is created which serves for visualization, analysis, optimization or management purposes. The term BIM is often confused with the process of modelling of a digital building model; however, with the previously proposed definition of BIM, modelling represents only one part of BIM and it can be considered little BIM or BIM level 1. Modelling is not limited to building modelling, it is a mandatory part in other design and engineering domains such are automotive industry or computer graphics. A building model can be represented in various ways, depending on the model purpose. As the focus of this dissertation is the data exchange between architectural design and structural analysis models, the modelling processes in these two domains are examined more thoroughly.

2.2.1. Architectural design modelling

The beginning of the computer-aided design (CAD) is considered to be the first commercial numerical-control programming system Pronto, created by Dr. Pattrick J. Hanratty in 1957 (Bozdoc 2003). CAD industry dates from 1963. and Ivan Sutherland's Sketchpad system that used graphic user interface (GUI) (Sutherland 1963, Bozdoc 2003). First commercial CAD solution was sold in 1969. Since early 1970s, CAD principles started affecting the AEC market. Today, the architectural design is unimaginable without the use of CAD software solutions. Today, architects can create building models with digital objects representing real-world building elements. This approach is called BIM modelling, whereby the border between CAD and BIM tools is not clearly defined. The required information scope for a BIM model is not standardized, therefore it is hard to define in which case a software tool can be considered a BIM software tool.

In practice, BIM-authoring tools for architectural design support modelling of 3d building elements and allow assigning non-geometrical properties to these, and often provide automatic documentation and additional calculation modules required for obtaining a building permit. Archicad was the first BIM implementation in 1987 (Svetel et al 2014). Since then, multiple BIM-authoring tools for architectural design emerged, and currently the most used are Revit and Archicad. Tools which are used purely for definition of geometrical information and parametric design are usually not considered BIM tools. The main goal of architectural design models is the presentation of visual properties of building elements, therefore, the geometry of building is similar to its real-world geometry, and includes additional properties important for visualization like material or color. This information is mostly generated from scratch by an architect when the model is first created. The

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concepts which are used by architects to define building objects are similar to the concepts which are used for the real-world building elements which they represent.

2.2.2. Structural analysis modelling

Parallel to the development of CAD, there was a development in computer-aided structural analysis tools. The development was especially influenced by the implementation of Finite Element Method (FEM) calculation for structural analysis. FEM was first discovered in 1956, and in 1969 MacNeal-Schwendler Corporation (MSC) launched NASTRAN (Engineering software research and development 2021). NASTRAN was the first generation of software using FEM. Current BIM-authoring structural analysis software tools are supporting building codes from multiple countries, some of them are ETABS, SAP 2000, Autodesk Robot, SCIA Engineer or RFEM Dlubal; however, their popularity differs between the countries.

Structural engineers generate model information based on the information provided by the architects. A building model is represented as analytical which is suitable for the analysis. Geometry of the analytical model used for structural analysis differs from a physical model representation used for architectural design. Building elements are represented with reduced dimensionality as surfaces, lines or points, depending on the type of building element and their role in the structural system of the building. Besides geometrical properties, the non-geometrical properties also differ compared to the architectural design models. For instance, material is defined with their structural behavior, not with the visual properties. The concepts used by structural engineers do not correspond the concepts used for real-world objects. The conceptual differences are traditionally intuitively overcome by structural engineers, who interpret the models based on their expert knowledge to create their own domain-specific model.

2.3. Data exchange

"In data exchange, data structured under one schema (a source schema) must be restructured and translated into an instance of a different schema (a target schema). Data exchange is used in many tasks that require data to be transferred between existing, independently created applications" (Fagin et al, 2005). The data exchange refers to the process of data restructuring and data transfer, and encompasses the whole communication between two applications. This section addresses various concepts for data exchange which can be found across the AEC industry.

2.3.1. Data exchange in the AEC industry

Data exchange frameworks represent the basic structure used for the data exchange process. That could be in a form of a non-digital communication like handover of printed plans, and digital:

- Static: direct communication between software tools if they do not achieve a synchronous communication, such is through single or multiple files (proprietary or non-proprietary). Data state is not changing in a receiving storage or software tool if it is changed in the native one. In the receiving application the change is happening only if the process is repeated.
- Dynamic: communication achieved through a synchronous connection between the software tools or a software tool and a central storage. In that way, a specific program or data storage can subscribe itself to the information in the native source of information. The changes that are made in the native source of information are recognized and synchronized in the receiving software tool/storage. The communication can be achieved

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between the software tools (proprietary) or between an interchange format and a software tool (non-proprietary).

The most common model-based data exchange in the AEC industry is a static file-based exchange using the IFC standard. The essence of IFC-based exchange is that it uses file-based building data models compliant with the IFC schema. In this framework, stakeholders exchange building data models defined as IFC files. A file-based exchange is not a data exchange solution that has potential in the future (Kiviniemi et al 2005). A file-based exchange framework is similar to the traditional paper-based approach; the main difference is that the exchanged information is digital (Figure 4). The file-based exchange can be both closed and open BIM, the distinction is in the format used for the exchange - if it is proprietary or not. The current open BIM approach using IFC files uses a schema which could be used for several domains. However, the exchange is taking place between two software tools, and the central model practically does not exist. Other approaches using the IFC standard besides a file-based data exchange are not widely used in practice. An open BIM framework where IFC files are exchanged is not an answer to the vision of a shared model that was identified as a necessary solution by Kiviniemi et al (2005) (Figure 5).

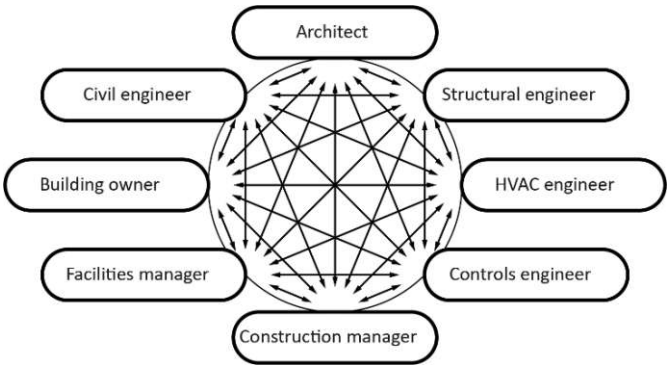

Figure 4 Common data exchange scenario in practice (redrawn from Kiviniemi 2006)

Kiviniemi et al (2005) suggest the use of an IFC-compliant model server to exchange information and domain-specific standardized APIs to communicate with the server. The data on the model servers examined in their research is compliant with the IFC standard. In general, model-based servers can be open or closed. A central shared storage could be used by multiple stakeholders and domains, and a software to software exchange would be avoided (Figure 5).

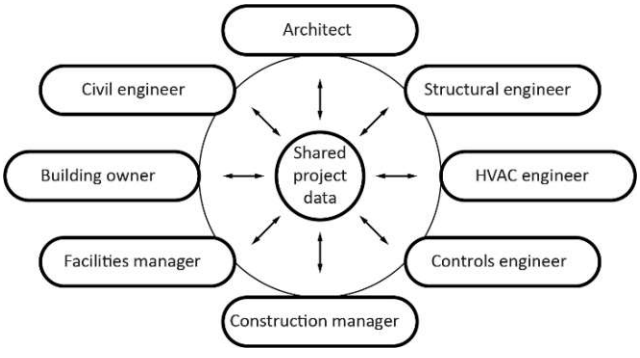

Figure 5 Vision of a shared model-based exchange (redrawn from Kiviniemi 2006)

The need to improve the data exchange in the AEC industry has been addressed by multiple researchers. Several approaches can be commonly recognized: introducing ontologies to overcome

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domain-specific differences, extending the existing IFC schema with new requirements, or managing the frameworks by changing the exchange-formats and processes. Aram et al. (2014) suggest a framework for cost estimation and quantity takeoff based on knowledge-based system which uses implicit besides explicit information. They add the information using the ontologies. In their framework, the system architecture is divided into four layers: domain layer is a knowledge base layer with various domains and representation tools; reasoning layer defines task-specific hierarchy and relations; task layer defines the rules to generate the output; and the interface layer enables user interaction. Venugopal et al. (2012) emphasize that a domain-specific subschema creation has to be simplified for the end user. They adopt ontologies based on the IFC definitions and within them define concepts for new IFC subschemas called model view definitions (MVD). The importing software needs to interpret the geometry and associate the meaning to the native objects for every domain except simple geometry clash check.

As exemplary research shows, the problems with the existing data exchange frameworks are detected in many domains within the AEC industry. Extending the IFC schema aims to encompass all domain-specific requirements, although at the same time the current size and complexity of the IFC schema is recognized as a problem. Data needs to be extracted, modularized and interpreted for specific applications across different domains. A more detailed state of the art regarding the data exchange between architectural design and structural analysis domains is provided within the research papers in the Part II of the dissertation.

2.3.2. Data exchange standards

Seamless data exchange represents one of the greatest obstacles for a successful BIM implementation (Sacks et al 2018). Each open data exchange requires a standard for central data storage and model definition. Therefore, numerous data exchange standards have been developed such are STEP or IFC, each of them facing specific challenges.

2.3.2.1. STEP

Aspirations for standardization for exchange purposes is present in all industries using digital models. STEP (Standard for the Exchange of Product Model Data) initially aimed to unify different national industry standards. STEP is widely implemented in the manufacturing industry, and it is the largest standard of all ISO standards. It defines a way to exchange digital information about a product. Instead of defining an integrated model, it originates from several part-models called Application Protocols (APs) (Eastman 1999). AP 225 called “Building elements using explicit shape representation” (ISO 1999) was a starting point for defining the IFC schema. Prior to testing of IFC, STEP as its predecessor has been considered for the exchange of building data, including its scope and software tools supporting STEP data.

STEP standard has high potential to be used as a schema for storage of building data for its possibilities to define geometrical data. Therefore, software tools that could facilitate a framework with STEP standard are tested. However, none of the software tools gave satisfying results (Section 2.4.3). It is possible to develop a new software tool by fixing and improving the existing ones. In the adaptation process some potentially existing errors and problems might easily get overseen. Another considered approach was to create a new software tool from scratch to deal with STEP-based models. Even though it is possible to develop a data exchange framework with the STEP standard, the decision fell on reconsidering additional options for several reasons: STEP standard is not supporting all the requirements that would come up in the AEC industry; it is not a flexible solution that would answer the changing industry needs; it lacks community interference (low number of users); the software tools that deal with STEP standards and compliant data are deprecated/not

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actively developed; the information technologies have significantly developed since the 80s when the STEP standard was created.

2.3.2.2. IFC

Actors involved in the AEC planning process perform domain-specific actions that involve different models of the same real-world product. Processes are complex and independent for each project in particular. Building models of different domains differ from each other, not only by scope of data, but also by information representation for a specific use. Unlike the STEP standards for the manufacturing industry, a whole range of domains that take part in the AEC industry is reduced to a single AP that is later accepted as a starting point for the IFC standard. The scope of the AEC industry with all its domains resembles more the STEP standard itself with multiple APs than a single AP.

buildingSmart is the leading organization in developing and promoting open BIM collaboration (buildingSMART 2021a). As a result of rising needs to improve the interdisciplinary cooperation throughout a very fragmented and heterogeneous software landscape in the AEC industry, buildingSMART developed the IFC standard to provide easier data exchange. There are over 300 software tools claiming to support the standard, aiming to realize open BIM-based data exchange (buildingSMART 2021b). The IFC standard is currently the most supported open data exchange standard in the AEC industry. Each user can access the schema and schema-based content. The IFC standard is described as “a standardized, digital description of the built environment, including buildings and civil infrastructure” (buildingSMART 2021c). The IFC support allows certified software to import and/or export data using its generic building data model. Consequently, the numerous data exchange possibilities for every software should be reduced to a single one.

The latest version of IFC schema is IFC4. Different domain specific requirements that exist between domains are managed by different subschemas called MVD. IFC4 comes with the two MVDs provided by buildingSMART: Reference View and Design Transfer View. Software tools that claim to support the schema can be certified for a specific MVD. Software tool certification for the latest IFC version is only provided for the Reference View at the moment. This MVD supports the IFC building data model that should be used as a reference only (buildingSMART 2021d). The model is not supposed to be used for further data editing. For Design Transfer View, which exists since July 2015 and should serve for further editing of the building model, the certification is still not launched (buildingSmart 2021d). Software tools that implement IFC 2x3 are officially certified only for MVD Coordination View version 2.0 (CV V2.0). CV V2.0 is used for three different domains: architecture, structural analysis and building services (Figure 6). The shared building information model is supposed to be re-editable by the receiving application, and not used as a reference only. It includes the definition for spatial structure, building elements, structural modeling elements, and building service elements with shape representations, including parametric shapes for a limited range of standard elements, and non-parametric shapes for all other elements with property sets, material definitions and other alphanumeric information (buildingSmart 2021e). In this open exchange workflow, different software tools in all three supported domains use the same CV V2.0 MVD. However, implementation of this MVD differs greatly between the software tools.

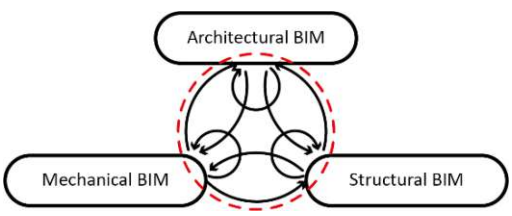

Figure 6 Data exchanges covered by CV V2.0 – dashed circle (based on information from buildingSmart 2021e)

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The analysis of the IFC standard showed that it is a rich schema and encompasses significant scope of concepts from multiple domains in the industry. However, it does not standardize some important requirements which are specific for the data exchange between architectural design and structural analysis domains. Main issues of IFC are that: it does not support all planning process stakeholders; it lacks possibilities to define all geometry information which are present in the native software solutions; there are no satisfactory software tools which support the IFC schema and data manipulation; its base - EXPRESS data modelling language is deprecated, many software solutions related to it are not maintained and the researchers switch to other languages for data modelling (e.g. Barbau et al 2010). That insight led to the consideration of the alternative geometry definition standards.

2.3.3. Comparison to other industries

Digital product models in other industries are used for the same purpose as building models, to aid with the creation of physical models; processes taking place in other industries also display similarities in certain cases. Best practices found elsewhere could be projected on the AEC industry, hence, a brief overview of other industries will be provided. In this section, the procedural specifics of the AEC industry are described, as well as multiple model representations existing in other industries.

2.3.3.1. Procedural differences

The manufacturing industry shows advanced level of digitalization. The reason can be found in the greater number of predefined processes and controlled systems in the manufacturing industry. Learning processes and development of knowledge is enabled by capturing experiences (de Giorgio et al 2020), which is generally repetitive for manufacturing processes. In manufacturing, the knowledge-based methods are based on expert knowledge that is codified in advance. De Giorgio et al (2020) define two types of knowledge: declarative and procedural, where declarative knowledge is systemic information of one system related to information about another system at an instant of time, and procedural knowledge is related to the variation of information about another system between two instants of time. In other words, procedural knowledge describes knowing how, or “skills for efficiently and effectively solving problems”, while declarative knowledge represents knowing that, or “concepts, terms and taxonomy for articulating, classifying and structuring things and phenomena in a logical mental representation” (Lee 2022). The AEC industry still lacks sufficiently detailed descriptions for both declarative and procedural knowledge.

Dubois and Gadde (2010) identify why the AEC industry is different compared to other industries. In other industries, the stakeholders deal with the interdependencies by tight coupling among them. The relationships among them are characterized by inter-firm adaptations. On the other hand, the AEC industry represents a loosely coupled system where every resulting product is unique. The tight coupling in the AEC industry is typically present in individual projects only with already established teams, mostly within a single company performing multiple domain-specific tasks. For those reasons it is difficult, or maybe even inadequate to implement principles from other industries in the AEC industry.

The interdisciplinary data exchange encompasses and unifies the very diverse sets of information and models required for each domain. The exchange needs to be defined by capturing and standardizing the descriptive knowledge manifesting through data models and data exchange requirements, but also the procedural knowledge which defines data editing processes and interpretations between the domain-specific data. Current successful practices in the AEC industry regarding the data exchange focus on workarounds, respecting the performance of software tools, sometimes tied to national or

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company standards. BIM managers try to find ways to achieve at least partly working data exchange. This results with the creation of a tightly coupled system for a specific project. However, the practice where professionals like BIM managers define the workflow is still common only in larger companies, where more than one domain is present “in the house”. Digital data exchange is still rarely present when smaller offices exchange information between each other, as the chances to achieve a tightly coupled system are lower. Tightly coupled systems are more commonly found within a single company with multiple domains. There are no general approaches defined that facilitate a seamless exchange by making the whole industry a tightly coupled system.

2.3.3.2. Model representations

Multiple representations of the same real-world products are commonly found across different industries, such are the manufacturing, cartography or AEC. Research investigating industries beyond the AEC also deals with multiple model representations and interpretations taking place between models. The geometry interpretations can be summarized as the interpretation of (a) same geometry and similar representation (e.g. different geometry kernels), (b) similar geometry and different representation (change of level of details, especially in cartography) and (c) different geometry and different representation (e.g. architectural design to structural or energy analysis). The lessons from other industries are useful, but the peculiarities of the AEC industry with the exchange possibilities that are not predefined, not regarding the procedural nor declarative knowledge, make the automation of all possible exchange variants far more complex. Formalizing all possible changes in the state of a building model would quickly result in scalability issues, thus requiring identification of focus points.

STEP was primarily developed for the manufacturing industry, and involves multiple APs for different representations. Within the IFC standard, multiple representations should be addressed with multiple MVDs and IDMs, but these approaches are not yet common in the practice. MVDs are not the only concept for dealing with a partial scope of data. In the practices using databases, various data can be retrieved and manipulated through data queries. Queries are specific to a database and data structure, and they can be predefined. They can be created for extracting building data if the data is placed on a database. The need for multiple models in the building design exists for more than two decades (Rosenman and Gero 1996). However, the data exchange technology such is IFC or other domain-specific standards were developing in the direction of an integrated model, without providing a way to manage multiple models outside the proprietary software tools. Rosenman and Gero (1996) state that the same real-world objects may have different abstractions across the domains, which need to be interpreted in order to be represented according to a particular abstraction in a particular domain. Therefore, they claim that multiple representations and models which are interrelated are needed, and accordingly managed throughout the design process. There is a visible improvement regarding the software tools, from CAD tools, mainly used for geometry definition, towards todays BIM-authoring tools with complex domain-specific non-geometrical properties beside geometry. However, although the support of multiple models may be supported within a closed system, the interrelation and interpretation between the models contained within these closed systems is difficult to achieve.

There is a strict asset hierarchy between the geospatial industry, the AEC industry, and the manufacturing industry. Succar (2019) suggests a graph where these three industries are described with the parallel set of peculiarities: the geospatial industry deals with the elements on the environmental scale and uses geographic information system (GIS) for its needs; manufacturing industry is on the product (or component) scale and uses product life-cycle management (PLM); AEC industry deals with the products on the building scale, and it uses BIM. However, some assets are not

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only part of a single industry. First, there is an overlapping between the assets where GIS requires the data of a built facility, and second, where the construction industry is interested in the digital representations of components from the manufacturing industry. AEC industry assets used in an open exchange BIM workflow conform to the IFC standard. Hence, the digital representations of building elements are based on the concepts predefined in the IFC schema. The assets of the manufacturing and the AEC industry are getting evermore present within the AEC and geospatial industries respectively. Architectural BIM software tools mostly support modelling of product models as well (*.rvf files for Revit, *.gsm for Archicad or *.nmk for Allplan) and in that way, they are becoming a part of an architectural model. Despite the fact that product manufacturers are also interested in providing digital content describing their products, the use of such digital product models within BIM workflow seems to be a research gap (Kin et al 2016). These product models also lack standards that relate them to the open exchange. For instance, compared to Revit, Autocad or Archicad files, digital objects provided in IFC are the fifth most numbered format on one of the largest online libraries for digital objects (BIMobject 2021). It is clear that product models are still generally exchanged with native software solution format and that the exchange is closed. The main intention for these digital products is to be used with software tools in the AEC industry. The new version of IFC5 (Amann and Borrmann 2015) defines infrastructure elements which bring the schema closer to GIS. In other words, in the future, IFC will include more assets originating from geospatial industry. The schema provided by buildingSMART is in that way increasing its complexity and size. Currently implemented and used IFC 2x3 is already considered rich and redundant, which causes problems for its implementation.

Finally, the concerns regarding the data exchange can be summarized. Behzadan et al (2015) describe the relations between knowledge, information and data, stating that the most important obstacle for data-driven simulations is not the lack of data, but the interoperability problems, where the improvement of open standards aims to address this issue and provide a sufficient amount of reliable data to allow simulations. Sets of information required for specific software tools are various. Intermediate models contain both data which is needed and not for the exchange. To prepare the data for use with a software tool, it is required to filter and interpret the information based on the captured existing processes. Proper data extraction is only party possible with standardized schemas like STEP or IFC, unless they are created for a specific implementation, as they do exclude some information. The AEC industry is a loosely coupled system, with various stakeholders using various software tools. Each software tool deals with a specific scope of information. While the information scopes of software tools belonging to a single domain are similar, information used in different domains is more diverse. Even the diverse information is often related to each other and dependent on each other. The dependencies are not easily achieved within a static schema defined with the EXPRESS data modelling language. A dynamical approach is more appropriate to extract non-explicitly defined information and to be able to establish non-defined relations and new elements in the data storage. Current trends are focusing on web technologies and big data rather than file-based data exchange. These facts directed this dissertation to the widely emerging and implemented web technologies, which are considered a future in AEC industry as well. Prior to that, different technologies were considered and tested, as will be presented in the following section.

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2.4. Data management technologies

Knowledge sharing and reuse is closely related to data exchange. According to Costa et al (2016), collaboration on building projects is considered an arena, engineering projects a target and knowledge a currency leading to successful collaboration. Knowledge management (KM) and adoption of KM models and tools still poses a challenge in many domains, especially within the AEC industry, where knowledge is deeply rooted in traditional processes with significant amount of tacit knowledge; therefore not delivering appropriate base for the available digital solutions as such. In order to provide an appropriate knowledge organisation for KM, classification, taxonomy and ontology are most commonly used approaches (van Rees 2003), whereby the difference between the terms is often not clearly stated.

In order to provide a suitable solution for the data exchange, multiple technologies are analysed, tested and implemented within this dissertation. Data management technologies are constantly evolving, and this work provides an insight which is a cut through the state-of-the-art technologies at the time of writing. The following topics are addressed: data organisation including classification, taxonomy and ontology, geometry definitions, software tools facilitating management of STEP-based schemas and data, MEAN stack and microservices and Docker. This is not an exhaustive analysis of software tools which could serve for achieving a seamless data exchange; the research evolved with time, the technologies able to overcome the issues found in the existing tools are tested until a satisfying solution is reached. The resulting system could be further optimized, especially due to fast development in the software industry, however a truly optimal solution requires testing on a large scale in practice.

The IFC standard as well as other STEP standards, ontologies, multiple geometry definitions such as OC geometry kernel, VDI, X3D and Three.js, relational, semi-structured and linked databases, parsing tools, as well as APIs of various software tools, MEAN stack, web APIs, and .Net framework with C# for data management and establishing relations with databases, building models and software tools have been tested and considered for this dissertation, and will be presented in this section.

2.4.1. Classification, taxonomy and ontology

Data organization concepts classification, taxonomy and ontology are often confused terms (van Rees 2003) in the AEC industry. Difference between ontology and taxonomy is that an ontology includes the knowledge on the meta-level and captures tacit knowledge (Borst 1997). Commonly used ontology definition comes from Gruber (1993) “An ontology is an explicit specification of a conceptualization. The term is borrowed from philosophy, where an ontology is a systematic account of existence. For artificial intelligence (AI) systems, what ‘exists’ is that which can be represented.” Further on, conceptualization is “a structured interpretation of a part of the world that people use to think and communicate about the world.” (Borst, 1997). In practice, the terms ontology and classification, or taxonomy are similar. The main difference in application of ontologies, taxonomies and classifications is that within an ontology the relations between the classes can be defined in any form, while taxonomy relates the objects with hierarchical relationships. The taxonomies are “a scheme of classification” (Usman et al 2017) and can be regarded as hierarchically organized explicit knowledge. Classification groups the objects by a specific criteria, not necessarily relating them to each other. Although all three terms are closely related to each other, it is considered in this work that classification means grouping objects based on specific criteria, taxonomy relating the classes with hierarchical relations, and ontology relating these with any sort of associative relation, which may also be hierarchical. Sometimes these data organisation concepts are formalized without a strict consideration of recommendations intended to regulate their development, such are ISO standards. The relation between these concepts could be approximated with the following equation:

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classification ≥ ontology ≥ taxonomy

The relation shows that classification, which defines classes with or without relations between them, is a superordinate data organisation model towards ontologies as it does not require any associations between the classes. The ontologies are classifications where any sort of the relations between the classes are defined, including the hierarchical relations. Similarly, ontology is a superordinate model towards taxonomy and it represents a taxonomy only in the case that relations between the classes are hierarchical. Taxonomy is therefore a special form of ontology, and ontology represents a more generic term.

The relations between the architectural design and structural analysis are not purely semantical; they include complex geometry transformations which mainly exist exclusively as expert knowledge. Therefore, the aim is to investigate the domain-specific classifications, taxonomy and ontologies in order to facilitate the knowledge sharing and reuse; however, it is required as well to capture a dynamical knowledge of geometry transformations which is not addressed with solely semantical KM solutions. A basic conceptualization unit of a building model for architects and structural engineers are building elements, which is also reflected within the software tools that they use, suggesting that building elements are the level of abstraction that should be used for classification. These enriched through internal relations might eventually develop into an ontology.

Classifications are the oldest way of organizing knowledge about the building project, as it can easily be defined in an analogue form. One of the oldest ones which was used by engineers is Library Classification System (LCS), and in Sweden the classification systems were developed and used more than 50 years ago (Lou and Goulding 2008). Classification systems used for architectural design and structural analysis are discussed in Publication 2 in Part II of this dissertation. Digitalizing the knowledge in the form of classification facilitates creating information from data, and subsequently from information knowledge (Lou and Goulding 2008). Defining and manipulating classifications is supported by numerous technological solutions.

Taxonomies are commonly found in data exchange schemas, as the relations between the classes which define knowledge in software tools in the AEC industry are generally hierarchical. In fact, the majority of work regarding taxonomies can be found in the knowledge areas construction and design (Usman et al 2017). IFC and STEP formats can be regarded as ontologies (Pauwels et al 2022). The technological solutions to define and manage ontologies exist, but some aspects such as authorisation and geometry definitions are still in development. Sometimes ontologies are derived from the existing taxonomies, meaning that the technology used is primarily intended for ontologies, but the hierarchical relations remain, distancing it from a true concept of ontology. IFC schema partly consists of taxonomy, for instance for product classification (Pauwels et al 2022). EXPRESS and UML data modelling languages are used for defining object-oriented IFC model. In Beetz et al (2009) the IFC schema is transformed to ifcOWL. Other EXPRESS-based schemas can be transformed the same way. They propose the use of XML and Resource Description Framework (RDF) to reduce the size and complexity of IFC files, and to improve the file-based exchange through a new framework. Modularization of the ifcOWL ontology is suggested by Pauwels et al (2017) with the aim to use only filtered model data. For that purpose, the particular modules need to be defined or the existing ones significantly redefined. They also rethink the geometry definition within the ifcOWL that is translated from the IFC schema, with the aim to simplify it. Redefining the geometry definitions is one of the focuses of this work, since the existing IFC geometry definitions do not support multiple geometrical concepts, in the first place geometric parameters.

There is a difference between the technological solutions used to define ontology, taxonomy and classification. The classifications, originating as an analogue knowledge definition, can be defined in

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any form of digital data, while the data can be stored in documents, tables or databases, such is Excel or SQL. Taxonomies are defined with a schema modelling language which allows creating hierarchical relations, such as EXPRESS, XML, and numerous others. Taxonomies are at the same time ontologies, with exclusively hierarchical relations. If the technology is used to represent non-hierarchical relations, an ontology is created which is not a taxonomy. The building data models can be stored in data files (e.g. IFC building model), but also in databases, whereby the databases supporting object definitions are the most suitable ones. Although relational databases provide ways to relate the elements, they are not the most suitable ones to store data defined with taxonomies as they are flat (Raguenaud et al 2002). Ontologies are commonly realized with semantic web technologies, such is RDF and OWL. Data defined with ontologies is often stored in graph databases that are able to display knowledge realized in the form of triples. Triples are a suitable form for defining ontologies as they include a subject, an object and the relations between them as a predicate. Lately, multiple ontologies have been developed for the AEC industry such are ifcOWL, COBieOWL, IfcWoD, SIMModel and Building Ontology Topology (BOT) (de Farias et al, 2016; Pauwels et al, 2017; Rasmussen et al 2017), some are however still mainly based on the hierarchical approaches.

2.4.2. Geometry definitions

Multiple building models in the AEC industry may display significant differences in geometry representations, besides the semantical differences, depending on the domains they belong to. Different domain-specific geometry representations are especially visible between architectural design and structural analysis. Hence, the differences between the representations in the architectural design and structural analysis can hardly be solved by overcoming solely semantical differences through proper classification, taxonomy or ontology. Differences between geometry representations are addressed by geometry interpretations that represent experience-based knowledge, which is not captured and makes a research gap. Geometry can be defined in two ways: with explicit and implicit geometry definitions (Borrmann and Berkhahn 2018). Most commonly used explicit geometry definitions are Boundary Representation (BRep) and its simplified variant triangulated surface modelling. BRep defines geometry with the hierarchically related concepts of bodies, faces, edges and vertices, and depending on the geometry kernel, can define various shapes by defining its shell. The triangulated surface modelling approximates the outer shell to triangles. Implicit modelling records the way a certain shape is created, and eventually renders a resulting shape. Two approaches for defining implicit geometry can be recognized, namely constructive solid geometry (CSG), which combines basic geometry elements to create geometry, and extrusion and rotation where a 3d geometry is created by moving a 2d shape.

Borrmann and Berkhahn (2018) describe the parametric geometry description as an approach which is able to define constraints and dependencies between geometric shapes, or within a single geometric shape. They state that BIM tools, unlike pure 3d modelling tools without BIM semantics, do not fully support parametric geometry definitions, except on the building element level. Parametric modelling is used with implicit geometry definitions. The IFC building data model was an initial consideration for geometry definitions in this thesis, as it had been recognized as the most popular exchange format. However throughout the process of fundamental research, a need for an alternative was identified due to several reasons:

1. IFC geometry definitions are not supporting the parametric geometry description, which is required during the planning process if the geometry is edited in the follow up. Through building shape representation concept it supports a limited amount of predefined geometry concepts. The geometry kernel needs to be standardised and support all required geometry definitions.
2. Software tools that continuously support the IFC schema development are few, and the

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majority does not supports the latest version of the schema.

3. The software tools that use IFC schema for data exchange generally have unresolved interoperability issues.
4. The schema does not support all the stakeholders in the process. The IFC schema has a significant number of predefined entities describing building elements but does not entirely support any domain or the corresponding software tool.

Four geometry standards are investigated:

- X3D (extensible 3d)
- VDI (Verein Deutsche Ingenieure) standard
- STEP
- OC

X3D is one of the technologies for 3d on the web, what usually means that it is a 3d technology that can be accessed through web browser. 3d on the web began when Virtual Reality Markup Language (VRLM) Consortium (a successor of Web3D Consortium) released the VRML in 1994 (Ortiz Jr 2010). It was replaced by X3D in 1997. X3D is an XML-based format that includes VRML extensions. However, it still was not accepted widely enough in the community. Universal 3D (U3D) is another standard for 3d computer graphics. There are currently more accepted approaches for 3d web technology, for example: JavaScript (JS) and HTML 5.0, WebGl, O3D, Adobe Flash. They are not addressed to detail in this dissertation.

VDI stands for the Association of German Engineers. Their standard 3805 called „Product data exchange in the Building Services" is a product catalogue of building services equipment. It supports numerous products, and standardizes the geometrical representation for this particular domain. However, the IFC building data model is used for the data exchange between different domains with the predefined mapping rules between the two standards.

ISO 10303 or STEP is the richest of all ISO standards. ISO 10303 - Part 42 (ISO 2014) describes the geometric and topological representation for product data representation and exchange. In this part of the ISO standard, all supported geometry definitions are described. APs describe a specific data exchange, using other parts of STEP standard. In that way, ISO 10303 – Part 225 (ISO 1999) is defined, which is an application protocol describing "Building elements using explicit shape representation", serving as a basis for the IFC data exchange standard. There are certain geometry representation differences between STEP geometry definitions and IFC.

OC is an open source geometry kernel used in many software tools. It has been developed since 1990s, has significant user community, and provides multiple classes to develop and manage geometry (OC 2021). Its open source version is provided with C++ programming language. Multiple similar parallel commercial solutions exist which are implemented in the software tools for architectural design and structural analysis.

A list comparing the considered geometry definitions is presented in the Table 2:

Table 2 Comparison of geometry definitions

	Advantages	**Disadvantages**
IFC	Widely used in the AEC industry software tools	Static schema not intended to be edited by the end-user
	Open source solution	Does not support parametric geometry definitions
		File-based exchange
		Limited possibilities to define geometrical and non-geometrical attributes

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X3D	Web-based	Not widely accepted in the AEC industry
	JS and HTML 5.0 –based technologies are well supported in the community	Mainly intended for visualisation, not geometry editing
VDI	Extensively describes multiple elements in building services field	Limited to one domain, not intended for exchange with other domains
	Support all the required geometrical definitions of the domain	Converted to IFC for the exchange with other domains
	Extents STEP geometries for parametric geometry definitions	
STEP	More possibilities to define geometrical attributes than IFC	File-based exchange
		Static schema not intended to be edited by the end-user
OC	Provides ways to manipulate geometry	C++ is open source version, other versions not
	Used for software tools in various domains	Low support for open source version

2.4.3. STEP-related software tools

Four software solutions are tested in this dissertation that could be used for validating and preprocessing STEP schemas or the data defined with the schema:

- JSDAI
- OSEP (Open Source EXPRESS Parser)
- ANTLR
- Express Engine

Schemas belonging to STEP standard are defined with the EXPRESS data modelling language. The IFC schema is also defined with the EXPRESS data modelling language. This data modelling language is also a part of STEP standard as ISO 10303-11 (ISO 2004). It is necessary to find a way to validate the schema and the corresponding building data model, and in the follow up to preprocess the data model, in order to use the STEP standard for the data exchange purposes. For that reason, a computer program JSDAI (JSDAI 4.2.0) is tested. Standard Data Access Interface (SDAI) is part 22 of the STEP standard which allows manipulating data defined with EXPRESS (ISO 1998). It can be used with C++, C and Java programming languages. JSDAI is an API for reading, writing and runtime manipulation of data, and represents an extension of the standardized SDAI. JSDAI is intended for users working with data models and not for the end users in the design process (e.g. architects or structural engineers). It is a plugin for Eclipse (Eclipse Project 4.6.0). It creates Java classes from the EXPRESS data modelling language which can be used for validation and editing of data models in the follow-up. JSDAI was tested on Windows and Linux platforms which delivered similar results. Few EXPRESS schemas are tested, and some of the files based on those schemas as well. After performing the tests, and realizing that it is a legacy software tool (last update was in 2010), this approach has been abandoned.

OSEP (OSEP v 1.14) is discovered as another possible software solution for testing STEP schemas and files. The idea behind OSEP is to use ANTLR (ANTLR v4.7) and Java to parse EXPRESS language, which is a basis for the STEP standard. It creates an Abstract Syntax Tree (AST) from the data models using ANTLR and makes it possible to “walk” and/or modify it using Java. OSEP is created for ANTLR 2.0. Current version of ANTLR at the testing time on the market was 4.0. The first test was performed with the ANTLR 4.0. It was possible to start the parsing with the newer version, however the results were not satisfying. This software tool is found to be outdated. Last update of the website happened in 2001. ANTLR version 2.0 is not working the same way as the ANTLR 4.0. ANTLR had many changes between the version 2 and 3, and also between versions 3 and 4. In order to make the OSEP up to date, it should be updated to work with the newest ANTLR version.

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ANTLR is a software tool which can be used to parse any sort of structured text or binary files. It uses the "grammar" which defines parsing and lexical analysis rules for each specific input which is to be analyzed. When parsed, it prepares Java classes where the elements from the grammar are recognized and can be manipulated. The idea to use the ANTLR came from OSEP. The ANTLR community is active, and the latest version was ANTLR v.4 (at the time of testing). It has been developed for almost 30 years now and is constantly being improved. Besides the lack of development of tools using ANTLR for processing of STEP data models, ANTLR alone is found to be a powerful tool for parsing and lexical analysis. A test workflow that deals with the STEP schema was established, where a small part of the schema is read. Conclusion following the test implies that it is possible to define grammatical rules which address STEP standards using ANTLR. With the schema definition interpreted in ANTLR, it would be possible in the next step to automatically create a new grammar based on the schema in order to validate and manipulate the files based on that schema with ANTLR. Finally, one more solution dealing with STEP is found that had more recent activities.

Another possibility to access, modify and validate the EXPRESS-based STEP schemas and the corresponding files is Express Engine Project (Express Engine Project v 4.3.4), also known as Expresso. It is a project initiated by the National Institute of Standards and Technology (NIST). Some issues occurred when installed on the Windows 7 platform, but it worked on the Virtual Machine with Linux. Expresso uses ANTLR parser generator. Eventually the problems with Windows installation were resolved. The Expresso 4.3.3 was tested with valid EXPRESS-based IFC schemas. It resulted with numerous errors. In the Express Engine User Manual (Express Engine Team 2018) some problems, as well as the tasks it is able to deliver, are described. One of the problems that also exists in JSDAI is that it does not properly validate derived attributes. The latest version is 5.0.21, while the tested version was 4.3.3, and the tool has some recent developments. Current version is also in the beta stage of development and does not cover all the rules within the STEP standard. Most of the functionalities are limited and not fully working. Hence, it is required to either further develop it or use it as a reference. Considering that the project start was 10 years, its development is rather slow.

Several solutions to edit the STEP schema and the corresponding files are compared in the Table 3.

Table 3 Comparison of software tools which can edit STEP schema and data

	Advantages	**Disadvantages**
JSDAI	Able to validate and edit schema definitions and corresponding files	Shows errors with some EXPRESS elements
	Creates JAVA classes that could be used to develop a framework	Deprecated, used only for the developers' company purposes
OSEP	Can validate the EXPRESS schemas and corresponding files	Still not completely functional, significant work must still be done
		Developed with an old ANTLR version, deprecated
ANTLR	Has a large community, actively used and developed	Big differences between the old and new ANTLR versions, old grammars cannot be used
	Can read and interpret all sorts of structured data, including STEP and EXPRESS	The grammar needs to be defined from the scratch
Expresso	Based on ANTLR grammars	Exists for a long time, missing many functions, slow development
	Has recent developments	Needs a lot of work until it can validate schemas and files properly

The results show some advantages and disadvantages of each tested technology. Despite of the considerable effort which was put into examining the software tools based on STEP standards, the

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dissertation followed a new path and analyzed MEAN stack as a popular web technology. This represents a break point for the definition of a system architecture, considering the technological possibilities provided outside of the existing tools referring to the AEC industry and corresponding standards: in the first place the structure definition for the data storage; followed by the data storage validation and extensive preprocessing framework; finally, the proof of concept with an implementation of a building model and realization of a data exchange.

2.4.4. MEAN stack

Since the STEP software tools do not display active development and the community involvement is limited, a web-based framework for data management received more attention to facilitate the exchange. At the time of writing, the project DATAFILTER in cooperation with Strabag, Vienna, was taking place. On the side of Strabag, a program called bim.js which exports geometry from Revit was under development. This program can export Revit families and store them on the database MongoDB. It inspired the implementation of data exchange framework with the MEAN stack. The MEAN stack has limited application within the AEC industry, the novel Revit plug-in bim.js represents one of its pioneer implementations. Although this Revit plug-in was in the development phase, it was already able to export the extruded geometries at the time of testing. Eventually, Strabag stopped actively developing bim.js and moved towards the SCOPE project (SCOPE 2022). The shift towards MEAN stack was not made in order to solve the problems found in STEP-related, mostly legacy software tools, but to try another approach with web-based actively developed tools, and to test its appropriateness for the data exchange. The MEAN stack represents a software stack, a combination of software components, which suffice for realizing a web platform, and within this dissertation it was considered for facilitating the data exchange with the use of web technologies. Setting up the new framework gave promising results as it offers numerous options as a widely used and supported solution. Preceding analysis described the possibilities to store building data models mostly based on the STEP standard. The problems of storing and visualizing of geometrical and non-geometrical data did not occur with the previously tested file-based solutions because the storage for files and viewers already exist. Therefore, the research is extended towards the analysis of storage and GUI realization with the MEAN stack, where a shift towards the web-based technologies is addressed. The main reasons for a switch to the MEAN stack are because the STEP schema is:

1. Not complete. A predefined schema can hardly encompass all the domains and software tools in the AEC industry. MEAN stack uses a semi-structured database allowing entries that are not predefined to be used. In that way there are no limits for the non-proprietary storage concepts.

2. File-based. The STEP schema framework, including the tested software tools, considers that the exchange of information is done via files supported by a specific schema. This type of the data exchange reflects a sequential exchange process, similar to an assembly line in the manufacturing industry. This approach is not suitable for the AEC industry, and in the industry of information technologies is considered deprecated. A real time exchange reflects the processes in the AEC industry, and it is a widely accepted exchange information technology.

3. Static. The STEP schemas cannot grow and shrink depending on the data requirements, which is possible with the dynamic semantic relations. In this way it is also possible to relate the data to other databases.

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As a new technology that might be more appropriate for the data exchange, the MEAN stack is considered. An important advantage of the MEAN stack is that it is actively developed compared to the legacy software tools used with the STEP standard.

MEAN stack (MEAN v2.0.1) is a combination of MongoDB, Express.js, AngularJS and Node.js. It is a JS-based framework used mainly for creating web application. This framework can be used with Three.js (three.js r90) library, which is a JS -based library that supports the definition of the 3d elements. That can facilitate the representation of the defined geometries using standard browsers that support JS. The use of proprietary specialized software solution could be avoided in that way for representing the geometry information. As Three.js does not provide sufficient geometry modification methods, the use of more rich geometry kernel such is OC will also be required.

In the MEAN stack, data is stored in the MongoDB. For that reason, the functionalities of the MongoDB (MongoDB 3.6.4) are analyzed. A framework is tested using a Windows 7 command prompt that can access the MongoDB and query the information. It is possible to modify the database straight from the command prompt. The easier way is to use additional software that helps accessing and editing the stored data. There are several GUIs that serve for the manipulation of Mongo database. As part of the MEAN framework research Studio 3T (Studio 3T 2018.2.5) and MongoDB Compass (MongoDB Compass 1.13.1) are reviewed. They also have their own command prompts that provide more possibilities for the manipulation of the stored data.

An interesting approach is described in Rasys et al (2014) which suggests use of semi-structured data for information integration that would be used for facility management in oil and gas industry. That concept could support the heterogeneous information which is common in the AEC industry. JS based 3d objects are used so the geometrical content can be viewed with web browsers and not dependent on a domain-specific software tool. Table 4 summarizes the characteristics of MEAN stack.

Table 4 Characteristics of MEAN stack technology

	Advantages	**Disadvantages**
MEAN stack	Large user community	This framework has not been widely used in AEC industry
	Semi-structured database MongoDB provides flexibility	Missing many standards (e.g. terminology)
	Web-based data exchange	Not implemented with AEC software tools
	Multiple possibilities to define geometrical information (three.js, OC)	
	Multiple software solutions accessing and managing the database (Studio 3T, Compass…)	

bim.js is tested as a rare application based on MEAN stack within the AEC industry. Since it is in its beta phase, the test files were provided to analyze the stored data. Bim.js is a plugin for Revit. When a family is defined (currently supporting only the extruded families) it is possible to connect the Revit family data to the MongoDB using the MEAN stack. In that way, the data stored in the native Revit storage is translated into three.js and stored in MongoDB. The two data storages can be synchronized during the work. Geometry of the elements in the MongoDB is defined in JSON format using the three.js JS library. In that way, the MongoDB storage can be accessed through the regular web browsers supporting JS. The server, communication and the front-end are developed using other parts of the MEAN stack, namely Express.js, AngularJS and Node.js.

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The advantage of MongoDB is that it is a semi-structured database and it does not strictly define which information will be stored in JSON format. In that way it is possible to support domains and elements which are not parts of the existing conventional schemas like STEP or IFC in an easier manner. Flexibility of the database is an advantage as it allows a developer to overcome the problems in the existing structures. However, the lack of structure and flexibility of the database is at the same time the downside for the implementation, as it difficult to follow continuously evolving structure with the applications using it.

The problem with the MEAN stack is its low implementation in the AEC industry, and currently there are no standards which can be implemented as such for the data exchange purpose which could make the best use of the technology. In order to use the data in multiple software tools, the data has to be recognized by other applications. The geometrical and non-geometrical attributes depending on the software- or domain-specific exchange requirements need to be found and eventually interpreted to be used by the receiving application. Since in this dissertation a pilot system architecture is realized with the MEAN stack, the existing terminology standards including classification, hierarchy and structure are reconsidered in order to facilitate data validation and preprocessing.

2.4.5. Microservices

Microservices is a type of a system architecture consisting of multiple independent applications instead of a single monolith application. Based on Dragoni et al (2017), a monolith software application consists of modules which cannot be executed independently. On the other hand, modules of a microservice application are distributed and perform partial services. The comparison of a data exchange application can be found in the research paper Sibenik et al (2021). The reason why microservices have been considered for the system architecture for data exchange between architectural design and structural analysis is the way the AEC industry operates. The project-specific teams are making a loosely coupled systems, heterogeneous workflows and numerous software tools, create a complex ecosystem which cannot be supported by a single digital solution. Microservices offer a possibility of creating a combination of modules for specific needs in a particular workflow or company. However, this approach has not yet been thoroughly investigated in practice.

Docker is the most popular product supporting deployment of microservices on the market, and it uses containers representing specific application modules. A solution with microservices has different advantages and disadvantages compared to the monolithic architecture, and it is summarized in this section. Single containers communicate with HTTP protocols and REST API. Containerizing a database which is an individually running server and not logically part of a monolithic system architecture does not make a significant logical change. The system with a separate storage can already be considered as individually deployed component regarding the database connection. The separation of presentation layer (GUI) and data management (business logic) makes the modules smaller and more task-specific, however, the geometry kernel can make this connection complex when the microservices are used.

Complex systems and changing workflows in the AEC industry could benefit from the distributed systems provided on the small scale: greater possibilities to integrate efforts in the disperse community which aim to solve the problems in the AEC industry; partial solutions can be used together to achieve a required solution, even if the underlying technologies differ; it can lead to an IoT ecosystem which is considered to be the industry's future (Woodhead 2018), not limited to the data exchange. Additionally, containers have multiple advantages regarding the performance, portability, more convenient deployment and sharing. Since the majority of data management tasks

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required during the exchange have not yet been standardized, they might need editing, or a complete replacement to support a specific planning workflow. Different workflows can involve multiple geometry interpretations for same building elements, requiring tailor-made solutions to serve varying needs of the industry. The tailor-made solutions can be created in microservice system architecture by combining multiple containers and adding the new ones instead of the development from scratch.

Hoffmann et al. (2019) find that combining modules which can be individually replaced and reorganized would make great advantage to support a heterogeneous business process and provide new technical solutions, but also deliver new problems, as coordination, which already poses a challenge for microservices. This can also deliver new business processes as the services can be individually software independently developed and provided to the end user. Since the considered concepts exchange serialized data, problems could occur if the containers are realized with different programming languages. The full potential of containerization could be used when the API Gateway is able to transfer more data with a similar performance as a monolithic system. This approach could deliver various business processes which have not been possible until now. The single containers could be setup in various ways to respond to different data-exchange needs of end users. The microservices as single methods can deliver new business processes not only limited to the data exchange process.

Multiple approaches for creating a data exchange solution based on microservices can be considered, involving various ways to containerize a database, business layer with data interpretation, and GUI. Continuous communication of a business process layer with the database requires implementing the conversion methods before and after each of the methods updating the data. This approach may end up being computational expensive compared to the monolithic architecture, but it provides a possibility of flexible constellation of interpretation methods which is desired for various heterogeneous processes. The advantage of individually containerized methods is that the methods can be separately edited, new ones can be added or existing ones removed, without distorting the whole system. This means as well that a different database, GUI or geometry kernel can easily replace the existing ones if needed. More attention must be paid to communication processes between the services. An overview of characteristics is presented in Table 5.

Table 5 Characteristics of Microservices and Docker technology

	Advantages	**Disadvantages**
Microservices / Docker	Large user community and good references (e.g. Amazon)	Not actively used in the AEC industry
	Actively developed	Extensive communication between containers could show performance drawbacks
	Web-based data exchange	Not yet developed to smoothly incorporate required aspect, e.g. GUI
	Possibility to automate single procedures and incorporate them in a required system	

To sum up the overview of the state-of-the-art technology: the research considered existing standards, geometry definitions, multiple system architecture frameworks, which could already or in the future answer the needs of the addressed data exchange. The most popular data exchange solutions in the AEC industry involve various applications of the IFC standard, which has its origins in the STEP standard. However, managing STEP schemas and data is not sufficiently supported with the existing software tools, as they resulted with some problematic performance and are not actively

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developed. At the same time, a pioneer use of MEAN stack with Revit, an actively developed web-based technology, was part of a DATAFILTER project. Besides its limited application in the AEC industry, initial tests showed great flexibility to support desired tasks. Therefore, the work was pursued with the MEAN slack, although its flexibility und lack of structure could represent a problem in the future. To reduce this disadvantage, existing accepted structures were considered for the implementation. Finally, the microservice technology was considered to modularize the framework, and will be part of the future work. The details of the actual implemented system architecture are presented in the second part of the dissertation. The future brings new technological solutions for data management, visualization, or storage, however, the current technological solutions could already be used to solve at least some of the occurring issues within the AEC industry, as will be demonstrated on the provided solution.

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3. Objectives

The main objective of this dissertation is to realize a seamless data exchange between the architectural design and structural analysis models. Since the solutions to the problem of erroneous data exchange have already been addressed in the industry and academia, but they have not solved the problem, it is necessary to identify the issues which still hinder the seamless exchange. Therefore, the initial objective of this dissertation will be the identification of obstacles which hinder the exchange process. The second objective is to define a new data exchange process which is able to overcome the existing obstacles. This objective will be realized with a proposal of a novel data exchange framework between architectural design and structural analysis. As the framework cannot be used in practice without a corresponding implementation, a system architecture will be developed which can support it. The system architecture will be developed with a single model, and verified with additional models. The final objective of the dissertation is to consider additional functionalities to extend and optimize the implemented framework. Therefore, an extension of the framework will be considered to allow for automatic preparation of structural analysis models.

The objectives will be addressed through the following journal papers:

1. “Assessment of model-based data exchange between architectural design and structural analysis”, Journal of Building Engineering, Volume 32, Goran Sibenik and Iva Kovacic (2020)
2. “Interpreted open data exchange between architectural design and structural analysis models”, Journal of Information Technology in Construction, Volume 26, Goran Sibenik and Iva Kovacic (2021)
3. “Implementation of open data exchange between architectural design and structural analysis models”, Buildings, Volume 11(12), Goran Sibenik, Iva Kovacic, Valentinas Petrinas and Wendelin Sprenger (2021)
4. “Automated preprocessing of building models for structural analysis”, Gradjevinar, Volume 74(3), Goran Sibenik, Iva Kovacic, Valentinas Petrinas, Wendelin Sprenger, Dario Bubalo and Nikola Ruzicic (2022)

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4. Research design and methodology

The dissertation is conceptualized with the aim to answer the main research question (RQ):

How to achieve a seamless data exchange between architectural design and structural analysis models?

Since the solutions already exist which promise such exchange, the reasons why the difficulties are still found in the practice need to be investigated.

Therefore the first question answered in this dissertation is:

RQ1: Which drawbacks in the existing technologies hinder seamless data exchange between architectural design and structural analysis models? Such analysis is required before a new proposal can be developed, and it is presented in Publication 1.

The second question aims on providing a solution for the identified problems:

RQ2: Which framework concept satisfies requirements for seamless data exchange between architectural design and structural analysis? Publication 2 includes an analysis of technologies which could be used to provide a satisfying solution. Additional overview of technologies is presented in Section 2.4. The resulting framework, presented in the research paper, is able to get around the existing problems and to reach a seamless exchange.

The proposed framework requires implementation with the building model:

RQ3: How can the novel framework proposal for a data exchange between architectural design and structural analysis be implemented? In Publication 3, presenting implementation and verification, the data exchange process is realized with a single prototype building model, to assess a full implementation of the novel data exchange framework. The implemented framework is verified for the use with additional models. In the verification step, the framework is tested with models originating from different practices and its potential for the use in practice can be studied.

Finally, this dissertation went a step further and considered achieving an automatic preprocessing of a structural analysis model, in order to reach a fully automated creation of analysis-ready models. The question:

RQ4: Can the proposed framework be optimized with additional functionalities? is studied with the novel framework in Publication 4. The preprocessing steps enhance the novel framework, and aim to direct the data exchange to a prompt design feedback.

The developed and implemented methodological steps are represented in Figure 7.

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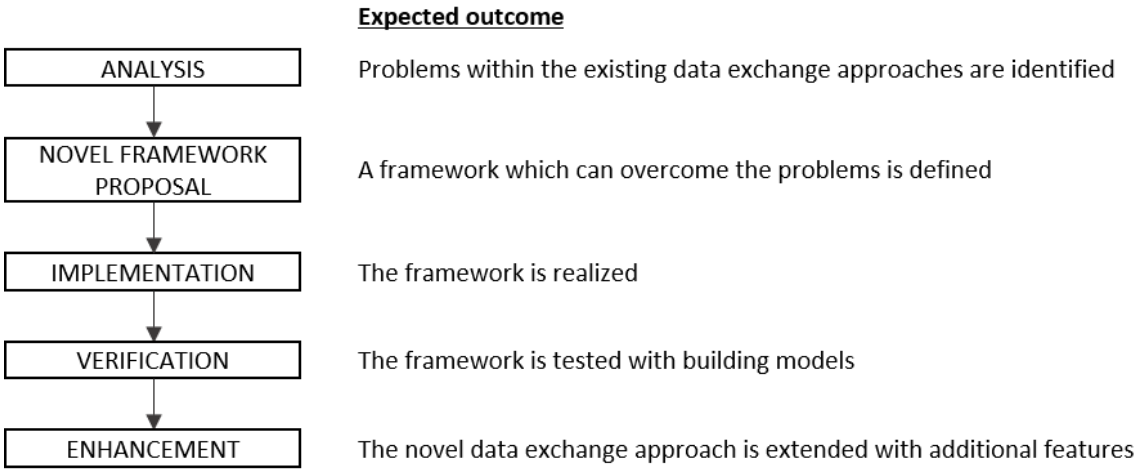

Figure 7 Research methodology

All the above described methodological steps have been successfully implemented and described in the research papers. The analysis part is described in the research paper "Assessment of model-based data exchange between architectural design and structural analysis". Novel proposal belongs to the research paper "Interpreted open data exchange between architectural design and structural analysis models". The implementation and verification are described in a single paper named "Implementation of open data exchange between architectural design and structural analysis models". The enhancement is presented in "Automated preprocessing of building models for structural analysis".

A detailed description of all methodological steps can be found in the corresponding papers. The overview of the methodology and methodological steps, each performed with a suitable combination of methods, are presented in the follow-up.

4.1. Analysis

Analysis of the data exchange process is performed through literature review, actor-network theory and critical reading, writing and thinking, and system analysis in order to assess the state of the art of the data exchange process. Further on, the data exchange process with multiple software tools is simulated through a comparative study which involved multiple pilot studies. Each study included modelling and transferring of building data, which is visually analyzed. Visual analysis, qualitative data analysis and causation are the methods that allowed to allocate the drawbacks in the existing technologies.

4.2. Framework proposal

The research step which aims to result with a novel framework is based on the analysis step and involves further literature review and critical reading, writing and thinking. Based on the findings, the framework methodology is used to direct the future steps for the data exchange process. The novel proposal sets a focus on classification and qualitative comparative analysis for interpretations leading to implementation.

4.3. Implementation

Implementation process involved classification and qualitative comparative analysis for a definition of rules for data exchange. Classification and qualitative comparative analysis are the methods already used in the framework development. The implementation process followed with the

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implementation driven research such as programming, database organization and management, algorithm definitions and APIs analysis and inclusion within the system architecture. It was developed as a pilot study.

4.4. Verification

The verification involved two more pilot studies which resulted as a comparative study. The verification was as well implementation driven research with programming, database organization and management, algorithm definitions and APIs analysis and inclusion within the system architecture. The classification and qualitative comparative analysis was further used for the missing parts of the implemented framework.

4.5. Enhancement

The enhancement was primarily developed around a case study methodology. The case study with a literature review served for reasoning and critical reading, writing and thinking in order to provide an additional part of the framework facilitating preprocessing steps. The new part of the framework was implemented, and included the system architecture development with the focus on programming, databases, algorithms and APIs. The additional part is verified through expert interviews organized as a panel discussion.

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5. Summary of publications

Answers to the posted research questions:
RQ1: Which drawbacks in the existing technologies hinder seamless data exchange between architectural design and structural analysis models?
RQ2: Which framework concept satisfies requirements for seamless data exchange between architectural design and structural analysis?
RQ3: How can the novel framework proposal for a data exchange between architectural design and structural analysis be implemented?
RQ4: Can the proposed framework be optimized with additional functionalities?

aim to provide the answer to the main research question:
How to achieve a seamless data exchange between architectural design and structural analysis models?

All the particular questions are answered by the corresponding journal papers.

Publication 1 addresses primarily the **assessment** of obstacles within the existing practices. The **novel framework proposal** is described in **Publication 2**. Publication 2 contains a brief explanation of **implementation**, which is extensively described in the third research paper (**Publication 3**). Publication 3 describes as well the **verification** step. The **enhancement** builds up on the previous steps, especially Publication 3, and is presented in the fourth research paper (**Publication 4**).

Publication 1: Goran Sibenik and Iva Kovacic (2020) “Assessment of model-based data exchange between architectural design and structural analysis”, Journal of Building Engineering, Volume 32, gives a thorough assessment of the data exchange between architectural design and structural analysis in academia and practice. In this paper, a literature review is performed to identify the state-of-the art in the existing practices. The state of the industry characterized by SME actors and heterogeneity of the workflows and software tools led to a conclusion that the greatest potential for a seamless data exchange lies in open standards. The most commonly used open standard for this particular exchange is the IFC standard. To further examine such a data exchange, a typical workflow is described and critically reviewed. The processes influencing the IFC-based data exchange have been mapped into the existing ecosystem directing the data exchange using literature and workflow analysis. The research was concluded with a comparative study to identify the drawbacks in the IFC-based data exchange between architectural design and structural domain models. The results of the comparative study are related to the drawbacks in the data exchange procedure and propose strategies for systematic improvements of inter-domain data exchange. Obstacles in the data exchange process are multiple, but can be ordered according to the origin of the problem. The highest ranked obstacle were missing interpretation processes between the domain-specific models, followed by the missing domain-specific subschemas, and finally the certification process which should be solved after the other higher ranked issues. The missing interpretation and domain-specific subschemas are the main issues addressed in the rest of this dissertation.

In Publication 2: Goran Sibenik and Iva Kovacic (2021) “Interpreted open data exchange between architectural design and structural analysis models”, Journal of Information Technology in Construction, Volume 26, a novel framework is developed which deals with the previously identified issues. The existing academic research and successful practices were presented, to provide a base for the novel solution. Automating of procedures are evermore present in the research, but not common for the data exchange between architectural design and structural analysis. The missing

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interpretation steps, which had been identified as the crucial obstacle for a seamless data exchange, are closely related to the multiple domain-specific models. Interpretations refer to model or data transformations, which have not been realized in standard data exchange practices, they are mostly manually performed by end-user and based on experience. Without the multiple models, no interpretation between them can take place. Therefore, the novel framework was conceptualized with three parts: classification, interpretation and automation. The classification part covers the multiple domain-specific models, the interpretation steps are defined which relate them to each other, and the automation part relates the domain-specific models to the native software tools used by architects and structural engineers. The automation part is closely linked to the certification process, but the problem of certification has not been considered in this work. The classification systems and the related standards were critically reviewed. The domain-specific classification systems need to clearly distinct the building elements, mainly based on their geometrical properties, in order to be suitably defined for digitalization purposes. The existing classification showed some properties opposing the recommended standards for classification. Therefore, the new requirements for the classification systems are proposed. The documentation about the interpretation steps are barely found in the literature, and do not exist in the form suitable for digitalization. The “black-box” implementation in the software tools is not sufficiently reliable for the end users. Therefore, an approach to document the intuitive interpretation procedures is presented, and the framework for interpretations is defined. Finally, the paper addresses the automation part of the framework with the help of APIs, specific for each software tool. A simple test case is presented to represent a possible implementation.

System architecture for the novel framework is described in Publication 3: Goran Sibenik, Iva Kovacic, Valentinas Petrinas and Wendelin Sprenger (2021) “Implementation of open data exchange between architectural design and structural analysis models”, Buildings, Volume 11(12). Publication 3 deals with the implementation and verification of the novel framework. The system architecture consists of multiple developed software tools, and each builds on multiple existing technologies, such as databases, geometry kernels, data standards, programming languages, etc. These had been reviewed before the new solutions were realized. The new solutions involve IFCtoJSON, strucToRISE, redDim and RFEMimporter. Autodesk Revit and RFEM Dlubal were chosen as the end-point software tools of the data exchange process, however, the implementation used the IFC export from Revit as a starting point because of the increased flexibility and possibility of using other IFC exports, although it gives a suboptimal starting point compared to a direct connection with Revit. IFCtoJSON reformats the IFC building data model to JSON format, so the building model can be used with a Mongo database. The IFC model is not used in its original format, although the majority of terminology originates from the IFC data model. The geometry is defined with the OC kernel, so the methods available within OC can be used to define the data transformations as interpretations. strucToRISE filters and restructures an IFC building model in JSON format, and a resulting building model is the architectural design model with the proposed classification. redDim is able to interpret architectural design models and create structural analysis models. The interpreted structural analysis model is imported to the RFEM Dlubal with the help of RFEMimporter which uses the RFEM Dlubal API. Such system architecture was developed with a pilot building model of Villa Savoye, characterized by typical geometries such as columns with square and circular cross sections, and walls, straight and rounded, and slabs, flat and tilted, with constant thicknesses, belonging to the research scope. The materials used in Villa Savoye are concrete and bricks. The implemented system is verified and extended with two external models from a German engineering company. The results are promising and the system architecture is able to interpret and correctly import all three models in the structural analysis software tool. The interpretations which were required are reduction of dimensionality and reconnecting elements.

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Publication 4: Goran Sibenik, Iva Kovacic, Valentinas Petrinas, Wendelin Sprenger, Dario Bubalo and Nikola Ruzicic (2022) “Automated preprocessing of building models for structural analysis”, Gradjevinar, 74(3), presents the extension of the framework with additional functionalities. The analytical building models, interpreted and imported with the system architecture presented in the Publication 3, available in the RFEM Dlubal, are used as a starting point for the new functionalities. Such models are not yet ready for the structural analysis, and require additional information which is usually assigned by structural engineers. This process is manually performed in practice. The preprocessing steps are investigated for a possible automation within the novel framework. The case study methodology is applied to understand and define the preprocessing steps. The preprocessing methods were implemented with the two models originating from the same company which was investigated within the case study analysis. The implementation of the framework extension involved the existing system architecture and RFEM Dlubal API. Although the methods assigning new information can be completely automated, additional inputs were left to structural engineers due to the lack of explicitly defined information in the models and multifold activities similarly frequently occurring in practice. The resulting models are verified within the expert panel discussion, and emphasising the discrepancy between the BIM approaches and possibilities of software tools and the practice. Difference between 2,5d and 3d analysis is evident, and the 3d analysis is not yet sufficiently reliable for the engineers. This problem of the “black-box” analysis is similar to the “black-box” interpretations, and do not allow the project stakeholders to stand behind closed software performance. However, the clear and open preprocessing steps are regarded as beneficial, whether implemented as part of 2,5d or 3d calculation. This paper rounds up the research of a seamless data exchange between architectural design and structural analysis models.

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6. Conclusion

This dissertation and its main question “How to achieve a seamless data exchange between architectural design and structural analysis?” opened several topics, which were addressed through multiple methodological steps of the research design. The problems which exist in BIM and the seamless data exchange cannot be solved from one perspective only, as they originate from the aspects of people, process and technology. This dissertation considers the existing processes and technologies and aims on improving the data exchange from the technological aspect. It is not possible to isolate closely tied issues regarding the process, people and technology, and therefore the proposed solutions tackle all three aspects in a certain amount. The point of departure for the new framework required an identification of the drawbacks in the state-of-the-art technologies, which is primarily found in the missing interpretation between multiple building model representations. The additional requirements were to provide a suitable way to support multiple model representations and facilitate the use of the existing proprietary solutions with it. These concepts, formalized as a novel framework, make a base of this work.

The novel framework deals with the identified technological drawbacks of the data exchange. The usefulness and usability of the proposed framework through implementation and verification demonstrates a potential in achieving a seamless data exchange. The framework can be extended to further automate design steps which was also implemented and verified within this work. The BIM planning approach needs significant improvements from multiple aspects, and the aim of this dissertation is to answer a single problem of the data exchange between architectural design and structural analysis.

The limitations of this study is that it focuses on several building models and isolated practices. The framework should however be able to satisfy other similar constructions. Structural analysis practices are similar for the Germany, Austria and Switzerland (DACH) region. The extended investigation should include other countries, even the ones legging behind with the BIM implementation, as better suited tools for existing practices could improve the implementation speed. A limited scope of software tools is investigated, other tools might show additional problems. A wide practical implementation of the proposed solution has not yet been performed, as it has not been developed as a market-ready product.

Next steps can be regarded from multiple aspects: a) improving the technology for the data exchange, b) improving the processes which exist in the practice, c) creating and delivering more intuitive and user-friendly solutions which will be more used in practice. In order to avoid the redundant work and increase the productivity in the planning process, all three aspects need to be considered. This doctoral thesis thoroughly addresses an important topic in the design process, and can serve as an exemplary solution for similar problems. The complexity of the AEC industry is multifold, whereas the standards are vaguely created to satisfy multiple heterogeneous workflows, the software tools are mostly globally used and the tailor-made solutions rarely exist on the marked. Further research is urgently needed to unify the local practices with the global standards, as the technologies to answer such market demands are available.

The new concept can be improved in two ways: i) technological improvement and ii) procedural improvement. The technological improvement involves further examination of existing technologies and finding new solutions for the existing problems. In that sense, the improvement of ontology-related solutions for achieving non-geometrical data harmonization, microservices as a support for handling heterogeneous interpretation automations, additional databases, etc. need to be kept up-to-date with the research to provide the optimal data management system, and can be investigated, or changed in future for each part of the framework, or a specific procedure within the framework.

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The procedural enhancement of the framework improvement examines the existing approaches with additional practices, requirements in other countries, and introducing the new domains to the existing workflow. As the novel framework is not limited to a specific domain, an exchange like architectural design to thermal simulation could reap similar benefits as an exchange to structural analysis since it involves similarly complex interpretations of geometrical information. Additionally, the exchanges between the predominantly semantically different domains need to be tested.

In-between the technological and procedural improvement is a development of a user-friendly interface, which already moves in the direction of product development and placing the solution on the market. The scope of this research can be extended in each direction: project phase – a similar solution for early design and technical design can be considered, some less common structural systems and corresponding building elements, geometries and materials. A bidirectional exchange is highly desired in the planning process, and the extension of the proposed framework will be considered in the future to integrate a data exchange from structural analysis to architectural design as well. All the future steps can be investigated on a smaller scale of a data exchange between architectural design and structural analysis models, and extended to a greater scale of the AEC ecosystem. The examined exchange due to its complexity has a potential to facilitate less complex communication processes during the development of a building project. Transparent and adaptive solutions are required on global scale to satisfy the heterogeneous and conservative AEC industry, accelerate and improve the workflows, and finally deliver more sustainable, safe and efficient buildings.

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PART II

PUBLICATIONS

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PUBLICATION 1:

Goran Sibenik and Iva Kovacic:

"Assessment of model-based data exchange between architectural design and structural analysis", *Journal of Building Engineering*, Volume 32, (2020).

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Journal of Building Engineering 32 (2020) 101589

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: http://www.elsevier.com/locate/jobe

Assessment of model-based data exchange between architectural design and structural analysis

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ARTICLE INFO

Keywords:
Data exchange
Industry foundation classes
IFC
Architectural model
Structural analysis model
Building information modeling
BIM

ABSTRACT

The emerging availability of numerous model-based design and analysis tools promises high interoperability in terms of data exchange, thus shorter planning cycles and higher design quality. However, seamless transfer of digital models across domains without significant data inconsistencies is still a major challenge in the practice. This paper aims to identify the procedural problems in the data transfer between architectural design and structural analysis and propose improvement.

This study reviewed the current data exchange practices, and concluded that data exchange based on the industry foundation classes (IFC) is the most spread in the research and software tools supporting architecture, engineering and construction industry. The study also analyzed the processes which affect the IFC-based data exchange. The interoperability of software tools through IFC files was tested in a comparative study. The testing results are reflected on the processes influencing data exchange, identifying the procedural problems and recommending the improvements.

Upon conducted analysis and testing, the authors propose the following strategies for the systematic improvement of the data exchange: (a) introducing interpretation rules in the data exchange standards; (b) focusing on multiple domain-specific building data schemas instead of on the integrated schema; and (c) developing a new certification process based on the domain-specific building data schema. The improvement proposal supported by the analysis provides a roadmap for the development of model-based exchange between architectural design and structural analysis.

1. Introduction

Digital data exchange between architectural design and structural analysis, when both domains use BIM authoring software tools, is still burdened with numerous difficulties, mostly caused by semantical problems and particularly challenging problems of geometric interpretation [1,2]. Seamless data transfer is essential for BIM-based collaboration; therefore the improvement of interoperability is a prerequisite to increase BIM usefulness and usability.

Within the scope of this research, BIM is regarded as a joint digital knowledge base supporting the activities of all stakeholders in AEC. It is based on various data sets, including geometrical and/or non-geometrical information; allowing data generation, exchange and processing within the life cycle of built structures. The full realization of BIM includes domain-specific modeling during the design phase as well as model-based information exchange which, when used together, demonstrate the full potential of BIM.

AEC industry stakeholders benefit in various ways from BIM workflows. The McGraw Hill Survey [3] identifies the reduction of errors and omissions as the most common benefit of BIM workflow, resulting in reductions of costs, duration and the amount of rework [4]. Identified that the main benefit of using BIM models in the design phase is the earlier collaboration of multiple domains, leading to a reduction of errors and omissions, and shortening the design cycle, resulting in a more cost-effective design.

There is a bulk of research involving technical improvements [2] or testing [5] of data exchange between architectural design and structural analysis. Research dealing with the data-exchange analysis on inter-organizational level addresses general processes rather than solutions for a particular domain-specific data exchange [6]. This paper adds to the existing body of knowledge through an assessment of domain-specific data exchange between architectural design and structural analysis models on inter-organizational level, in which next to the end-user processes, also normative, regulative and software

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https://doi.org/10.1016/j.jobe.2020.101589
Received 21 January 2020; Received in revised form 22 April 2020; Accepted 16 June 2020
Available online 7 August 2020
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development processes are included.

The aims of this research are to review the state-of-the-art of data exchange between architectural design and structural analysis, to identify the main problems via a comparative study, and to develop an improvement strategies proposal for this domain-specific data exchange.

The main question this paper aims to answer is**: Why does model-based data exchange between architectural design and structural analysis still not function without significant data and information losses?**

This paper aims to address the problems and issues of still flawed model-based data exchange between architectural design and structural analysis by:

a) Exploring the model-based data exchange practices between architectural design and structural analysis;
b) Exploring the procedures influencing the open IFC-based data exchange;
c) Identifying the origins of data losses and misinterpretations in the IFC-based data exchange between architectural design and structural analysis;
d) Identifying the necessary actions leading to a systematic improvement of the IFC-based exchange between architectural design and structural analysis.

In order to answer the research question and propose improvement strategies for the data exchange between architectural design and structural analysis domains, we will:

1) Assess the state of the research of data exchange between architectural design and structural analysis;
2) Analyze the state-of-the-art of data exchange in AEC practice;
3) Review and identify processes influencing the IFC-based data exchange using literature and workflow analysis;
4) Conduct a comparative study to identify the inconsistencies in the IFC-based data exchange between architectural design and structural domain models;
5) Link the detected inconsistencies to the procedure and propose strategies for systematic improvements of inter-domain data exchange.

This paper is structured as follows: Section 2 presents the problem statement and discusses current issues; Section 3 reviews the state of research regarding the data exchange between architectural design and structural analysis domains; current data exchange practices, including the IFC-based open data exchange, are presented in Section 4; the comparative study and results are presented in Section 5; Section 6 discusses the systematic procedural improvement strategies for the IFC-based data exchange and proposes an improvement roadmap; finally, Section 7 concludes the findings, limitations of the research and addresses the need for future research.

2. Problem statement

Building projects are unique by nature; the stakeholders and software tools vary from project to project, creating numerous planning workflows. A building model changes during the design phase and differs between the domains. The design phases and domains depend on the project-specific workflow. In this research, we analyze one of the most common exchanges – architectural design to structural analysis – that are part of the core design team and which is especially important in the developed design phase [7]. Although this research focuses on the design phase before a building permit is granted, similar data exchange practices between architectural and structural analysis models can be found during the whole building life cycle. During the construction, renovation or demolition phase, a structural model coupled with information such as construction schedule and activities, also called 4D structural information model, is needed for the time-dependent structural analysis [8], which is of particulate importance for structural safety management. The generation of such models from architectural models should be enabled at any user-specified time point, for which again a precondition is seamless exchange from architectural design to structural analysis.

The architectural design and structural analysis domains require two types of building models: physical model for architectural design and discretized model for further numerical simulation. Data exchange has traditionally been conducted by redefining information provided by the architects in a structural analysis domain-specific software tool. The more advanced model-based data exchange practices use digitally transferred building models. However, due to lacking interoperability or coordinated modelling conventions, a model-based data transfer leads to significant remodeling efforts, prone to errors and misinterpretations [9, 10].

Successful data transfers are based on specific modeling instructions, however often requiring various software-dependent workarounds [1]. Those workflows are commonly found within the “in-the-house” practices, or if a third party (e.g. project coordinator or BIM manager) defines the modeling and exchange workflows. Positive experiences also depend on the software tool combinations, as will be shown in Section 5, on interoperability testing. The focus of achieving a successful interoperability needs to be extended from solely technological issues towards the business processes, culture and values and management of contractual issues [11].

Numerous attempts to achieve satisfactory data exchange between architectural design and structural analysis can be found in the research or industrial practice related literature. However, these have not significantly improved the performance of data exchange in practice, and interoperability in the industry continues to improve very slowly [12]. To date, proposals have not been able to cope with the heterogeneity of the AEC industry.

This research aims to tackle the problems that occur within the data exchange process, while taking into account the reported findings from the current literature and research. The identification of errors in data transfer is a topic that is often explored in the literature. A major innovative contribution of this paper is the linking of these errors to the procedures on the inter-organizational level, from the perspectives of end users, software developers and normative and regulative instances.

The processes influencing the open IFC-based data exchange between the architectural design and structural analysis domains on the inter-organizational level are identified and analyzed based on the simulated end-user experience on the project level, which allows for more practice and end-user focused improvements.

The IFC-based data exchange between architectural design and structural analysis is examined on an inter-organizational level within the AEC ecosystem [13,14] in order to grasp the procedural problems. For instance, software development or software certification can be identified as the inter-organizational procedures strongly influencing the data exchange workflows.

Further, current research mostly proposes single and specific frameworks or new regulative or policy making practices (e.g. on the national level), without considering the implications on the existing practices in the industry, omitting to tackle the end-user experience which is dependent on various business processes and cultures and values. The novel contribution of this research paper is the proposal of improvement strategies for the existing processes on an inter-organizational level for the IFC-based data exchange, thereby distancing the improvement strategies from differing practices and cultures on the project level.

3. State of the research

This Section reviews the current research and theoretical academic models for data exchange between the architectural design and

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structural analysis domains.

3.1. Data exchange between the architectural design and structural analysis domains

Research within the academic community on the topic of BIM-based data exchange between architectural design and structural analysis mainly involves the use of the open IFC schema. First attempts to improve the IFC-based data exchange involved improvements of the IFC schema. The focus in the work of Weise et al. [15] was to introduce the requirements of the structural engineers into the IFC schema, based on the structural analysis and steel construction requirements. Weise et al. describe a workflow in which the structural engineers require information about the building elements from the architects, but the relationships between the proposed structural elements and the architectural elements were not part of their research. Later, Wan et al. [16] assessed the suitability of the IFC schema for the requirements of SAP2000 and six other structural analysis tools, and suggested several improvements to the IFC schema. In their work, the data exchange workflow was server-based and involved an additional step to transfer IFC building data model to S2K format because the SAP2000 software was not able to read IFC files. Serror et al. [17] introduce an extension to the IFC schema based on the FEM and CIS2 standards, focusing on earthquake simulation. The current version of the IFC schema is able to support most requirements in their structural analysis representation; however, the relationships between the corresponding domain-specific representations are still not defined within the IFC schema.

Several authors continued to work on improving data exchange from architectural BIM tools to structural analysis tools by proposing third-party tools that redefine exported IFC building models. Deng et al. [18] suggested the conversion of IFC files to an XML-based General Format of Unified Finite Element Model that can be imported to SAP2000, ETABS and, eventually, other structural analysis tools. The workflow suggested by Deng and Chang involved the filtering and adjustment of building element connectivity in order to exchange a useful structural analysis model. Qin et al. [19] further developed Deng and Chang's framework by using XML-based unified FEM as a communication tool between an IFC file holding the architectural model and the structural analysis software tools (ETABS, SAP2000, PKPM and STAAD). Liu et al. [20] created a software-specific integration tool which was able to use the IFC file to create a PMCAD file that can be imported into the PKPM structural analysis tool. Differences between the architectural and structural analysis tools were managed in the proposed third-party software-specific integration tool. Wang et al. [21] showed that the models exported from structural design tools in the form of IFC structural models need to be transformed before they can be used in structural analysis software tools such as MIDAS. Zhang et al. [22] developed an approach using the IFC-based unified information model, which is created from the architectural IFC-based model; thereby proposing the algorithms for four structural analysis tools (SAP2000, ETABS, ANSYS and MIDAS) which can map the prepared data from the unified information model. They propose using WebGL for the representation of geometry and a bidirectional web-based platform for the data exchange. Hu et al. [23] further developed this approach by introducing other case studies on exchanging architectural design and structural analysis models. Oh et al. [9] created an integrated information management system – a platform which can be connected to Revit and can manage multiple domain-specific models to emphasize the need of integrated planning. Ramaji and Memari [24] focused on the interpreted exchange between the two domains, and proposed a framework with the direct and interpreted data exchange units from an IFC file which, in the follow up, is imported to SAP2000 and SCIA. The same authors [2] defined a framework where the interpretations are performed within the IFC coordination view version 2.0 (CV V2.0) and two versions of IFC building data models: an architectural design input and a structural analysis output, with the interpretations similar to their preceding work.

All of the research described above addressed the data exchange problems between architectural and structural domains; identified the considerable differences between the models, and provided various solutions to the problems identified. The problems were addressed on a practical level, with numerous software or project-specific solutions being proposed.

Although most of the contributions listed above propose new frameworks, none of the proposed solutions have been widely accepted in practice, because of the heterogeneity of the AEC industry (particularly in the European market) and varying standards. The most promising proposals involve IFC-based data exchange that is intended to be software independent. However, IFC-based data exchange still depends on the software tool combination (see Section 5), lacks the required confidence of the end users, and keeps the aforementioned frameworks software-specific and dependent on the setup of each individual project.

[25] assessed IFC interoperability over a period of five years. They proposed four interoperability concerns (business, process, service and data), but they investigated interoperability of data only. Their results reveal a slow development of IFC-based interoperability. [5] tested data exchange between architectural design and structural analysis via a comparative study. However, they tested a model originating from Revit only and compared three types of exchange (direct link using native files; direct link using application programming interfaces (APIs); and indirect link using IFC), stating that the indirect link is the most common exchange. They identified the value change and information losses as technical problems of IFC-based data exchange. [26] also tested the interoperability of software tools with the IFC model originating from Revit, identified some technical problems and proposed solutions. Their research focused on IFC performance from the structural analysis perspective, with single building elements imported into various structural tools, but did not include a complete case study reflecting end-user experience.

Various problems, such as lack of motivation for software developers, lack of funding for standards development or insufficient testing procedures, have already been identified and improvements proposed to IFC-based data exchange by the academic community (e.g. [6,12,27]). The improvements proposed are at the level of the AEC industry, and are not focused to a professional domain, domain-specific data-exchange or software tool. The effects of these proposals to the particular exchange between architectural design and structural analysis was not considered by the above-mentioned authors.

3.2. Data exchange testing

This subsection provides a review of the data exchange testing methods, as used to test various software tools and their data exchange properties within the comparative study (presented in Section 5).

Two types of software testing are relevant for data exchange [28]:

- **Conformance testing**: This is performed when a product is compared to a reference system, such as a standard. Software tools are more likely to successfully work together (interoperate) if both conform to the same standard. Conformance, however, does not guarantee interoperability. In the conformance testing, software import and export possibilities were tested against the reference system separately.
- **Interoperability testing**: In software interoperability testing, the behavior of a tool is tested when it is interoperating with another product. Interoperability testing has certain advantages and disadvantages over conformance testing. It indicates problems that are interesting to the user and it can address issues that are not defined in a standard. The number of test cases is substantially bigger because the data exchange is separately tested for each combination of software tools.

In the literature, software tool tests regarding the IFC-based data

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exchange were based on both approaches: conformance testing and interoperability testing. In Lee et al. [29], conformance testing was used to validate a single IFC file on IFC schema compliance, its conformity to the IFC subschema (model view definition (MVD)) and design programming requirements. The main part of the IFC certification process for CV V2.0 (IFC2x3) is a conformance test. Software tools have a better chance of working together if they conform to the same standards, but conformance tests do not reflect the end-user experience and software interoperability in practice. A common approach to testing interoperability is by comparing two IFC files [10,30,31]. Multiple methods used for comparing two IFC files are unified in the study that defines metrics for quantifying the similarities and differences between the two IFC files [31]. The workflow described in [31] includes creating an IFC file using architectural BIM software, importing it to another software tool and then generating the second IFC file without making any changes. If software tools are tested using this methodology, the first tool needs to support the export by using the IFC schema, and a second one needs to do this for both the import and export. This requirement reduces the number of available software tools for testing. "Round-trip testing" is a special form of interoperability testing which tests the interoperability of a program with itself. It compares the IFC files imported into a design tool and exported back to IFC without making any changes. Support for round-trip scenarios is excluded from the support of IFC coordination view [32]. However, round-trip testing is specified as a recommendation for self-testing in [33].

4. State-of-the-art in data exchange practices

The following Section describes different data exchange practices; including the IFC-based open exchange, which is the most relevant data exchange practice for this assessment. Further on, the IFC-based data exchange between architectural design and structural analysis is explored in more detail. In addition, the processes influencing the IFC-based data exchange within the AEC ecosystem will be identified and analyzed on the inter-organizational level, from various perspectives – end user, normative and regulative instances, and software developer – via a literature review and workflow analysis.

4.1. Types and formats of data exchange

Data exchange between architectural and structural analysis models is particularly important within the design phase, because providing the architectural design together with the structural concept and calculations is a precondition for a building permit. It is also a process that benefits the most from the BIM workflow [34]. Several approaches to data exchange between the two domains exist. Ramaji and Memari [2] identified three possible ways to create a structural analysis model from BIM authoring architectural tools: (1) the structural analysis model is created in a native software tool; (2) the structural analysis model can be created from a native model by a structural analysis tool; or (3) an additional software tool (or a plug-in) is used to generate the structural analysis model. This classification is based on the primary role of the software tool that generates the structural analysis model: architectural tool, structural analysis tool, or a third-party data exchange tool (Fig. 1).

Looking at the data exchange process from the other direction, Aldegeily and Zhang [5] tested three ways to exchange data: (1) a direct link using a native file; (2) a direct link using API; and (3) an indirect link through a third-party channel. In this classification, the emphasis is on the parties defining the data exchange: a single software provider, two interoperating software providers, or an additional provider that is not part of the interoperating software tools.

Similar to Aldegeily and Zhang [5] and related to the most common BIM-based exchange in practice (buildingSMART open standards), two data exchange approaches are recognized: open and closed BIM. [35] defined the terms as follows: closed BIM refers to a workflow where software tools from only one software producer (or several cooperating producers) are used and the data exchange takes place via software-to-software interfaces; the open BIM approach refers to a workflow where an open, non-proprietary format is used for data exchange purposes. This data exchange classification is based on whether the accessible and modifiable intermediate building data model is used for the communication.

The software industry provides tools for the AEC industry that can support both open data exchange and closed software-to-software exchange. As described in the literature review (Section 3), the academic community focuses on improving open exchange, especially the IFC standard. The focus of the academic community in the data exchange classifications as suggested by Ramaji and Memari [2], Aldegeily and Zhang [5] and Bormann et al. [35] is on an additional software tool, an indirect link through a third-party channel, or open BIM respectively.

There are numerous reasons why third-party non-proprietary formats are considered the most promising solution for the digital data exchange in the AEC industry, such as:

- European statistics on AEC [36] show that offices mostly perform the tasks of a single domain, and therefore usually choose a software tool for their own needs without considering future collaborations. It is unlikely that all possible software tool combinations aiming to exchange information of interest will achieve a seamless data exchange with direct exchange interfaces;
- BIM workflows need to facilitate work with an integrated model. A single software tool that supports all the involved domains in design phase is lacking [4].

Other ways of achieving the exchange are therefore regarded as special cases and do not represent the current or future general practice. The only widely supported open building data exchange standard between architectural and structural analysis domains is IFC. At the moment, IFC is the most frequently implemented standard for BIM-based data exchange, with over 150 software tools claiming to support the schema [37]. Leading market software applications in the fields of architectural design and structural analysis claim to support either import or export or both of IFC data models.

Next to the software tools supporting export and/or import of IFC building data models while primarily dealing with their native data formats, there are tools intended for the management of IFC models. Although most of these support model viewing, mapping to additional file formats or checking the syntax of IFC files, some allow editing IFC

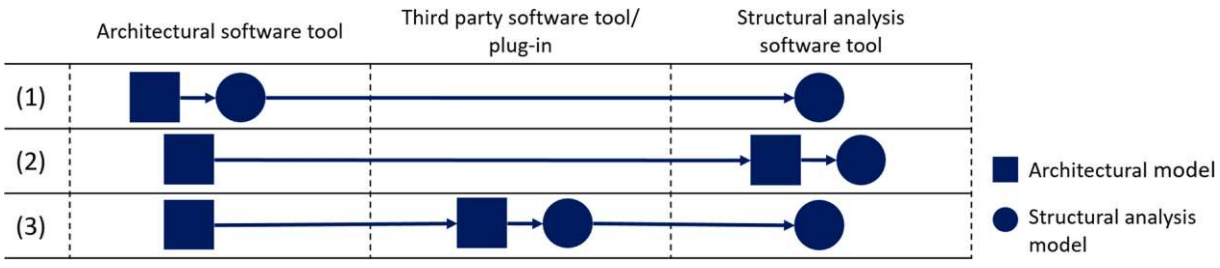

Fig. 1. Ways to generate a structural analysis model based on the authoring tool.

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files and preparing them for further collaboration (e.g. open source BIMserver platform, BIMData or xbim). However, focus of these tools is data management, rather than the conversions between architectural design and structural analysis models.

Data exchange workflows using IFC building data model are still sequential. The first model in the design phase is generally defined by an architect, in the architectural BIM authoring software tool. If the BIM authoring tool supports the IFC-based export, the architect is able to export the model to an IFC subschema, MVD. The export provides the user with the building data model based on the IFC schema, which can then be imported into software tools which support IFC-based import (e.g. structural analysis tools).

4.2. Process analysis in open data exchange

Ecosystems are dynamic and purposive networks where participants collaborate to create value that would not be possible for a single participant alone [38]. In this paper, we conceptualize the AEC industry as an ecosystem, as it is described in [13,14]. The concept of the AEC industry as ecosystem makes it possible to analyze an IFC-based data exchange system on two levels:

- Project level involving data exchange processes of import and export of building models from the end-user perspective;
- Inter-organizational level involving higher-level processes of various AEC stakeholders and their perspectives.

This two-level approach (project and inter-organizational interactions) shifts the focus from the already well examined project level and its processes, namely export and import of data, thus striving to achieve a more systematic insight by analyzing the processes taking place on the inter-organizational level. By investigating one use case (project level) through six similar workflows involving various software tools, the normative and regulative as well as software development perspective is included. Thereby the proposed improvement strategies address inter-organizational issues such as software certification or interoperability issues reflected in various software tool. There is a knowledge gap on the influence of higher-level inter-organizational processes, such as software certification or development, on the efficiency and efficacy of project level processes and data exchange performance.

On the inter-organizational level, the processes influencing IFC-based data exchange between architectural design and structural analysis are assessed from different stakeholder-perspectives in the AEC ecosystem using:

- Literature review [6,27];
- Recommendations of organization buildingSmart [32,37,39];
- Results generated through previous research-led teaching [40] and ongoing collaborative research with the industry [41].
- And finally testing of software tools (comparative study in Section 5).

The analysis showed that in addition to the direct influence of end users, data exchange is affected by the normative and regulative instances, as well as the software industry:

- **End-users: generation and exchange of building models** through various workflows as practiced by the end users (architects or structural engineers);
- **Normative and regulative instances: data exchange standardization and software certification** linking AEC practices with the software industry;
- **Software industry: software development** resulting in tools that support AEC practitioners.

The particular processes and their impact on the project level and data exchange results are described in the subsections below.

4.2.1. End-users: generation and exchange of building models

Generating and exchanging building data in software tools primarily depends on the authoring software tool interface, which will be more closely described from the software industry perspective (see Subsection 4.2.3). BIM authoring software tools provide architects and structural engineers with object classes representing building elements for specific domains. The software tools can provide multiple ways to generate the same building element. In addition to the software tools, this process depends on the end users' skills and competencies. The end-user concepts of the same building element can differ, which can result in multiple representations of the same real-world product.

Architects and structural engineers use the software tools for their design and analysis tasks intuitively or as instructed. The behavior of the end users can be influenced through the instructions, for instance, on the ways to generate and exchange building data provided by the software industry, but also through the norms and practices that define the workflow.

4.2.2. Normative and regulative instances: data exchange standardization and software certification

Within the AEC ecosystem, the AEC industry recognizes the need for regulative and normative instances to deal with specific topics, and establishes these instances with the aim of improving the planning workflows. Compared with other industries, the AEC industry is slow in adopting new processes and technologies [42]. The lack of new processes and technologies slows down innovation, increases risk and reduces productivity. Construction projects are often over budget and not finished on schedule. The greatest potential to change this comes from digitalization of the industry. However, in workflow digitalization, there are still many topics which have not been addressed, especially regarding the digitalization of data exchange. buildingSMART defines the standards for the IFC-based exchange, integrated building data model, and domain-specific data models (Fig. 2), as well as the regulative process for software certification, as summarized below.

- **Normative: inter-domain relations**

ISO 29481-1 [43] and ISO 29481-2 [44] describe information delivery manual (IDM) standards; where the former (part 1) defines the methodology and format and the latter (part 2) defines the interaction framework. Both are concerned with interoperability between software applications used during the design phase. Part 1 defines a basis for reliable information exchange and information sharing for users, as well as how user requirements are to be documented. Part 2 specifies the way in which events or "coordination acts" during the project have to be described. IDMs are intended to standardize the mapping of the exchange requirements for the exchange process.

- **Normative: integrated data model**

ISO 12006-3 [45] describes a taxonomy model; that is, how the

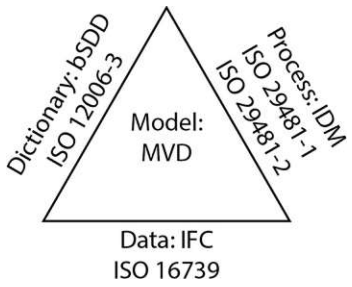

Fig. 2. Basic standards (based on [32]).

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concepts are defined, grouped and their relationship, where basic entities of a model are objects, collections and relationships. This taxonomy model is called buildingSMART Data Dictionary (bSDD) (previously called International Framework for Dictionaries (IFD)). The dictionary specifies a language-independent information model that can be used for the development of building data schemas for storing and providing information related to construction works. ISO 16739 [46] specifies the IFC schema defined using the EXPRESS data specification language.

- **Normative: domain-specific data model**

Interdisciplinary data exchange needs to encompass and unify the very diverse sets of information and models required for each domain, so standards are needed which specify the domain-specific data scopes, including the data exchange requirement lists. Therefore, there are currently two MVD standards valid for IFC4 data schema; namely, "IFC4 design transfer view" and "IFC4 reference view". The MVD reference view is suitable for workflows where a model is used only as a reference, while the design transfer view is designed for workflows where the next task is performed with the exported model and the modification of content is expected.

However, the most widely implemented MVD is CV V2.0, created for IFC 2x3, which is primarily intended for information exchange between architecture, structural and mechanical engineering, as explained in [37,39]: "The shared building information model is supposed to be re-editable by the receiving application. It includes the definition for spatial structure, building, and building service elements with shape representations, including both, parametric shapes for a limited range of standard elements, and the ability to also include non-parametric shape for all other elements."

- **Regulative: software certification**

The software certification process for MVDs created within the IFC 2x3 schema is only applicable to MVD CV V2.0. Since 26 June 2017 it has been available for IFC4 reference view. The comparative study in this paper (Section 5) tests the software tools certified with the most commonly used MVD, CV V2.0, which is currently the only certified MVD intended for information to be edited in a receiving tool. IFC4 design transfer view, which will be used for the same purpose with IFC4 has not yet been certified (at the time of writing). Several software tools claim to support design transfer view without certification, but the structural analysis tools still do not support the import.

The certification workflow is described in [33]; and for CV V2.0 it is organized by the Model Support Group and the Implementation Support Group within buildingSMART. The workflow is divided into export and import certification. For export certification, exchange requirement concepts are provided depending on the domain for which the participating software is used. There are three different types: architectural, structural and building services. The export validation is carried out through a self-check performed by a software developer and an additional check by a certification tester. Consequently export is checked automatically and manually. Import certification involves importing a series of import calibration files that correspond to the exchange requirements. In addition, complex test files are provided. Next, manual self-tests are carried out and the results are validated by the certification tester. Finally, software developers design an adequate user interface for export and import, as well as appropriate documentation.

4.2.3. *Software industry: software development process*

The way the building models are defined largely depends on the technical possibilities, usefulness and usability of the interfaces provided by the software industry. Although there are a large number of computational tools on the market, they are often developed without input from people with professional domain knowledge, thus failing to meet the end-user needs. Digital planning workflows are not standardized, so the software industry aims to support flexible user workflows, but there is a lack of modeling rules for specific tools, and the software tool architecture is not necessarily reflected in the interface.

In specific cases, such as data exchange, the digital tools being used must conform to regulations in order to provide certain exchange functionalities. For example, for data exchange with IFC, software tools can be certified for export and/or import of IFC building data models with a specific MVD (i.e. CV V2.0), which is intended for data exchange between architecture and structural analysis tools and is accepted by all leading software producers.

Fig. 3 illustrates the part of the AEC ecosystem examined by the current research, namely the data exchange ecosystem. It shows the processes taking place during the data exchange between architectural design and structural analysis models using the IFC schema. The data exchange processes taking place on the project level are shown in the inner dashed rectangle. The influencing processes on higher inter-organizational level such as software certification, standardization, software development and generating and exchanging building data and their relation to the project level is represented within the outer dashed rectangle.

5. Comparative study: interoperability testing

After conducting a thorough literature review and analyzing the procedures on the inter-organizational level that affect data exchange on a project level, a comparative study was conducted in order to determine the origin of the data-exchange-related problems. The comparative study presented below tested the software interoperability of various architectural design and structural analysis BIM authoring tools by transferring representative building elements.

The study began by setting the boundary conditions: interoperability testing was chosen as the software testing method; the software tools included Archicad, Revit and Allplan for the architectural design, and SCIA and RFEM for structural analysis; for the IFC-based data exchange the data generation and exchange practices recommended by software producers were used; a use-case building with structural system consisting of load-bearing walls and columns was modelled and transferred.

Next, an evaluation framework was developed, with a focus on geometry transfer, based on the adapted interpretation units from [24]. Four geometrical interpretations are evaluated: punctual, linear, planar and connectivity interpretations.

The comparative study was then conducted and presented according to the evaluation framework.

Finally, several exchange requirements from the comparative study were isolated and investigated from the end-user, normative and regulative, and software developer perspectives through the corresponding processes of generating and exchanging building data, standardization, and certification and software development. The analysis of the requirements within the procedures makes it possible to identify the points in the ecosystem that are responsible for problems in data exchange between architectural design and structural analysis.

5.1. *Research design and methodology*

- **Software testing methodology**

In order to test the end-user experience, we chose interoperability testing as the software testing methodology, because conformance testing does not give insight into the actual software behavior between software tool pairs. The aim was to test only one-way exchange: architectural design to structural analysis model. The comparison of two IFC files was not considered, because that requires an additional export from the structural analysis tool, and structural analysis tools do not always support import and export with the IFC schema [32]. Therefore, interoperability was tested with one IFC export and one import.

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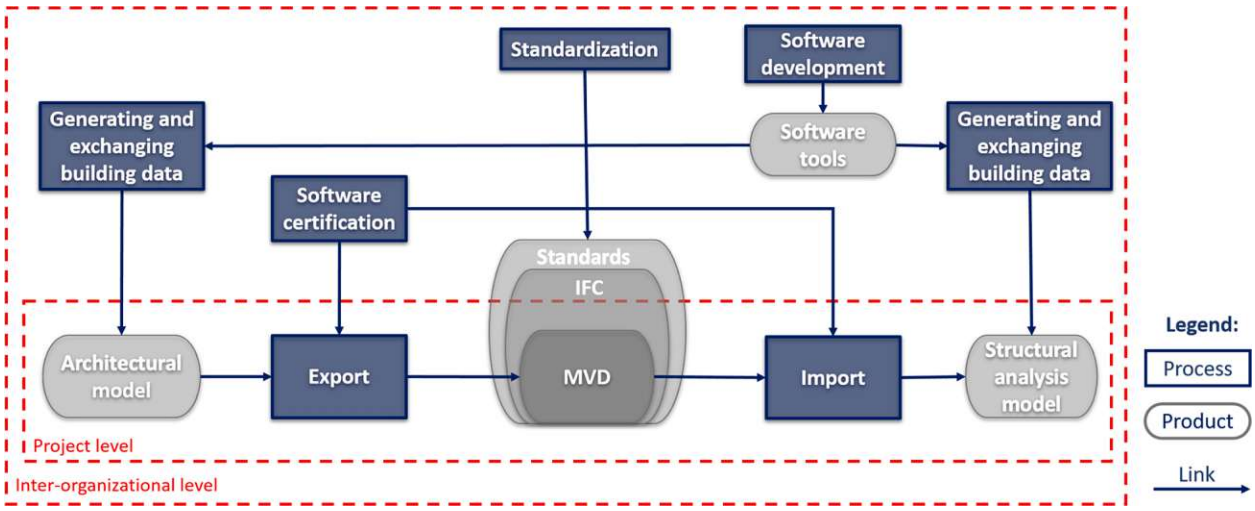

Fig. 3. Data exchange ecosystem: Processes within project and inter-organizational levels.

- **Software tools**

For the architectural design (creation) of BIM model variants and their export to three IFC building data models, we used three software tools: Allplan [47], Archicad [51] and Revit [48]. The two structural analysis software tools that were used to import the IFC building data models were SCIA [55] and RFEM [54]. Every application that was used in this research was certified for CV V2.0.

- **Modeling and exchange workflow**

The modeling workflow followed the modeling instructions, if provided, or the most intuitive approach for each software interface. Although all three BIM tools offered the possibility to edit IFC export-related properties of a single building element, the default assigned properties were not changed. Only the default interface settings for CV V2.0 export were used. In this way, three IFC building data models were exported. Following the generation of three model variants, the IFC files were imported into the two different structural analysis software tools. For the import, the default options were used and the complete model was imported. Thus, data exchange was accomplished with minimal end-user intervention.

- **Use case design**

The iconic building Villa Savoye (plans courtesy of Fondation Le Corbusier) was chosen as a use case model for the comparative study because it incorporates all relevant building elements (foundation, column, slab, wall, roof) commonly used in concrete frame construction, or load-bearing masonry and concrete wall constructions.

5.2. Evaluation framework

The imported models were evaluated by visually comparing the results with the required models, focusing on the geometry. Building elements were analyzed separately to see whether they contain all required geometrical data in the structural analysis software tools; and element coordinates were compared. Based on the reviewed literature, which defines the problems of data exchange between architecture and structural engineering, three groups of geometry-related "interpretation units" were identified: linear elements transformation, planar elements transformation and connectivity adjustment [24]. Single foundations, which are part of the generated use case model variants and are not addressed in the analyzed literature, were added as punctual elements transformation. Punctual elements are represented as points in the structural analysis software tools and their geometrical shape parameters become relevant for the analysis, but not for the building model. The results were summarized and categorized based on the interpretation type and the building element type, thus demonstrating a systematic interoperability overview.

5.3. Results of the comparative study

The comparative study looked at the inconsistencies that occurred in the data transfer from the architectural to the structural models, focusing on geometry issues. The results showed that the correct import and interpretation of building elements depends on the combination of software tools used, but none of the combinations gave satisfying results. Export from Allplan consists of 33.286 entities, from Archicad of 39.691 entities and from Revit of 32.387 entities. Building elements are represented similarly, with IFC classes IfcWallStandardCase, IfcOpeningElement, IFcColumn, IfcFooting, IfcBuildingElementPart, IfcSlab, IfcRoof, IfcStair, IfcDoor or IfcWindow, IfcStairFlight, but the number and occurrence of these entities differs between the exports. IfcShapeRepresentations with "Body" representation identifier that define 3d geometry of building elements also largely differ. In Allplan export 88% representation types are swept solid and the rest are boundary representation (brep), in Archicad export is 99% swept solid and the rest is surface model, whereas Revit has 66% swept solid, 31% mapped representation, 2% clipping and 1% brep. Inconsistencies found in the comparative study can be traced back to individual IFC entities, but as none of the elements did render completely satisfying, only some will be demonstrated in this paper. Table 1 shows the screenshots of the exported IFC models, Table 2 and Table 3 some of the inconsistencies found in the importing tools. Table 4 is a summary of interoperability performance during the data exchange from the architectural to the structural analysis model. A proper axis position was not regarded as an excluding factor.

Within this study, only a limited number of elements was used, so the identified problems are limited to these particular building elements. Multi-layered slabs were modelled as multiple one-layered slabs in Allplan, since Allplan does not support multi-layered slabs. The problems identified within this research were limited to the geometrical interpretation of the building elements involved in this comparative study. However, there are a number of further building elements relevant for the data exchange (these are often workflow specific). Nevertheless, the scope of the geometry interpretation problem is evident. All the geometry interpretation groups (i.e. punctual, linear and planar element transformation) and connectivity were part of the use case. The interpretation of punctual elements and the interpretation of the

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Table 1
Screenshots of models exported to IFC CV V2.0

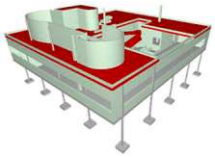
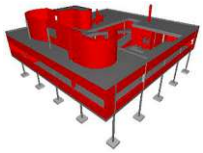
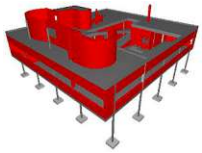
Model screenshot			
Native software tool	Allplan	Archicad	Revit

Table 2
Screenshots of inconsistencies identified in importing software tools (1).

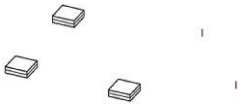
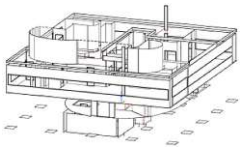
Model screenshot			
Interpretation	Punctual interpretation	Linear interpretation	Planar interpretation (a)
Software tool combination	Revit export/RFEM import	Revit export/RFEM import	Allplan export/RFEM import
Inconsistency	Foundations interpreted as planar and linear elements instead as joints	Columns are missing	Wall interpreted as slab, offset for half of the height

Table 3
Screenshots of inconsistencies identified in importing software tools (2).

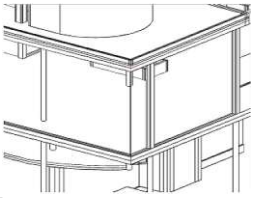
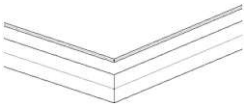
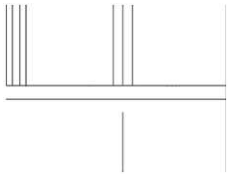
Model screenshot			
Interpretation	Planar interpretation (b)	Planar interpretation (c)	Connectivity
Software tool combination	Archicad export/SCIA import	Allplan export/RFEM import	Archicad export/SCIA import
Inconsistency	Missing multi-layered walls with air layer	Axis of planar element placed on the top plane of a slab, instead of the middle	Elements lose their connectivity after being interpreted

Table 4
Results of the comparative study.

Interpretation Type	Building element properties			Software used for the exchange					
	Type	Number of layers	Flat (–) Tilted (/)	Archicad		Revit		Allplan	
				SCIA	RFEM	SCIA	RFEM	SCIA	RFEM
Punctual transformation	Single foundation			×	×	×	×	×	×
Linear transformation	Strip foundation			×	×	×	×	×	×
	Column (square)			✓	×	✓	×	✓	×
	Column (round)			✓	×	✓	×	✓	×
Planar transformation	Floor slab	1	/	×	×	✓	✓	×	×
		1	–					✓	✓
		2+	–	✓	✓	✓	✓		
	Slab opening	2+		✓	✓	✓	✓	✓	×
	Roof	2+	/	×	×	✓	×	×	×
		2+	–	✓	✓	✓	×	×	×
	Roof opening	2+	–	×	✓	✓	×	×	×
	Wall	1		✓	✓	✓	×	✓	×
		2+		×	×	✓	×	✓	×
	Wall opening	1		✓	✓	✓	×	×	×
	Wall opening	2+		×	×	✓	×	×	×
Connectivity				×	×	×	×	×	×

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connectivity of interpreted building elements did not take place in any of the examined use cases. Linear and planar building elements were, in some cases, interpreted but the performance differed depending on the combination of software tools. The variants generated unexpected and unpredictable results. This emphasized that the use of a BIM workflow with IFC is not yet fully qualified to fulfill the inter-domain data exchange tasks.

Product models must be based on accurate information to serve the stakeholders' needs at every specific project stage. As the comparative study showed, at present this is not the case. For instance, the load-bearing property of a layer and information about the adjacent elements was generally lost during the exchange, so even the non-load-bearing elements were imported. Even if the load-bearing property of a specific element was available in the exported building model it was not considered by the importing software tool, thus representing significant problem for structural engineers, as the loadbearing properties get lost throughout the data transfer process. On the other hand, some information – such as axis position or foundations – was interpreted in a way that rendered them incorrectly in the structural analysis software tools. Certified software tools did not provide the means of performing the data exchange satisfactorily, because they failed to achieve interoperability.

5.4. Comparative study: effects of inter-organizational processes

This subsection links the exchange requirements identified as problems in the comparative study to the procedures of data exchange, as proposed in Section 4. Some exchange requirements from the results of the interoperability testing are located within the software tools and their interfaces, the buildingSMART concept lists and certification check lists [32] in order to allocate the problems in the procedures and develop proposals for procedural improvements of inter-domain data exchange.

The effects of inter-organizational processes on data-exchange performance were tested as follows:

- Several exchange requirements were selected and their presence in the software tools for architectural design and structural analysis models was investigated, documenting the effects of software development process;
- The exchange requirements were located in the MVD, where they are described as concepts, and in the IFC schema, in order to analyze the exchange requirements in the standardization process;
- The certification process was analyzed using the certification lists provided by buildingSMART and the software industry;
- The generation and exchange of building data was assessed by examining the availability of instructions and clarity of interfaces to perform the required modeling and exchange tasks.

Exchange requirements in MVDs are defined by buildingSMART through a selection of attributes and relations called root concepts. The root concepts are represented through entities that can be spatial, building, building services or structural elements. buildingSMART uses the concepts lists for the certification process which are available online for each of the root concepts [37,39]. These concepts are categorized as mandatory, optional, not relevant, or excluded. Furthermore, it is indicated whether each is an export or import requirement. The export requirements can be a requirement of architecture, building services or structural software tools. The concepts are the base standard for each MVD implementation in software tools. Additionally, checklists are available [32], which explain how the certified software tools supported the MVD concepts during the certification.

Table 5 presents the correlations between the MVD concept list and the exchange requirements from the end-user perspective. Concepts are described, as in the buildingSMART CV V2.0 concept list, by using the code, name and the relevance for the export and import, as well as the respective exchange requirement based on the end-user conception.

Table 5
Comparison of the MVD concept list and the exchange requirements.

Concept code	Concept according to buildingSMART concept lists	Exchange requirement	Export relevance	Import relevance
030-6-1	Geometry sweptsolid	Column geometry	Mandatory	Mandatory
030-6-9	Geometry mapped	Column geometry	Mandatory	Mandatory
030-6-1	Geometry sweptsolid	Wall geometry	Mandatory	Mandatory
210–1	Property set IFC common	Load-bearing property wall	Mandatory	Mandatory
110–2	Connectivity path	Connectivity wall	Mandatory	Mandatory

Table 6
Behavior of the concepts as described in certification checklists.

Concept code	Export certification			Import certification	
	Archicad	Revit	Allplan	SCIA	RFEM
030-6-1	Supported		Restricted[a]	Supported	Supported
030-6-9		Supported		Supported	Supported
030-6-1	Supported	Restricted[b]	Supported	Supported	Supported
210–1	Supported	Supported	Supported	Not tested	Supported
110–2	Restricted[c]	Supported	Restricted[d]	Not tested	Not supported

[a] Certain geometries in the certification process cannot be created within a software tool; however, elements from the use case are supported.
[b] Revit does not support layers thinner than 1.6 mm; such layers were not part of the use case.
[c] One type of connection is not supported, which was not a part of the use case.
[d] Allplan calculates the connectivity path only from straight walls.

Table 6 shows the same CV V2.0 concepts as given in Table 5, but with their behavior in the software tools during the software certification process as described in the certification checklists [32], for each of the tested tools. While columns are exported as swept solid geometry from Archicad and Allplan (concept code 030-6-1), they are exported as mapped representation (030-6-9) from Revit.

Finally, Table 7 shows if and how the concept was supported by the importing tools. The "properly imported" and "not properly imported" columns show the number of software tool combinations in the comparative study where the import results were or were not properly rendered in the importing software tool.

6. Data-exchange improvement roadmap

Based on the previously conducted problem identification on inter-organizational level and its effects on project-based data exchange, in the following Section the improvement strategies for the data exchange between architectural design and structural analysis on inter-organizational level, including relevant stakeholders and processes

Table 7
Behavior of the concepts in the software tools.

Concept code	Properly imported	Erroneously imported	Remarks when the exchange requirement is erroneously imported
030-6-1	2	2	Geometry not properly interpreted
030-6-9	1	1	Geometry not properly interpreted
030-6-1	2	4	Geometry not properly interpreted
210–1	0	6	Element not recognized by the importing tool
110–2	0	6	Property not recognized by the importing tool

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will be proposed.

6.1. End-user: generating and exchanging building data

In the comparative study the end-user actions were reduced to minimum deviations from the default options available in the software tools. All exchange requirements were supported in the software tools, and most of them could be created in multiple ways. Most of the software tools did not provide clear instructions on how to properly model the elements: this option was left to the architect. Multiple name and property definitions are left to the architect, without any instructions on how to define them (e.g. material).

The interfaces for the exchange differed significantly between the software tools. To change the export information, the architect has to be familiar with the IFC schema. On the other hand, the importing software tools provide little possibility to influence the import. This nears the "black box" scenario which should be avoided in the AEC industry [49]. [49] state that it is necessary to allow the end users without expert programming skills to make changes in a collaborative framework. This is provided to varying degrees in the investigated software tools; however, none of the export or import interfaces were completely open to the end user (allowed insight into the background processes).

In this research, the interoperability testing was conducted from the point of view of the end user following default settings. This means that the existing instructions, provided mostly by software developers, although lacking the digital building data regulations on the AEC industry level, were used for the generation and exchange of building data. In this way, the research does not focus on various workarounds which exist as common practice in the market, because they are software-tool-specific and exclude numerous stakeholders in the design phase. Thus the strategic improvements for this process are (a) more detailed modeling instructions for the end user and (b) clear descriptions of the open exchange interfaces allowing for end-user interventions. The effect of the improvements would still greatly depend on end-user behavior and it might not result with the same improvements between different software tools.

6.2. Normative and regulative instances: data exchange standardization and software certification

- **Normative: inter-domain relationships**

The data exchange workflow in the AEC industry lacks important inter-domain relationships between the domain-specific representations that are required for the digitalization of data exchange. The exchange requirements are exported as architectural elements to the IFC building data model, but the relationships between the architectural elements and their respective structural representations were not defined. This issue is partly addressed by buildingSMART through the IDMs, yet it was not considered for the most widely implemented CV V2.0 [50]. The mapping of the business process with the inter-domain relations remains in the hands of the software developers and software industry, and not the AEC industry or the end users.

The insufficiently defined workflows within the AEC industry and lack of collaboration with the software industry result in misinterpretations and models that cannot be used for the structural analysis as such. The outcome of digital data exchange depends on the interoperating domains and the complexity of the interpretation processes, the interpretation between the architectural design and structural analysis domains are significant. Slow standardization is recognized as a general AEC industry problem. The standardization of inter-domain relationships is greatly influencing data exchange and could systematically improve the inter-domain exchange. Defining the relationships for the purpose of digitalization requires a significant effort, and needs to be implemented through software development processes before it can be applied by end users.

- **Normative: integrated data model**

The IFC2x3 schema supports all the analyzed building elements from the comparative study. The exchange requirements defined in the architectural building data model as well as the exchange requirements needed in the structural analysis model are both represented in the IFC2x3 schema. However, the integrated data model of the IFC2x3 schema was not used for the data exchange between architectural design and structural analysis because MVD CV V2.0 encompasses both disciplines. Only the exported architectural building data model was defined within MVD CV V2.0, so the architectural model was directly imported to the structural analysis tools.

The workflow used in the comparative study involved a single MVD, so the structural analysis exchange requirements were never part of the integrated building data model, and the structural model was created from the architectural export by the structural analysis tools. In the comparative study, the role of the integrated data model is completely taken over by the MVD CV V2.0 for the exchange between architecture and structural engineering. Here, the proposed improvement strategy is to have the integrated data model resulting from the relevant MVDs.

Equally, the IFC schema does not reflect the end-user concepts, which makes IFC exports difficult for most end users to understand. Therefore any intervention with the IFC building data model requires professional assistance (e.g. from a data analyst or schema specialist). Thus the integrated model would need to be either simplified or supported with user-friendly interfaces that would allow for more user interventions.

- **Normative: domain-specific data model**

MVD CV V2.0 is a subschema defined by the list of concepts for IFC2x3. This MVD defines diverse requirements for a single MVD schema which software tools need to fulfill: three export and unique import requirement lists. However, the ability of satisfying these requirements still varies among the tools, and none of them was able to fully satisfy the requirements. When a specific exchange requirement is not addressed in the concept list, software developers treat it based on their own interpretation or judgment. In the comparative study the concept list was only partly answering the exchange requirements.

The list of concepts for export software tools is based on the unique concept list of the architectural export. CV V2.0 is a subschema of IFC2x3, and although it is rich some information can be represented in multiple ways (i.e. it contains redundancies). Occasionally the necessary exchange requirements are getting lost when being mapped from the architectural BIM software tools.

The list of concepts for import software tools is based on the unique concept list of import. Capabilities for importing specified exchange requirements vary among different software tools, and especially between the domains. Information which is not standardized in the MVD, but is still part of the export, is unexpected and unused in the importing software tool.

The concept of multiple MVDs has not properly come to life within the software tools. Most of the tools only support the CV V2.0 subschema, which was not suitable for any of the analyzed software tools in its full extent. The improvement strategy proposed here is to develop domain-specific schemas with an emphasis on the relationships between the building elements in various representations.

- **Regulative: software certification**

Another process affecting the quality of data exchange is software certification. The concept list specifies requirements for export and import testing. Certification checklists document the performance of the software tools during the certification process. Although concepts can be mandatory, optional, not relevant, or excluded, these concept descriptions are not necessarily respected for all tested elements, meaning

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that mandatory concepts are not always supported in the checklists of a certified software tool.

Domain-specific requirements are only specified for export testing. The standards according to which the software tools are certified do not follow the domain or the requirements of the specific software tool. Consequently, it cannot be expected that all the concepts are supported in each software tool. This is possibly the reason why software is certified without supporting all concepts that are described as mandatory.

The proposed improvement strategy is a new certification process that reflects the domain or software-tool specific exchange requirements. The performance of interoperability testing with the open schema is an important usability indicator for end users, which should be clearly described with the certificate.

6.3. Software industry: software development

The software development process has a direct impact on overcoming the majority of data exchange inconsistencies. Although most of the inconsistencies can be first traced to suboptimal software development, the software tools for the AEC industry conform to the normative and regulative processes, if available. In order to achieve a satisfactory data exchange the software tools need to conform to standards, as is the case with the open data exchange. Software development is primarily focused on the performance of a specific tool, whereby interoperability with the open standards depends on the normative and regulative elements responsible for it. However, because software development attempts to answer the needs of the heterogeneous AEC industry and because of missing standards, the industry is provided with rich as well as redundant ways of generating and exchanging data.

Therefore in this study software development is not regarded as a process that can systematically improve data exchange, because it addresses the improvement of a single software tool, whereas for collaboration purposes within the heterogeneous industry systematic improvement is required.

7. Summary

Table 8 lists the data exchange requirements that showed inconsistencies in the comparative study, the respective procedures and the improvement strategies. The problems are listed according to the effect on the end-user experience: namely, the first problem solved can directly affect the end-user experience and the last problem solved has to be implemented through other processes before it can reach the end user. For example, the inter-domain interpretation standards must be introduced in the integrated schema, domain-specific schema and the software certification first, before they reach the end user. Incorrect or missing exchange requirements in the comparative study can be traced back to all four normative and regulative processes. Exchange requirements that do not deliver expected results received different treatments within the processes: some exchange requirements are tested during certification processes but are still missing after the data exchange; some exist within the MVD CV V2.0 but are not tested during the certification; some exist in the IFC schema but are not part of MVD CV V2.0; and some are transferred but rendered incorrectly by the importing structural analysis tool.

Table 8
Identified problems and proposed improvement strategies that influence the end-user experience during the data exchange.

	Problem	Process	Improvement strategy
1	Exchange requirements tested during certification, but missing in the resulting model	Regulative: Software Certification	Improved or new software tool certification that is software or domain specific
2	Exchange requirements exist in the MVD, but not tested in the software tool	Normative: Domain-specific data model	Domain-specific data models supporting the necessary exchange requirements
3	Exchange requirements not part of the integrated data model	Normative: Integrated data model	Integrated data model encompassing all domain-specific data models
4	Exchange requirements transferred but incorrectly interpreted	Normative: Inter-domain relations	Building data interpretation standards

Therefore, we propose the following strategy for the systematic improvement of data exchange between architectural and structural analysis:

1. Missing interpretation rules need to be developed and introduced in the data exchange workflow;
2. The interpretations need to take place between domain-specific models, supported by domain-specific building data models;
3. Integrate building data models as a result of multiple interrelated domain-specific building data models;
4. Introduce a domain-specific or software tool specific certification process.

8. Conclusion

This paper assessed the flawed data exchange between architectural design and structural analysis via a literature review and a comparative study, and linked the results to the inter-organizational procedures influencing the data exchange processes on the project level. The particular focus was on the analysis of IFC-based data exchange. The paper proposes and prioritizes improvement strategies for data exchange between architectural design and structural analysis.

The research question "Why does model-based data exchange between architectural design and structural analysis still not function without significant data and information losses?" addressed the identification of the origins for still flawed data transfer between architectural and structural analysis models. Thereby the data exchange was examined not only from the end-user perspective, but also from the normative and regulative, and software industry perspectives. The respective processes of generation and exchange of data, software certification and standardization and software development influencing the data exchange were analyzed and supported by the comparative interoperability testing study.

The generation and exchange of building data and the software development processes directly impact the end-user experience. However, improvements to these processes are dependent on the software industry, which works on a tool-by-tool basis, and cannot systematically improve the data exchange. A systematical improvement is especially necessary because of the heterogeneity of AEC industry. On the plus side, regarding normative and regulative processes: software certification and standardization could systematically improve the exchange.

The certification process directly affects software development. Tested certified software does not necessarily support the exchange requirements it is tested for. A single concept list (as CV V2.0) with some variations cannot satisfy the diverse needs of multiple domains and software tools. Hence, software tool certification cannot be regarded to be a valid indicator of interoperability.

The MVD standard, as a domain-specific data model, is the base for the certification process. In addition to the fact that it is not being properly implemented in the software tools, MVD CV V2.0 does not recognize the need for multiple domain-specific MVDs because it supports three domains at the same time. In that way MVD CV V2.0 overtook the role of the integrated building data model in the case of data exchange between architectural design and structural analysis. The domain-specific models need to reflect the domain-specific concepts in order to achieve communication with domain-specific software tools. The integrated model relates the inter-domain concepts so the communication between the domain-specific concepts could be accomplished.

The data interpretations that occurred in the comparative study are

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defined by the software developers responsible for import applications, and are not yet standardized. The study showed that missing standards for the interpretation steps that describe the inter-domain relationships result in inconsistent imports of the same IFC-based model in multiple software tools. The lack of inter-domain interpretation standards reflects on the IFC schema, lack of MVDs, on the erroneous certification process, and finally the software development, affecting the end-user experience.

In conclusion we propose the following solutions to improve end-user experience:

- Improved or new software tool certification process;
- Multiple domain-specific building data models which would eventually reflect on the integrated building data model;
- Introduction of the interpretation rules in the current data exchange workflow.

Systematic improvement needs a top–down approach. First, it is necessary to define interpretation rules, then introduce these to the domain-specific models, then finally create a domain-specific certification procedure. Although there have been numerous attempts to improve data exchange between architectural design and structural analysis in the AEC industry, end users are still not able to achieve a seamless exchange. This review identifies the most important procedural problems and potential for improvements which would systematically develop the data exchange. In particular, the missing inter-domain interpretation rules are found to be the most critical procedural problem. This work will serve as a basis for future research and technological development regarding data exchange between architectural design and structural analysis.

The research described above is limited to the testing of the software tool performance for the particular building elements used in the comparative study (mainly the geometrical properties). The proposed strategy is based on existing data exchange using the IFC standard, and other standards/schemas could show different problems. The applied modeling practices affect the results of the comparative study to a certain degree; the required structural analysis model might also differ based on the workflow and practices.

Future research will examine existing standards in architecture and structural analysis domains in order to generate tools to develop new and improve existing domain-specific knowledge and inter-domain relationships that would optimally meet the needs of the AEC industry. The objective is to expand the knowledge of the BIM-based concepts for structural analysis and relate them to the architectural concepts. In the next step we will aim to define the interpretations between the domain-specific models.

CRediT authorship contribution statement

Goran Sibenik: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing - original draft, Visualization. **Iva Kovacic:** Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was conducted as part of the Doctoral College “Computational Design” funded by TU Wien (Vienna, Austria).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2020.101589.

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PUBLICATION 2:

Goran Sibenik and Iva Kovacic:

"Interpreted open data exchange between architectural design and structural analysis models", *Journal of Information Technology in Construction*, Volume 26, (2021)

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ITcon
www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

INTERPRETED OPEN DATA EXCHANGE BETWEEN ARCHITECTURAL DESIGN AND STRUCTURAL ANALYSIS MODELS

SUBMITTED: December 2019
REVISED: October 2020
PUBLISHED: February 2021
GUEST EDITORS: Francis Siu, Hung-Lin Chi, Hsi-hsien Wei & Minkoo Kim
DOI: 10.36680/j.itcon.2021.004

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SUMMARY: *The heterogeneity of the architecture, engineering and construction (AEC) industry reflects on digital building models, which differ across domains and planning phases. Data exchange between architectural design and structural analysis models poses a particular challenge because of dramatically different representations of building elements. Existing software tools and standards have not been able to deal with these differences. The research on inter-domain building information modelling (BIM) frameworks does not consider the geometry interpretations for data exchange. Analysis of geometry interpretations is mostly project-specific and is seldom reflected in general data exchange frameworks. By defining a data exchange framework that engages with varying requirements and representations of architectural design and structural analysis in terms of geometry, which is open to other domains, we aim to close the identified gap. Existing classification systems in software tools and standards were reviewed in order to understand architectural design and structural analysis representations and to identify the relationships between them. Following the analysis, a novel data management framework based on classification, interpretation and automation was proposed, implemented and tested. Classification is a model specification including domain-specific terms and relationships between them. Interpretations consist of inter-domain procedures necessary to generate domain-specific models from a provided model. Automation represents the connection between open domain-specific models and proprietary models in software tools. Practical implementation with a test case demonstrated a possible realization of the proposed framework. The innovative contribution of the research is a novel framework based on the system of open domain-specific classifications and procedures for the inter-domain interpretation, which can prepare domain-specific models on central storage. The main benefit is a centrally prepared domain-specific model, relieving software developers from so-far-unsuccessful implementation of complex inter-domain interpretations in each software tool, and providing end users with control over the data exchange. Although the framework is based on the exchange between architectural design and structural analysis, the proposed central data management framework can be used for other exchange processes involving different model representations.*

KEYWORDS: *data exchange, classification, interpretation, architectural design, structural analysis, BIM*

REFERENCE: *Goran Sibenik, Iva Kovacic (2021). Interpreted open data exchange between architectural design and structural analysis models. Journal of Information Technology in Construction (ITcon), Special issue: 'CIB World Building Congress 2019: Constructing Smart Cities', Vol. 26, pg. 39-57, DOI: 10.36680/j.itcon.2021.004*

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1. INTRODUCTION

The AEC industry aims to improve efficiency and quality through digitalization of planning process workflows. One of the digitalization goals is to create a model-based communication and seamless data exchange between professional domains. The structural analysis domain is responsible for dimensioning the load-bearing building elements. These elements usually originate from architectural design, which tends to be a step preceding structural analysis. Data exchange between architectural design and structural analysis is one of the most important and common exchanges during the planning process, and needs to be included in the data exchange framework (Kepplin et al, 2017, Kovacic et al, 2015).

Data exchange between architectural design and structural analysis models is still conducted via physical documents (paper), digitized documents (pdf files) or files containing two-dimensional (2D) geometry (dwg drawings), while three-dimensional (3D) model-based exchange currently takes place only in isolated cases and intrafirm workflows. If a 3D building model is created from 2D documents, geometry needs to be remodeled in 3D structural analysis tools, which is an expensive, redundant and error-prone process (Kepplin et al, 2017). Despite these problems the industry has so far failed to achieve a model-based exchange that displays a sufficient level of usability as well as trust for the end users (Sibenik and Kovacic, 2020).

To support the exchange between architectural design and structural analysis, researchers have proposed adapting non-suitable or creating new domain-specific frameworks (Ramaji and Memari, 2020, Hu et al, 2016). However, a lack of professional knowledge means that such data exchanges are often implemented incorrectly in the various software solutions. Practitioners, however, have established various workarounds to overcome the shortcomings of software tools (Holzer, 2016). Still, geometry transfers are very common in AEC practice, and usually require geometry interpretation (Sanguinetti et al, 2012, Venugopal et al, 2012), especially the transfer to structural analysis.

In our previous research (Sibenik and Kovacic, 2020), the analysis of data exchange in practice showed that crucial preconditions for systematic improvement are: (1) the interpretation rules between different domains, and (2) data models supporting domain-specific requirements. These preconditions are not clearly defined in the existing standards or frameworks. A single integrated model supporting various AEC domains does not suffice: the AEC industry is stepping towards multiple domain-specific data models (Scherer and Schapke, 2011, Solihin et al, 2016), as well as the automated or semi-automated interpretation rules between them (Sanguinetti et al, 2012). Data exchange between architectural design and structural analysis requires extensive geometry interpretations, which are not considered in an open exchange framework such as industry foundation classes (IFC). In this paper we underline the need for paradigm shift from a product-model-centric to a process-model-centric information space, as did Scherer and Schapke (2011). The new paradigm needs to be reflected in the data exchange framework, and should consider the exchange to structural analysis.

Therefore the main research question this paper addresses is: *how to efficiently support a model-based exchange between architectural design and structural analysis tools*.

In order to support the model-based exchange, we will propose a new framework that overcomes the shortcomings of existing data exchange frameworks. The strategies to overcome the shortcomings have been identified in our previous research (Sibenik and Kovacic, 2020). Thus, we will introduce domain-specific classification and inter-domain interpretations, based on a review of existing classification standards, software tools and data exchange standards. In addition to that, the relationships between the systems will be proposed as interpretation procedures. Automating the exchange will be achieved by establishing the connections with proprietary building models. Finally, the framework will be implemented and demonstrated with a new system architecture. The aim of the research presented in this paper is to close the knowledge gap by including the complex geometry interpretations needed for data exchange between architectural design and structural analysis in the data exchange framework. By relocating the interpretation procedures from the importing software tools to the open central model, end users gain insight into the processes, thereby reducing the need for customized, individual development for each software tool.

This paper is structured as follows: Section 2 reviews the literature related to the data exchange framework; Section 3 presents the methodology and background on existing classification standards in the industry, the analysis of classification systems in software tools and the IFC data exchange standard; Section 4 provides an overview of the

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novel framework that consists of classification, interpretation and automation; classification and interpretation are presented in Sections 5 and 6, respectively; Section 7 describes a framework implementation and test system architecture, while Section 8 discusses the proposal; and Section 9 concludes with the significance of the framework, wider implications and the future outlook.

2. LITERATURE REVIEW

2.1 Data exchange between architectural design and structural analysis

There are significant differences between the architectural design and structural analysis models, hence interpretations are need. Ramaji and Memari (2016) list three possibilities for creating a structural analysis model from native BIM tools: (1) a structural analysis model is created in a native software tool; (2) a structural analysis model is created from a native model by a structural analysis tool; (3) an additional software tool (or a plug-in) is used to generate a structural analysis model. The focus of this paper is on open data exchange between architectural design and structural analysis, where IFC is the most frequently used standard. Specifically, this paper emphasizes that the end user needs to be able to access and change not only the building data model, but also the interpretations taking place during the creation of structural modes. Existing model interpretations are not open to an end user and generally work as a 'black-box' scenario (Holzer et al, 2007).

The literature review identified several framework proposals using IFC building data models as an exchange starting point, which is interpreted to a structural analysis model. Deng and Chang (2006) describe a framework which uses the IFC 2x2 schema; a schema version not supporting the structural analysis concepts. As the IFC schema did not sufficiently support the structural analysis representations of building elements, they developed an additional XML-based file format suitable for importing to several structural analysis tools. Deng and Chang converted an architectural IFC model to a 'general format of unified finite element model'. Liu et al (2010) developed an integration tool to convert building models between IFC and the PKPM structural analysis formats, with a 3D viewer supporting the exchange. Qin et al (2011) improve the exchange using a similar approach to Deng and Chang (2006); that is, describing the IFC building model as an architectural physical model and creating a complex system that prepares it as an XML-based unified finite element method (FEM) model, and can then further prepare the information for several structural analysis tools. Zhang et al (2014) also deal with the conversion of IFC models to multiple structural analysis formats. They additionally propose a bidirectional conversion as well as the conversion between structural analysis models on their web-based platform. The same platform was used by Hu et al (2016), where further case studies are also described.

The current version of IFC supports the majority of structural analysis requirements. Ramaji and Memari (2016) develop a framework describing direct and interpreted exchange between architectural and structural analysis models, meaning that some of the information provided by the architects can be directly imported while some needs to be interpreted. They later implement this framework with the IFC (Ramaji and Memari, 2020), where their workflow involves two variants of IFC files: architectural design and structural analysis.

In the literature above the interpretation steps are based on the input model; creating a new structural analysis model from a specific IFC export. However, because of the IFC schema redundancy, solutions using IFC are software tool specific (Sibenik and Kovacic, 2020); that is, the problem-solving approaches proposed above do not reflect the needs of the various current design practices. The conceptual differences between the models and relevant interpretation steps are defined for the particular research needs, rather than being extensively investigated on a more generic level. Thus there is a lack of investigation of how domain-specific requirements could be incorporated into existing exchange frameworks.

2.2 Data exchange frameworks

Some researchers question the use of the central integrated model, and instead pursue the use of multiple models. Lee and Jeong (2012) report that the integrated model is not feasible for technical and procedural reasons, because the model quickly becomes too large and does not support dynamic design processes. Scherer and Schapke (2011) move from all-in-one models and focus on a multi-model concept. They propose link models to relate multi-models, focusing on semantical interoperability. Solihin et al (2016) separate a single model into multiple domain-specific federated models; however, complex geometry interoperations are not part of their framework. Lee et al (2014) describe a web-based framework involving domain-specific filters as an intermediary step between a

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complex central model and domain-specific models; thus stepping away from the concept of integrated model. Sanguinetti et al (2012) address the need for multiple geometric models and describe two types of geometric operations for model processing – union and split operations – that can be used for models that adopt a similar approach to building element representation. Our previous research (Sibenik and Kovacic, 2020) recognized the need to separate multiple domain-specific building data models such that the relationships between multiple models are retained and originate from the inter-domain conceptualization.

The need to separately deal with the geometrical and non-geometrical information within the central storage was recognized in our previous analysis (Sibenik and Kovacic, 2018). Both types of information are usually treated similarly in data exchange frameworks, where researchers often focus on one type only. However, the interpretation of the semantic and syntactic description of the building information models do not have many similarities with the geometrical data interpretations. Lee and Jeong (2012) distinguish between geometric and non-geometric information in their work, but do not focus on geometric interpretations. Andrade et al (2008) state that ontology is only concerned with static and not dynamic knowledge. Work relating to ontology, taxonomy and classifications mostly deals with the non-geometrical information (e.g. Pauwels et al, 2017); whereas our view is that the geometrical information during the exchange is dependent on geometrical kernels used by the interoperating software tools, interpretations taking place and the geometrical definitions supported by the mediatory model such as IFC (if any). The exchange between geometrical kernels is usually separately researched (Zhu et al, 2019), especially if the semantic information differences are manually or easily overcome. In addition, the geometric transformation of building models involves complex geometrical methods, and some researchers have already suggested introducing a geometry kernel to perform interpretations (e.g. Romberg et al, 2004; Mora et al, 2008).

Introduction of business processes, procedural or expert knowledge in data exchange frameworks is discussed in work dealing with interoperability issues in the AEC industry. Rezgui et al (2011) emphasize the existence of tacit and explicit knowledge in the AEC industry and propose a process-driven framework, which is web-based and supported by ontologies. Rezgui et al shift the focus from standardization to automation of processes, using service-oriented IT architecture. A framework for collaboration platform presented in Singh et al (2011) describes the need for organizations to develop their own data management practices to suit their business models, with flexible and user-friendly user interfaces. More recently, Lindgren and Widen (2018) stress that academic research focuses on technical interoperability while ignoring business processes. Although their work deals with dissemination of building information management, they regard knowledge as domain-specific, procedural and general, instead of tacit and explicit. Amann and Borrmann (2016) introduce ‘procedural knowledge’ to the IFC schema through IFC Procedural Language (IFCPL). IFCPL displays numerous advantages compared with the limited IFC EXPRESS schema; however, it does not provide a solution to complex interpretations of geometry, which is still based on the IFC that lacks predefined geometry manipulation methods. A framework created by Sacks et al (2017) incorporates expert knowledge to semantically enrich the models originating from point clouds (a set of data points in space). The rules are based on element geometries and their relationships, which produce new non-geometric model information. Ladenhauf et al (2016) improve the data exchange process specifically for energy performance simulation. Their interpretations are mainly geometrical, and are called geometric simplification. Ladenhauf et al introduce several algorithms to manage IFC models, based on expert knowledge to achieve automatic generation of new building models for energy performance simulation.

Thus data exchange frameworks are moving towards multiple domain-specific models and introducing interpretation processes between the models. An integrated approach that can process both geometrical and non-geometrical information is necessary in the AEC industry. In summary, the proposed frameworks consider expert knowledge and interpretation of semantic information, while geometry interpretations are limited to filtering of same geometric representations. Complex interpretations of geometry are still lacking in the context of BIM data exchange frameworks, despite the above-mentioned proposals.

2.3 Geometry interpretations in other domains

Geometry interpretations can be found across the AEC industry, as well as beyond. One such example is the computational design approach (Caetano et al, 2020). It deals with design, analysis and implementation of algorithms for solving geometrical problems and it is present in domains such as geographic information systems (GIS), computer graphics or computer aided design (CAD). The generative design approach belongs to computational design and uses algorithms to generate designs (Caetano et al, 2020). Singh and Gu (2012) explore

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five different generative design approaches and create a framework which can combine them. Use of generative design in AEC is often related to evolutionary processes and multiple solutions, which is especially desirable in the concept design phase (Hofmeyer and Davila Delgado, 2013); in the developed design phase the term 'algorithmic design' would be more suitable for generation of structural analysis models because it is characterized by an identifiable correlation between the algorithm and its outcome (Caetano et al, 2020).

Zhu et al (2019) integrate BIM and GIS, mainly by converting the geometry defined using IFC building data model into shapefile geometry which is then used in GIS. The geometry remains the same: its underlying geometry definitions are changed. Davis and Laender (1999) describe standard geometry transformation methods for creating different resolution, detail level and representation styles in GIS. They use unification, derivation and replication to avoid consistency problems caused by redundant information. Unification holds a single representation in the database, and all the following representations are obtained from it. Derivation stores a primary representation and secondary representations derived from it, but only the primary one may be modified, while the other ones are updated. Replication holds multiple representations that need to be synchronized between each other. In the AEC industry multiple stakeholders change and define building models with complex CRUD (create, read, update, delete) rights that often change between projects, making only replication a feasible solution.

Vangenot et al (2002) use two complementary approaches – integrated and inter-relationship – to deal with consistency of different viewpoints and resolutions in representing geographic data. Borrmann et al (2015) deal with a specific problem of tunnel design, which belongs both to BIM and GIS domains. Their approach supports tracing the geometry development and establishing procedural geometry descriptions because the design process and data modification are highly dynamic compared with conventional geographic data.

Manufacturing industry is more digitized than the AEC industry: the processes are more repetitive and therefore easier to capture and automate. Learning processes and development of knowledge is enabled by capturing experiences (de Giorgio et al, 2020). In manufacturing the knowledge-based methods are based on expert knowledge that is codified in advance. De Giorgio et al define 'declarative' and 'procedural' knowledge, where declarative knowledge is systemic information of one system related to information about another system at an instant of time, and procedural knowledge is related to the variation of information about another system between two instants of time.

Research in the industries beyond AEC also deals with multiple model representations and interpretations taking place between the models. The geometry interpretations can be summarized as the interpretation of (a) same geometry and similar representation (e.g. different geometry kernels), (b) similar geometry and different representation (change of level of details, especially in cartography) and (c) different geometry and different representation (e.g. architectural design to structural or energy analysis). Fig. 1 shows possible model states in a three-axial coordinate system (similar to Scherer and Schapke, 2011). The lessons from other industries are useful, but the peculiarities of the AEC industry, where the model is changed in all three directions and the relationships are crucial, makes the automation of all possible exchange variants far more complex. Contriving all of the possible changes in the state of the model would quickly result in scalability issues, thus requiring clear descriptions of the process and the focuses.

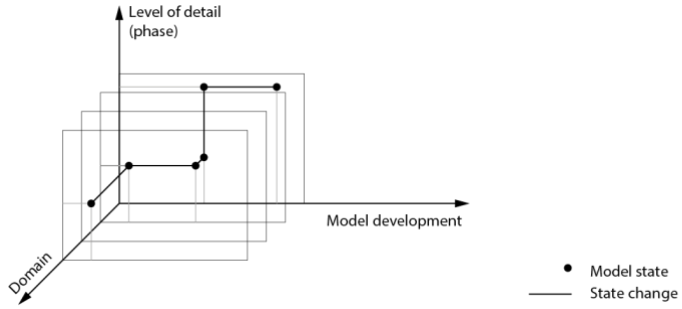

Fig. 1 Model in three-axial model space

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3. METHODOLOGY AND BACKGROUND

Existing interpretation methods within software applications lack transparency, are not exhaustive and, in some cases, are incorrectly implemented, discouraging designers and planners from using automated data exchange. Automated or semi-automated interpretations need to describe the most repetitive tasks during the design process in such a way that they remain understandable and open, as well as reliable to the end users.

On the basis of the above literature review and our previous research (Sibenik and Kovacic 2020), we have identified:

- The deficits in the data exchange frameworks; and
- The requirements of data exchange between architectural design and structural analysis models.

This has enabled us to develop a proposal for a novel data exchange framework.

The framework is based on three parts:

- *Classification* – Classification in the AEC industry is a well-established topic, and the classification standards, classification systems and implementation in software tools will be analyzed in Section 5.
- *Interpretation* – Existing standards will be analyzed for the presence of interpretation rules in Section 6.
- *Automation* – Automation is software-specific (i.e. proprietary tools are used) and is closely related to the application programming interface (API) of a specific software tool. It is not discussed in detail in this paper, but will be explored at a later date.

In Section 7, the framework proposal will be demonstrated and tested using a test building model, for which the supportive system architecture will be developed and implemented. The building model consists of three building element types: wall, column and slab. These have been chosen because they are the basic, most common elements in building models suitable for testing a building model. Geometries of building elements are simple: rectangular walls and slabs with constant thickness and columns with square cross-section. Classification, interpretation and automation will be applied to all three elements as follows:

- The proposal of the classification system used in the test building is primarily based on the analysis of the IFC standard.
- Interpretations are developed by comparing the existing physical model with the required analytical model of the test building, and by developing the algorithms that can overcome the model differences.
- Automation is achieved by mapping the information from the test building model in IFC format to the central architectural model, and by mapping the central structural analysis to the RFEM model (see Section 7).

The development of detailed methodology to define and test geometry interpretation rules will be discussed in future work.

The rest of this section discusses the state-of-the-art regarding classification and interpretation. First, a review of classification-related standards is presented with terminology and rules in creating a classification system. Further on, an analysis of software tools provides an insight in the implementation of classification systems. The analysis is extended in Sub-section 3.3 to the IFC data exchange standard.

3.1 Classification standards

The most significant standards describing the approaches for classification systems and terminology are ISO 1087-1 (ISO, 2000a), ISO 860 (ISO, 2007b), ISO 704 (ISO, 2000b) and ISO 22274 (ISO, 2013). These standards define most common terms in classification systems, such as objects, classes, concepts, and classification and concept systems. A ‘concept system’ establishes the relationships between specific concepts in three different ways (ISO, 2000b):

- *Hierarchical generic* – the intention of the subordinate concept is included in the intention of the superordinate concept (the subordinate concept is a specific, whereas the superordinate is generic).
- *Hierarchical partitive* – superordinate concept represents the whole and subordinate concept a part.
- *Associative* – the non-hierarchical associative relationships can be of various types, and are a ‘thematic connection by virtue of experience’.

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The basis of each classification system is an appropriate concept system. Recommendations on how to use a concept system and build a classification system are given in ISO 22274 (ISO, 2013). Consistent terminology is a mandatory condition for achieving unambiguous communication. Users must be provided with definitions for the class in order to reduce ambiguities. A concept system reflects the knowledge about the concepts in a specific domain, and the relationships between them. However, multiple classifications can be a product of a single concept system. ISO 22274 (ISO, 2013) defines three types of classification systems: (1) the enumerative system, which represents all the classes through the hierarchic system; (2) the faceted system, which lists multiple classifications of the object, where an object can belong to any combination of classes from the facets (e.g. material and building element for a concrete wall); and (3) the combined system which, according to ISO 22274, is recommended as enumerative on the higher levels and faceted on the lower levels.

ISO 860 (ISO, 2007b) suggests that when there are multiple classification systems with non-minor differences, even if the concept systems are from the same subject field, they should not be harmonized. But architectural design and structural analysis are domains with major conceptual model differences; therefore harmonizing the terms present in architectural and structural analysis software is considered unfeasible. Although both domains take part in the building design process, the two classification systems have different purposes.

Classification systems in the AEC industry are mainly created at the national level. Examples include Uniclass 2015 (United Kingdom); Omniclass, MasterFormat and Uniformat (United States of America); CoClass (Sweden); CCS (Denmark); building 2000 (Finland); STABU LexiCon (Netherlands); and NS 3451 (Norway) (Dikbas and Ercoskun, 2006, Lou and Goulding, 2011). Significant attempts to classify building information in the so-called DACH region (Germany, Austria and Switzerland) can be found in the classifications for costs in construction; namely, DIN 276, ÖNORM 1801-1 and SIA 112, respectively. The common procurement vocabulary (CPV) developed by the European Union defines a classification system for all matters pertaining to public contracts.

There are two ISO standards related to classification systems in the AEC industry: ISO 12006-2 (ISO, 2015) and ISO 12006-3 (ISO, 2007a). ISO 12006-2 provides several classification tables regarding all stages in the construction project lifecycle, with definitions. Classification systems such as CCS and Uniclass 2015 are based on this standard. ISO 12006-3 specifies the language-independent model defined using the EXPRESS data modelling language. The model identifies the way in which the objects, groups and relationships within them are created to represent the knowledge. STABU LexiCon and buildingSMART Data Dictionary (also known as bSDD) are based on this standard.

Ekholm and Haggstrom (2011) criticize the classification standard ISO 12006-2 for failing to bring together the existing national systems and for not being suitable for specific domains in the construction sector (e.g. cost calculations using the Swedish and Danish systems). Ekholm (2005) describes the difference between the ISO 12006-2 and IFC building data model, identifying some issues in the ISO 12006-3-based IFC building data model, such as elements being defined without reference to their spatial, functional or compositional view. Ekholm (2005) also suggests several steps necessary for harmonizing the existing systems based on the two standards.

The classification systems aim to encompass the whole AEC industry at the international level, eventually harmonizing the term codes, but at the moment they do not recognize the heterogeneity of the various domains. Classification systems are a prerequisite for organizing building product libraries so that building data models with different purposes could communicate. The first critical step in creating a classification system is defining the purpose of classification (Ekholm, 1996, Jorgensen, 2011). The purpose of the classification defines various exchange requirements that will need to be supported, depending on the software and domain.

Most of the existing classification systems are not used in the products developed by the international software industry for architectural design and structural analysis. Generally, terminology is not harmonized among the software tools supporting the AEC industry. ACCA software (2018) identified the following reasons for the low implementation of classification systems:

1. Local – limited by their geographical and linguistic character;
2. Incomplete – they do not encompass all the relevant knowledge;
3. Technically behind – there are more advanced ways to classify information that can be supported with current technology; and
4. Specific – they are mainly created for cost calculations; differences in representations are not addressed; and interpretations would make data management more complicated in some cases.

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3.2 Classification in software tools

The conceptualization of objects in software tools is often software-solution sensitive and follows the software development logic, so lacks understanding of the professional domain (Andrade et al, 2008). The software industry provides the AEC industry with the tools for architectural and structural design, analysis and optimization (i.e. BIM tools). BIM authoring tools support object-based modelling and use different classification systems. The objects represent the concepts of a specific domain. 'Objects in the domain of interest are modelled as software objects with properties that represent domain object properties' (Ekholm, 2005). For the software industry, the property is known as an 'attribute'. By using the classification, software developers are able to use the same code to deal with multiple object properties, methods, relations, etc. The need to accommodate the classification systems in the AEC sector to work effectively with the advances in the software industry was recognized more than 20 years ago, in order to develop a classification system which will be used for both AEC and software industry. According to Ekholm (1996), product modelling needs to be classified within a series of different classifications, and Ekholm refers to various project stages as 'purposes'. More recently, Jorgensen (2011) has emphasized the need to explore new opportunities in the software industry that can be used in classification systems, and describes multiple misconceptions in existing classification systems that need to be reconsidered because software tools are increasing their stake in construction projects and could provide new possibilities if suitably designed for the AEC industry.

We have analyzed the classification systems of five of the software tools mostly used in the Central European region and conducted a comparison of these systems with existing standards and literature. The software tools are for architectural design (Archicad 21), architectural and structural design (Allplan 2018 and Autodesk Revit 2019), and structural design and analysis (Dlubal RFEM 5.17 and SCIA Engineer 18.1). Classes representing building elements found in almost every high-rise building project were reviewed: namely, column, wall and slab. All the analyzed software tools claim to be suitable for BIM workflows and are IFC certified. One of the characteristics of BIM models is that they consist of parametric 3D objects containing additional information, alongside geometrical information. All of the examined tools are object-oriented modelling, design and analysis tools. The software classification systems were analyzed primarily through software tool interfaces, but also in regard to corresponding APIs and the behavior of resulting objects. Fig. 2 presents the existing classification systems graphically based on ISO 704 (ISO, 2000b), and shows the differences in the classifications used by these tools.

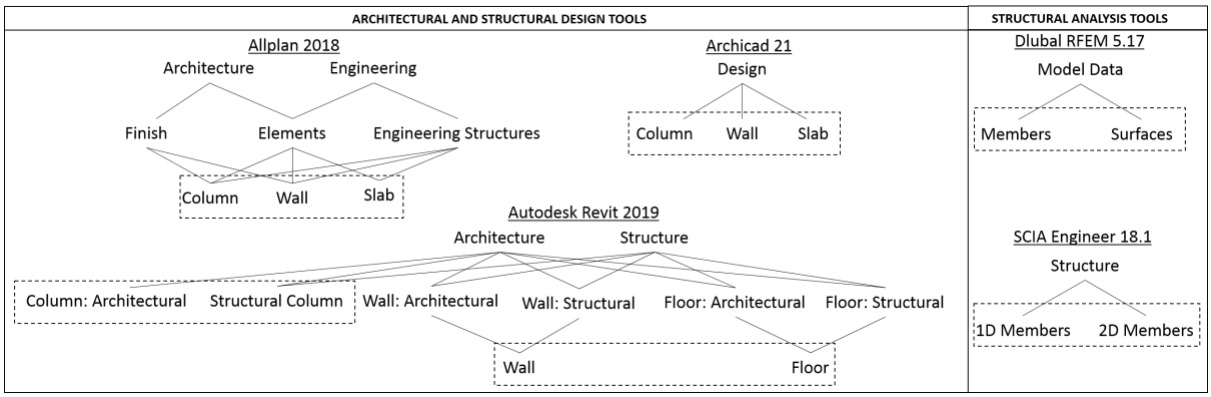

Fig. 2 Classification systems in software tools

Our analysis found that the relationships between classes are hierarchical generic. On the one hand, we found that terms generally differ and the definitions describing the terms are missing; however, they can be compared by analyzing the object behavior. Among the tools mainly used for architectural design and architectural and structural design, the main difference is the possibility to access the same class (except for columns in Autodesk Revit, which are divided into two classes). The terms are similar in all three software tools, but the way they are structured differs. On the other hand, the structural design and analysis software solutions show similarities and the three building elements are represented in only two classes. This results from the reduced dimensionality of analytical models. In structural models, columns are defined as linear elements, where the cross-section is non-geometrical information (i.e. not modelled), and walls and slabs are planar elements where thickness is non-geometrical information. The column class suggests that a linear element is vertical, the wall class that the planar element is

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vertical and the slab class that a planar element is horizontal. These classes are not necessarily part of the structural analysis software tools (Dlubal RFEM), or the class is not limited to the characteristic of the building element (e.g. direction), meaning that it can be changed during the design and still remain in the same class (SCIA Engineer). Therefore, the classes 'column', 'wall' or 'slab' are considered irrelevant for structural analysis models, and the main classification is on a higher level, involving 'linear' and 'planar' elements.

3.3 Classification in data exchange standard

End users are required to deliver information that conforms to the relevant national standards, using the templates and defining the data exchange properties. This process is often not sufficiently defined and software tools do not guarantee that the information will retain the definition after the data exchange. The process of information mapping during the exchange processes is left to software developers. This research primarily addresses structural analysis tools, and the data originally created in architectural design software tools. The classification systems mentioned in Sub-section 3.1 do not recognize the building elements in their structural analysis representation (linear and planar elements).

Early work on the IFC building data model (Weise et al, 2003) introduced the majority of the structural representations and their corresponding properties. The IFC standard conforms to the buildingSMART data dictionary, which is based on ISO 12006-3. The IFC is the most widely accepted standard for data exchange in practice and it defines the building elements' classification in an object-oriented manner. It tends to grow and aims to encompass all the elements present in the AEC industry. The standard recognizes all three building elements considered in this research in their architectural as well as their structural representation.

This means that the same building element can occur in the same model multiple times – as a structural and an architectural element, without any interdependency between them. Our previous work (Sibenik and Kovacic, 2020) concluded that the crucial data-exchange problem is that the relationships between the element representations do not exist and are not defined in an IFC-based data exchange framework. The relationships are supposed to be described using information delivery manuals (IDMs) or varying model view definitions (MVDs), but this concept has not been widely accepted in practice (buildingSmart, 2011). Fig. 3 shows an extract of IFC schema representing the classes from the analysis for this paper and emphasizes the crucial problem within the standard that we identified; namely, the missing relationship between the representations of the same building element.

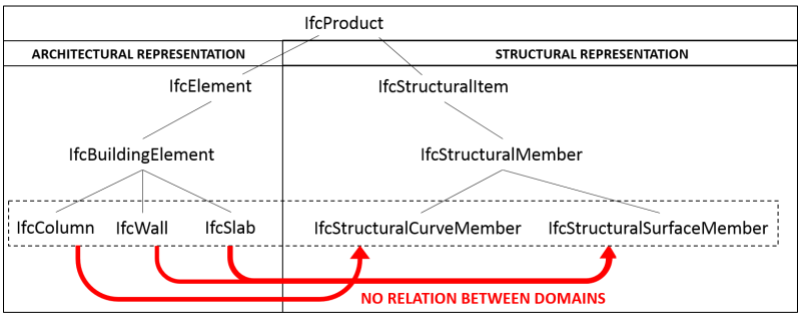

Fig. 3 Classification used in the IFC standard

The relationships between the IfcElement and IfcStrucuralItem are not part of the standard. Ekholm (1996) states that it is necessary to disregard the properties that are not of interest and create a definite and exhaustive system, where 'definite' means that an object may not belong to more than one class of the same rank, and 'exhaustive' means that every object must be assigned to a class. A unique encompassing schema in the AEC industry becomes exhaustive by supporting each domain-specific representation, software tool and corresponding classes. The industry heterogeneity makes this task highly complex and results in a constantly changing redundant schema; achieving 'exhaustiveness' is more feasible by focusing on multiple domain-specific schemas. Thus, the IFC exchange standard does not manage to be definite because the elements may occur in multiple classes simultaneously.

The software tools mostly deal with a single representation of elements and support domain-specific concept systems. The interfaces do not necessarily follow the underlying classification system, and allow multiple terms and ways to access the same resulting class. Each object contains a number of additional properties, addressed in

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different ways by each software tool, requiring additional analysis and harmonization; in order to reduce the complexity our analysis does not include properties.

4. NOVEL FRAMEWORK PROPOSAL

Having analyzed the state-of-the-art in terms of standards defining classification, existing domain-specific classification systems, lack of inter-domain relations and other approaches to data exchange frameworks, a new framework has been developed that introduces inter-domain relationships as a mandatory part of the data exchange process. The three mandatory parts in the proposed framework are: classification, interpretation and automation (Fig. 4).

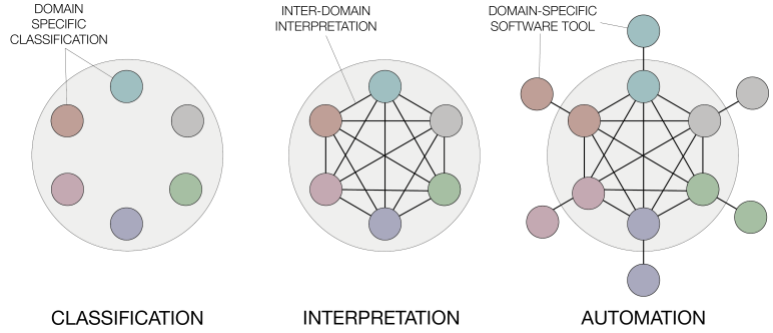

Fig. 4 Framework overview

Classification (see Section 5) – This is the part of the framework where classification systems defining domain-specific terms are developed. The systems can include building elements, properties, relationships, and the containers used to interrelate multiple element, of all domains partaking in the data exchange processes; eventually creating a master central classification as a loosely coupled system of domain-specific classification systems, supporting all exchange requirements of all domains partaking in the planning process. The relationships between the terms must be derived from the inter-domain concept system. The concept system is the existing knowledge that is not limited to a single domain.

Interpretation (see Section 6) – This part of framework overcomes the differences between centrally available information and a domain-specific model required in an importing software tool. The model is prepared for import in the software tool, in terms of its semantical and geometrical requirements, based on the available information. Interpretation comprises the multiple procedures required to prepare the model, such as validation, filtering, non-geometrical interpretations, geometrical operations, enrichment and reasoning.

Automation – This part of the framework puts the created central classification and interpretation parts in context with other software tools. In this way, classification and interpretation are related with proprietary software tools by information mapping. Mapping processes between a domain-specific open model and the native building model are simplified to establishing relationships with already prepared data; no complex interpretation or reasoning tasks are required for automation. To connect the central systems with software tools, APIs provided by the software tool producer are used. The quality of the API governs the level of access to information and influences exchange to a certain extent.

5. CLASSIFICATION

The analysis of software tool and data exchange classification systems implies that the relationships between the architectural and structural representations are missing. Nevertheless, structural engineers are able to distinguish and interpret the elements without significant problems. We consider that it is necessary to understand the concepts from both perspectives and unite them in a single concept system. This approach allows for definition of interpretations between the domains. The first recommendation from ISO 12006-2 (ISO, 2015) for developing a classification system is defining its purpose. As already discussed, the harmonization of classification systems for architecture and structural analysis domains is not a feasible solution. Thus, our recommendation are *two classification systems* with architectural and structural purposes, based on a *unique concept system*. The analysis of classification systems and the standards responsible for the classification discussed in Sections 3.2 and 3.3 above implied the classification systems for the examined building elements illustrated in Fig. 5.

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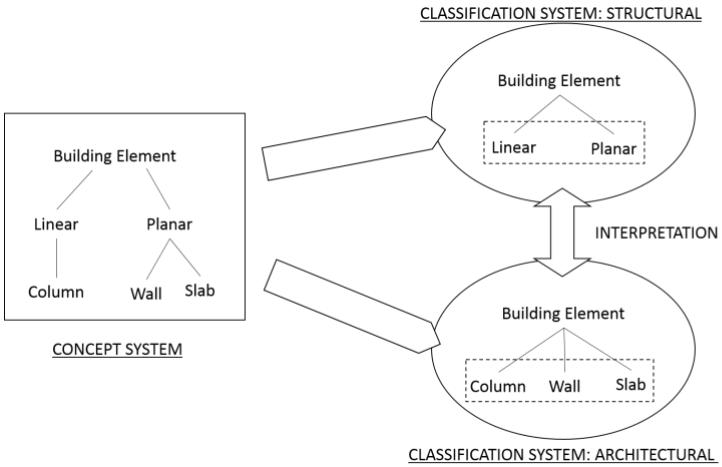

Fig. 5 Proposal for domain-specific classification systems based on the concept system

An approach involving multiple classification systems must retain the interpretation rules existing in the concept system. Without the interpretation rules, the systems lose their conceptual origin relationships and the data exchange between two classification systems becomes impossible. The proposal can be defined as:

concept system = classification systems + interpretations

Each concept is separated from the other concepts by its intension: the unique set of its characteristics. Each terminological entry should be composed of a statement explaining what the concept is (ISO, 2000b), but the software tools usually do not provide the end users with the clear definition. From the analyzed classification systems, only the IFC standard describes the terms textually. However, the definitions from IAI (IAI International Council Limited, 2019) define columns as 'structural member of slender form, usually vertical', walls as 'usually vertical, or nearly vertical, planar elements' and slabs as 'the construction that normally encloses a space vertically', and these definitions are too vague for automatization of the interpretation rules without introducing clearly defined tolerances. The AEC industry lacks definitions that would facilitate the automatization of the interpretation rules. This leads to over-differentiating of classes in software tools and excludes the possibility of automating interpretations. To facilitate the seamless data exchange, definitions of elements are required that will make automated interpretation possible and reflect the underlying concept system. Therefore the three building elements compared in this study are regarded strictly as horizontal or vertical. The following are examples of building element definitions that allow for the automated interpretation:

- *Column*
  A linear vertical building element.
- *Wall*
  A vertical planar building element.
- *Slab*
  A horizontal planar building element.
- *Linear element*
  Building element where the largest dimension of its bounding box equals or is greater than 10 times next greatest dimension.
- *Planar element*
  Building element where the largest dimension of its bounding box is smaller than 10 times next greatest dimension.

The definitions are used as an example only and have no roots in any reviewed standard; rather, they are used to describe a necessary amount of information that could be used to clearly distinguish building elements and automate the processes between them. The differences are based on the element's geometrical information that can be automatically recognized. Proposed definitions serve for the classification proposal testing in Section 7 below; however, the comprehensive automation-suitable definitions need to be made with mutual consent in the industry and need to consider more building elements.

The interpretation of elements from the architectural to the structural classification is straightforward, because the

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structural classes are superordinate concepts towards the architectural ones. In this case, columns are linear elements in the structural classification system, and the walls and slabs are planar. The interpretations in the reverse direction are more complex: the easiest method is to address the object by its ID if possible and update it, if it originates from the central database. If not, the elements can be interpreted by analyzing the geometrical information. Linear and planar elements contain information about cross-section and thickness, respectively, as non-geometrical information. For the three element types, it is possible to identify whether the element is vertical or horizontal: a horizontal planar element is a slab; a vertical planar is a wall; and a vertical linear element is a column.

6. INTERPRETATION

The three building element types (column, wall, slab) are not sufficiently distinct in standards regarding their domain-specific representations, so it would be possible to automate the conversion between architectural and structural classes. In fact, the majority of building elements are not sufficiently standardized regarding the relationships between multifold representations, and automation steps are not considered. However, there are recommendations about some relationships (e.g. Pech and Kolbitsch, 2005, Schuler, 2016) which suggest how to treat architectural elements when interpreting them for structural analysis manually. In this paper interpretations are defined by finding the existing knowledge about the elements in the standards, by instructions provided for structural analysis software tools, and by capturing the intuitive knowledge in a form suitable for automation from our experience. We focus on the basic interpretation concept in order to construct the framework, while in future work we aim to investigate the methodology to define the interpretations more thoroughly.

The framework presented here proposes interpretation of a centrally available architectural design model to a structural analysis model and it consists of five procedures.

6.1 Interpretation procedures

Interpretation to define a structural model from a central data model involves the following procedures (illustrated in Fig. 6):

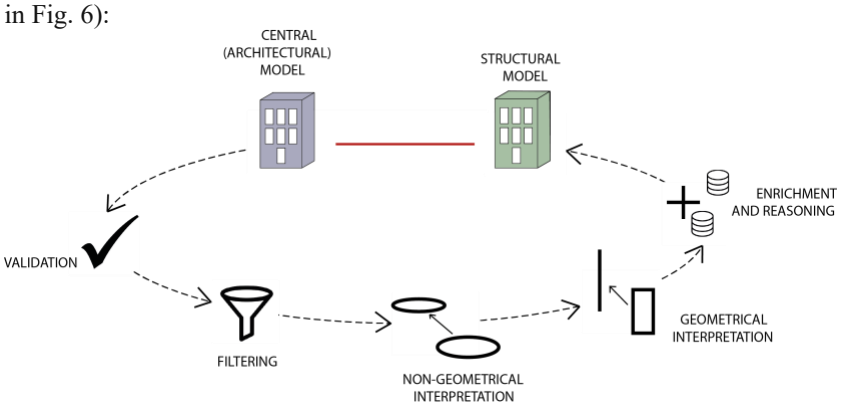

Fig. 6 Interpretation procedures

- *Validation* – Identifying the terms available in the central data model, if the elements of the model contain all necessary properties, relationships, and so on to allow for the creation of a structural model. The validation is performed on specific classes or a group of classes within the central model. The validation can be implemented in a way that automatically reports the inconsistencies to the stakeholder who generated specific information. Additionally, validation of geometrical properties can be introduced. For instance, linear elements are considered the ones where two dimensions are considerably larger than the third one (w<<l) and (h<<l) (Schuler, 2016). Further on, a planar element has one dimension considerably smaller than the other two ($t<<l_1$, l_2). The difference between the column and the wall is described as the (h/b>5) (Pech and Kolbitsch, 2005) in the case of the concrete and reinforced concrete walls.
- *Filtering* – The elements and properties identified in the validation procedure are reduced to those necessary for further interpretation procedures. For structural analysis the load-bearing properties are considered to isolate only the building elements relevant for structural analysis.

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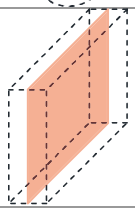
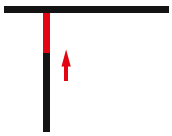
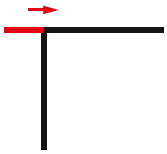
- *Non-geometrical interpretation* – This is mostly ontological data interpretation. Since the original model is the architectural design model, structural analysis classes of building elements can be identified solely based on the available architectural classification: column is a linear element, wall is a planar element and slab is a planar element.
- *Geometrical interpretation* – The geometrical interpretation for this data exchange are complex and are described in Section 6.2 below.
- *Enrichment and reasoning* – This involves adding new information, by using external databases or methods that can enrich the existing elements with additional knowledge, for instance recognition of the architectural material and assigning a structural material.

6.2 Geometrical interpretations

The following geometrical interpretation workflow is proposed based on the test model and knowledge of practices employed by structural engineers.

Table 1 Geometrical interpretation steps

Step	Description	
Linearization		Architectural columns are interpreted as linear elements. A linear element is created by connecting central points of lowest and highest face of a column, which represent the end points of a central axis. The cross-section information becomes a non-geometrical property of the linear analytical element.
Planarization		Walls and slabs are converted to planar elements. The largest face is identified and placed in the central position towards the second largest face. The thickness information becomes a non-geometrical property of the planar analytical element.
Vertical connectivity adjustment		In order to be able to transfer the forces, vertical elements must be connected to horizontal ones transferring the forces to the ground. Therefore, the vertical elements are tested for their connectivity with the horizontal 3D elements in their physical representation. Tolerances can be introduced as well. The elements connected in the physical model are then extended in the corresponding analytical model.
Horizontal connectivity adjustment		a) Vertical planar elements need to be checked for connections in the physical 3D model, then connected in the analytical model. Horizontal connections of vertical linear elements are used in the next step: horizontal connectivity adjustment. b) Edges of planar horizontal elements need to be aligned with vertical linear and planar elements. First, the vertical elements located under the horizontal element closest to the edges need to be identified. After testing if the distances are in a tolerance scale, the edges are aligned to the vertical elements underneath.

7. SYSTEM ARCHITECTURE PROPOSAL

The framework described in this paper has not yet been implemented in any available software tool or combination of software tools in such a way that the interpretations are open to the end user. Therefore the implementation of the proposed framework took place by developing a new system architecture (Fig. 7), which will be briefly presented in this section.

First, a central storage database was chosen, which replaced the building data stored in computer files, so the synchronous exchange can be achieved. Behavior of the end users is unpredictable: domains that could take part of the central storage as well as the software tools differ from project to project (Holzer, 2007). Therefore, the degree of flexibility available was an important factor for choosing a database, and was achieved by choosing open system architecture and the semi-structured database. For data storage, a semi-structured database (MongoDB) was chosen. The advantage of a semi-structured database rather than a relational database is the flexibility it provides to support unexpected information (Rasys et al, 2014, Lee et al, 2014).

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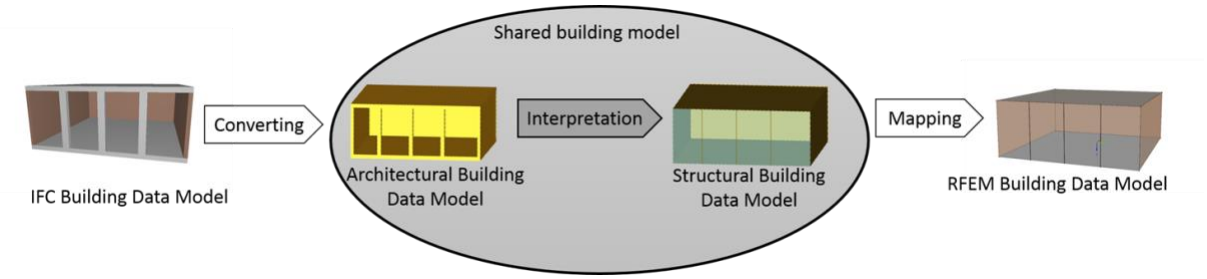

Fig. 7 Classification proposal testing workflow with screenshots

The interpretation, including validation, filtering, geometrical and non-geometrical interpretation and enrichment, can be realized using .NET Framework and C#. Automation was achieved by mapping the Revit model to the central storage, and the Dlubal RFEM model from the central storage. The Revit model was not directly mapped but its IFC 2x3-based export was used. However, in order to achieve a fully synchronous data exchange, a direct connection between Revit and the central storage needs to be realized through Revit API. The export from Revit was performed with the default setup for Coordination View 2.0. In order to map the architectural model available as an IFC file to the central storage, we created the IFCtoJSON parser, which converts the IFC file to Java Script Object Notation (JSON) format, keeping only the classes necessary for the data exchange. This JSON-based central data is then regarded as a starting point of the exchange.

Mapping processes depend on the API of the proprietary software tools, and in the case of Dlubal RFEM mapping methods are provided in C#. Since the starting point was the prepared architectural model edited to serve the new framework, the validation was not performed and filtering steps were performed during the conversion of the IFC model to JSON.

A consistent and clearly structured geometrical representation for every element with the geometrical representation was defined with the help of a geometry kernel. In order to implement geometrical interpretations the open geometry kernel OpenCascade was used. In this way, the complex geometry editing methods are simplified because of the predefined options provided by the OpenCascade kernel. OpenCascade was used with a C# wrapper, although the original version of OpenCascade is created for C++. In order to use this geometry kernel, IFC geometries are converted to OpenCascade with IFCtoJSON, and Dlubal RFEM reads the geometries from their OpenCascade definitions.

The central architectural building data model is converted to the central structural building data model, both available on MongoDB. All interpretation procedures take place before communication with the structural analysis software is initialized. The interpretation reduces dimensionality of a physical architectural model to an analytical structural model, retaining connections between elements and converting geometrical and non-geometrical data on the central storage. The process is fully automated, involving geometric and non-geometric interpretations, and enrichment and reasoning.

8. DISCUSSION

With the growth of BIM tools and digital building models in various domains, there is potential to reduce redundant remodeling tasks. A significant effort to achieve a seamless data exchange is recognized in the IFC standard. This standard encompasses multiple domains and supports varying representations of the same building element. The lack of relationships between different representations make seamless exchange between the representations impossible (Sibenik and Kovacic, 2020). Relationships between different geometrical representations are not considered in standard BIM-based data exchange frameworks. The work presented in this paper aims to improve the model-based exchange between architectural design and structural analysis tools by providing a novel data exchange framework that is able to overcome differences between model representations.

The novel framework is based on domain-specific classification, interpretation between the domains, and automation of communication with proprietary software tools. The concepts present in architectural design and structural analysis clearly require two classification systems (ISO, 2007b), and the academic community implies the use of multiple schemas (Lee and Jeong, 2012). The analysis of classification systems showed that software tools support domain-specific concept systems, but mandatory interpretation procedures between the domains are not standardized. The interpretation, representing expert knowledge as procedures or algorithms, is generally

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missing in data exchange frameworks, although this lack is highlighted by the literature (Singh et al, 2011, Ladenhauf et al, 2016). In the novel framework the interpretation is centrally placed. The lack of clear interpretation rules represents a gap in standardization which, in this work, is addressed by proposing some basic interpretations. The interpretation rules are implemented in the data exchange frameworks between architectural design and structural design, but their complexity and heterogeneity is not considered, which delivers project-specific solutions (Ramaji and Memari, 2020, Hu et al, 2016). In the novel framework we introduce a geometry kernel to facilitate the complex geometry interpretations, as in Mora et al (2008). The main innovative contribution of the novel framework are the multiple open central domain-specific classifications supported by inter-domain interpretations.

A possible implementation of the framework using software independent central storage and processing has been developed with a test building model. The framework test shows that the process of importing building data models to structural analysis tools can be significantly simplified when the structural analysis tools import an already interpreted model. The interpretation procedures are taking place on the central data storage, based on the conceptual differences of domain-specific building models, and therefore they do not have to be implemented during the import step. If a structural analysis tool imports a structural analysis representation of a model, the importing process is mainly reduced to mapping of information. This is the main benefit of the novel framework: a substantial and expensive effort of defining and implementing interpretation rules from an architectural model to a structural model is relocated from an importing tool to central storage. Thus the process of data import is simplified and the origin of most of the problems in this particular exchange are bypassed.

The framework was implemented with a test building model. New definitions for each element were created before the interpretation process could be developed. Implementation is only possible with clearly defined algorithms for element interpretation. The lack of standards suitable for automation of data exchange processes is the main obstacle for the new framework. Scalability issues of the whole framework were not considered at this stage of research. However, the idea behind the multiple domain-specific classifications is to reduce the scope of a standard defining the classification, which would also reduce the existing scalability issues (Lee and Jeong, 2012). The automation part of the framework and its scalability are the same as for the frameworks with open standards, because the communication with central storage needs to be implemented in each software tool individually. Interpretations could raise scalability issues when defined for multiple workflows. Similarities between the workflows need to be investigated in future research with real-world projects, and eventually new solutions would need to be developed if interpretations become difficult to maintain.

In summary, the automation of repetitive tasks during the model exchange is unavoidable, and it will significantly improve the data exchange between architectural design and structural analysis models (Ramaji and Memari, 2020). This research aims to contribute to the body of knowledge that bridges the interdisciplinary differences between architectural design and structural analysis models in a suitable framework.

9. CONCLUSION

This paper describes a new framework for overcoming the semantic and geometrical differences between the architectural design and structural analysis models. The novel framework encompasses three parts necessary for achieving automated exchange: classification, interpretation and automation. The proposed framework allows a significant simplification of the process of importing building elements to a structural analysis software tool because it is addressing a pre-processed architectural model with prepared geometries, avoiding the usually error-prone software tool-based interpretation process.

The research demonstrates the alternative approach to a data exchange framework and the results suggest that the complexity of information interpretation defined separately for each software tool combination could be avoided and moved to a central data management system. Multiple classification systems allow for the improvements in many aspects of the AEC industry by supporting domain-specific knowledge and allowing for more understandable central models for end users. Interpretations between different representations primarily serve for data exchange. Currently, the greatest challenge between the architectural and structural analysis data exchange are the geometrical interpretations which would have to be clearly defined for the new framework.

The proposal has several limitations: it was developed on the basis of only three building element types; the properties of elements were not included in the classification analysis; geometries and interpretations could

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become very complex depending on the element's physical representation; and interpretations were defined only for architectural design and structural analysis representations. There are several possible technical improvements of the system architecture that could be considered: the semi-structured database could be replaced with a graph database; and other programming languages or the geometry kernel with additional methods and possibilities can be considered. However, the technical optimization is not the topic of this work: the system architecture is merely used for demonstration purposes. The framework implementation should eventually consider a more user-friendly interface, still leaving the methods understandable and open for end users.

The next step is the completion of the system for a proof-of-concept, involving more specific geometries and interpretation rules that need to take place in the central communication system. Implementing classification systems and interpretation rules into a framework will be further developed. The framework will be tested with multiple workflows and address the scalability issues. Implementation of system architecture needs to deal with the way to create, update and maintain interpretations, and on top of that offer a user-friendly interface. The approach discussed in this paper has implementation potential in various AEC domains, especially the ones using multiple concepts for the same building elements (e.g. energy performance analysis, structural analysis), but has potential even if only the filtering of centrally available data takes place (e.g. cost calculation, life cycle analysis).

ACKNOWLEDGEMENTS

This work was conducted as part of the Doctoral College 'Computational Design' at TU Wien (TUW) and the project DATAFILTER in cooperation with Strabag AG. The authors wish to express their appreciation to Dr Wendelin Sprenger and Theodor Sansakrit Strohal for their support and contribution to the study on the part of Strabag AG.

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PUBLICATION 3:

Goran Sibenik, Iva Kovacic, Valentinas Petrinas and Wendelin Sprenger:

"Implementation of open data exchange between architectural design and structural analysis models", *Buildings*, Volume 11(12), (2021)

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Implementation of Open Data Exchange between Architectural Design and Structural Analysis Models

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Abstract: Building information modelling promises model-based collaboration between stakeholders in the project design stage. However, data exchange between physical and analytical building models used for architectural design and structural analysis respectively rarely takes place due to numerous differences in building element representation, especially the representation of geometry. This paper presents the realization of a novel data exchange framework between architectural design and structural analysis building models, based on open interpretations on central storage. The exchange is achieved with a new system architecture, where the program *redDim* was developed to perform the interpretations, including the most challenging transformations of geometry. We deliver a proof of concept for the novel framework with a prototype building model and verify it on two further building models. Results show that structural-analysis models can be correctly automatically created by reducing dimensionality and reconnecting building elements. The proposed data exchange provides a base for missing standardization of interpretations, which facilitates the non-proprietary automated conversion between physical and analytical models. This research fills the gap in the existing model-based communication that could lead to a seamless data exchange.

Keywords: BIM; data exchange; structural analysis; physical model; analytical model; geometry interpretation

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Citation: Sibenik, G.; Kovacic, I.; Petrinas, V.; Sprenger, W. Implementation of Open Data Exchange between Architectural Design and Structural Analysis Models. *Buildings* **2021**, *11*, 605. https://doi.org/10.3390/buildings11120605

Academic Editor: Junbok Lee

Received: 15 October 2021
Accepted: 24 November 2021
Published: 2 December 2021

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1. Introduction

The construction industry, as one of the least digitized, aims to increase productivity by implementing building information modeling (BIM) and achieving digital collaboration [1]. An obstacle still present in achieving a seamless data exchange for digital collaboration is the lack of software interoperability [2]. The interoperability concept needs to be expanded beyond information systems towards business processes, employees and culture, and the management of external relationships [2]. The computer integrated construction needs to be directed towards the process-oriented systems to achieve a natural level with human elements that are found in the day-to-day businesses [3].

Attempts to improve data exchange and software interoperability have yielded domain-specific success, whereby for architectural design and structural analysis it has been limited. This exchange is still characterized by sharing of drawings, documents with bad interoperability and redundant work [4]. The existing solutions are not able to support the human element and to reliably support the data exchange process [5]. Therefore, this research aims to improve the current data exchange frameworks between architectural design and structural analysis models by overcoming the existing obstacles.

In the previous research, the need to focus on domain-specific data models instead of integrated building models, and the interpretations between them for improving software interoperability and eventually automating data exchange, was identified [6]. The need for multiple models, especially multiple geometries, has been recognized by other

researchers [7,8]. As interpretations or transformations of building models, we understand the methods that edit geometrical and non-geometrical data available in one domain-specific representation according to the representation requirements of another domain. Based on our novel data exchange framework, supporting multiple open domain-specific data models and interpretations between them [9], we follow with the implementation of this data exchange approach in the presented research. The emphasis of our novel approach is on non-proprietary or open interpretations, realized as transparent to end users, which can be edited or extended for heterogeneous practices typically found in the AEC industries.

Structural engineers cannot rely on completely automated processes unless they are transparent or comprehensible ("black-box scenario") [10]; as they carry the responsibility for the calculation and require a completely reliable model as a starting point. Therefore, a framework needs to support open interpretation rules, which could be tailored for additional workflows and practices. Hence, the research question we aim to answer is: How to define and realize open interpretations for the transfer of architectural design to structural analysis building models?

For this purpose we propose, implement and verify a novel data exchange concept supporting domain-specific interpretations on an open central data storage. Due to the lack of documented cooperative knowledge of structural engineers and architects, in this paper we are mapping several common rules for generating an analytical model from a physical model. The novel concept shows potentials in overcoming current misinterpretations in data exchange practices, in particular the geometrical interpretations that pose the main challenge, by reducing numerous software-tool-specific processes to a single central interpretation process. In this way, communication with the proprietary tools is simplified to the information mapping.

This paper is structured as follows: literature review is provided in Section 2; Research design is briefly described in Section 3; Section 4 will present the data exchange framework, followed by a proof of concept for a prototypic model in Section 5; Verification of the proposed approach through implementation on additional two models generated by a different modeler will be presented in Section 6; In Section 7, the results of the research will be discussed, and the work will be concluded with Section 8.

2. Literature Review

Data exchange between architectural design and structural analysis models has been researched from different aspects, mainly as part of research in BIM domain. Since this paper deals with the implementation of the novel framework, the following two subsections review first concepts and challenges of a model-based exchange between the domains in question, followed by the review of technologies that were considered for the novel system architecture.

2.1. Data Exchange Concepts and Challenges

Data exchange implies restructuring and translating data in a source schema in one application to a target schema in another application [11]. The level of achievement of a seamless data exchange varies between professional domains. Interoperability is "the ability of two or more systems or components to exchange information and to use the information that has been exchanged" [2]. Numerous software tools belonging to different professional domains have also differing internal structures, which hinders the full interoperability across software tools [12]. However, the stakeholders belonging to various domains still aim to exchange information of interest. One of the greatest challenges is the transfer of a building model between architectural design and structural analysis [13]. The experts exchanging information of interest need to have mutual understanding of each other's domains in order to facilitate the communication [14]. The collaboration during the developed design stage (i.e., *Einreichsplan* in Austria) is particularly interesting, since both the architectural design plans and structural analysis are required for the building

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permit [15]. Software tools in both domains allow for the use of building models; however, the model-based data exchange is still burdened with problems [6].

Levels of interoperability are described as technical, information and organizational, dealing with signals, data and processes, respectively [16]. Technical interoperability is secure data transfer, information interoperability deals with data processing and organizational interoperability with alignment of processes and workflows. While information interoperability has been achieved, with some issues remaining, organizational interoperability still lacks clear conceptualization. The distinction between geometrical and non-geometrical information is required for data interpretation [16]. Complex manipulation of geometrical information are rarely introduced in frameworks proposed to improve interoperability in the AEC industry, whereby the research focus remains on restructuring geometries by splitting, unifying, excluding or including them [7,17]. These methods do not suffice for achieving interoperability between architectural design and structural analysis models. Interpretations between these models are not pure information interoperability, they depend on the processes and workflows, and bend towards the organizational interoperability.

As in [18], models used for architectural design are referred to as physical (or architectural [19], or BIM models [20]), while the structural analysis models are analytical (or structural [19]). Representations of building elements have significant differences, especially regarding the geometry representation. While physical models aim to render the elements similarly to their real-world 3d shape, analytical models tend to simplify the geometries and reduce dimensionality of building elements to points, lines and surfaces. We identified the need to further explore these geometry interpretations in order to improve the interoperability itself. The interpretations (or transformations [20]) have been performed mostly intuitively based on the experience of structural engineers [13], and are therefore based on implicit knowledge, which is difficult to codify. The interpretations represent the process of defining analytical models based on information available in physical models.

The overview of considered literature investigating model interpretations is provided in Table 1, where different approaches towards requirements, interpretations and exchange formats are visible. The creation of structural analysis model is described as information extraction [19] or fixing (e.g., node adjustment in [20]), without considering the intuitive decision making in the workflows. The previous findings have shown that missing interpretation procedures are the main obstacle in achieving a seamless exchange [6]. Thorough documentation of the interpretations can be found in [20], giving a list of required interpretations for a transformation of an industry foundation classes (IFC) physical model to an IFC analytical model. They emphasize the importance of interpretations, however it is limited to swept-solid geometry defined with the IFC standard (naming physical and analytical representations as swept-solid and topological respectively). In order to further edit the interpretation methods for IFC geometry definitions and contribute to the framework, expert IFC knowledge is required. Authors may focus on developing new data exchange frameworks between architectural design and structural analysis [19,21,22]. Although geometry interpretations are an unavoidable part of each framework, they are not described in detail, serve the examined case studies, but cannot be validated for the general use or other business processes. The existing intuitive interpretation practices are not documented, nor related to the proposed interpretation methods. The interpretations serve for an "end-to-end" model transformation automation without allowing a detailed insight to end users. The interpretation rules are highly dependent on the geometry of building elements, but that aspect is either vaguely described or missing in the literature. As the reviewed research does not focus on the interpretations, corresponding data exchange solutions do not consider editing or creating new interpretations. Due to the heterogeneity of software tools and interpretation practices, such proposals have limited use on the market, similarly as proprietary data exchange solutions. Therefore, we implement open interpretations to data exchange between architectural design and structural analysis models.

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Table 1. Literature describing the interpretations.

	Structural Requirements and Interpretations	Exchange Format
[23]	Geometry: beam and column; section properties; geometry interpretation; joints redefining based on connectivity	IFC can be exchanged on the server (XML-based) with Java3d graphical representation
[24]	Geometry: beam, column, slab, wall; section; material; filtering, no interpretation of geometry	IFC export converted to unified finite element model (XML-based), placed on server and imported to structural tools
[10]	Geometry and the associated attributes: no further details about requirements and interpretations	Basic CDF application (VB.Net) bidirectionally communicates between parametric design and structural analysis tool through proprietary file-format
[21]	Geometry: wall, slab, beam, column, brace; material; thickness; section; node modification; filtering based on geometry and material	IFC and other file formats can be exchanged and edited through unified information model on server (JSON-based) which uses OpenGL and WebGL for graphical representation
[25]	Interpretations of non-geometrical information and filtering	Multiple domain-specific SketchUp models communicating through central storage (XML-based with X3D and XPath)
[22]	Geometry: beam, column, wall, slab, opening; section property; material; node modification	Revit directly connected with YJK software tool, which further communicates with structural analysis tools
[19]	Geometry: beam, column, wall, slab; section profile; material; data extraction, no interpretation of geometry	IFC export converted to unified finite element model (XML-based) on IFC-structure model server and imported to structural tools
[20,26]	Geometry: beam, column, member, slab, wall; material; reducing dimensionality; material properties editing; connectivity adjustment	IFC physical to IFC analytical model with the help interpretation platform in C++
[27]	Geometry: wall, columns, openings, floors, roofs, stairs; material; material interpretation; geometry simplification mentioned, not explained in detail	IFC export is extended with additional material information for structural analysis
[28]	Geometry: plates, beams, columns, slabs; geometry discretization without reducing dimensionality	IFC with ACIS geometry kernel; no import to FEM tools
[29]	Geometry: beam, column, wall, slab; material; section properties; joints; reducing dimensionality	Web-based platform which bidirectionally interacts with several proprietary formats through unified information model (IFC-based)

Data exchange between architectural design and structural analysis is reported as the one with the lowest value/ratio and highest frequency [20,30]. This can be assigned to three problems: (i) the structural engineers work with established standards and recommendations which are not suitable for automatic data exchange as such; (ii) academic proposals of data exchange solutions are project- or software-tool-specific and vaguely integrate existing data exchange rules, making them unreliable for engineers as they are held responsible for their calculations; (iii) software industry does not manage to answer the heterogeneity of workflows and provides software-tool-specific solutions whose usefulness and usability depend on specific combinations of software applications. Regarding problem (i), in the previous work [9] the existing standards are investigated and included in the new data exchange framework. Rules with digitalization potential found in standards are mainly

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suitable for the validation step, before the interpretations take place, whereby the rules suitable for interpretation of geometry are rarely found. In the new framework, the issue (ii) is addressed by a detailed description of interpretation methods and their implementation as open methods. With such approach structural engineers have insight into the background processes and can edit them if necessary for their needs. The problem (iii) is in the novel data exchange framework resolved with non-proprietary interpretations that can be accessed and edited. Temporary organizations responsible for delivering a building project are generally not assembled based on the software tools utilized in domain-specific enterprises. Proprietary data exchange solutions do not deliver a satisfying performance in numerous possible combinations in the industry characterized by SMEs. However, enterprises encompassing multiple domains can adopt software tools based on their interoperability, but the problem of non-transparent model interpretations remains, and is often overcome by mastering the behavior of the software tools and adapting to adequate workarounds.

2.2. Data Exchange Technologies

Data exchange processes between architectural design and structural analysis have been document- (or file-) based until now. This document-based approach is digitalized with the data-exchange platforms where the advantages of a data-centric approach have still not been fully exploited [31]. The implementation of databases and a data-centric exchange of information provide a possibility to perform synchronous analysis, knowledge representation and large-scale data management. A set of international standards ISO 19650 deals with the organization and digitization of information about buildings and civil engineering works and recommends a common data environment (CDE) for data transfer throughout the whole life cycle of buildings. Part two [32], which describes delivery phase of the assets, is of particular importance for this research. For a successful collaboration via a data-centric CDE, an information delivery planning and responsibility matrix is required along with a higher level of standardized processes. However, the standard [32] does not describe the processes on the scale of specific geometries and building elements, as needed for the exchange between the architectural design and structural analysis. The presented research aims to further build on the recommended framework for information management systems with the processes required for this particular data exchange. The data-centric approach is also seen as a way to distance the data from proprietary solutions. Because of the high data fragmentation in the AEC industry, flexible data integration and sharing is required [4]. The NoSQL (not only SQL) databases have been recognized as a possible solution for the heterogeneous data originating from various proprietary solution [4,33]. The NoSQL database provides scalability, flexibility and performance compared to a relational database. In our work, we use a MongoDB semi-structured database to provide a data-centric open exchange.

Semi-structured schemas are not strict and evolve with time, which is suitable for the AEC industry. Popular serialization formats for a semi-structured schema are JSON (JavaScript Object Notation) and XML (Extensible Markup Language) [34]. Advantages of using the JSON format for being lightweight and human-readable are recognized and it is utilized for data management frameworks in the oil and gas engineering sector [35]. This framework is realized with MongoDB, and certain advantages compared to other JSON databases such as multiple indexing and SQL-similar query language are recognized. IFC building models may be serialized as JSON, and the resulting ifcJSON format arguably shows advantages towards the existing ifcXML serialization [36]. In our work, the JSON format will be used to support a web-based data-centric framework.

A popular approach when it comes to dealing with semantical differences between different applications is the use of ontologies [34]. The ontologies are omitted in this work due to the lack of necessary access control, especially needed in a decentralized collaboration environment [37]. This deficit is currently the subject of improvement efforts and could increase the implementation potential of ontologies in the future. The focus

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of the works investigating ontologies in the AEC industry has been primarily set on non-geometrical information, while the most complex parts in the data exchange in question are geometrical interpretations. The geometry description of building elements with ontologies is a recent work [38]. Therefore, we focus on the solutions which offer access control and settled structures for describing geometry.

Discrepancy between life spans of long-lasting products such are buildings and software tools used for their creation should not be reflected on digital product representations which are needed during the whole product life cycle. X3DOM technology can be used to represent geometry in web browsers and help with the plant layout design process [39]. They use a dynamic representation to store geometry information by recording the modelling history. Geometry kernels such as 3d ACIS Modeler (ACIS) have already been used to overcome the differences between architectural design and structural analysis [28,40] and to manage complex geometric interpretation. An additional geometry kernel can be used to generate meshes for finite element modelling, with the focus on boundary-representation (BRep) models [41]. A geometry kernel is useful to store and manipulate the geometrical information for complex geometry methods, therefore the serialization used in our work will not correspond entirely to the existing IFC standard. We chose Open Cascade Library (OC) as the free and open source geometry kernel for the storage and editing of geometric information.

3. Research Design

The presented paper describes the implementation of the novel framework for data exchange supporting open interpretations, including the proof of concept and verification. The main aim of the paper is to facilitate interpretations or transformations of building models independent of proprietary tools used for architectural design or structural analysis; which are not realized as editable, open or extendable in practice, nor any of the existing structural software packages. Table 2 gives a brief overview of the research design. The conceptual framework is thoroughly described in [9]. The current work describes the details of the framework implementation, and tests its applicability in practice.

Table 2. Research design.

Framework concept	Data exchange concept based on domain-specific classification, non-proprietary interpretations between domains and automation of central storage and proprietary solutions [9]
	Implementation of the framework with detailed explanation of system architecture (Section 4)
Implementation: Proof of concept	Development of algorithms describing individual open interpretations for building elements and belonging geometries found in a single prototype model (Section 5)
Verification	Testing of interpretations developed with the protype model with two additional models and identifying required modifications needed to support new models (Section 6)

Each research step is built around open interpretations, with the aim to identify, implement and verify interpretation methods. The system architecture which is developed for the novel framework is explained in Section 4. Interpretations are developed with the proof of concept, and their usefulness and usability are verified with two further verification models. Open interpretation methods and their realization is a research gap which we bridge with this paper.

4. Novel Data Exchange Framework

A novel theoretical framework and the corresponding system architecture, which incorporate interpretation rules in an open data exchange, were developed in the previous

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work [9]. Hence, a brief description of the framework as a base for further development will be presented, followed by a detailed description of the corresponding system architecture.

4.1. Concept

The proposed theoretical framework for interdisciplinary data exchange is based on three parts: (i) classification, (ii) interpretation and (iii) automation. The classification part defines the terminology and domain-specific requirements. Semantical and geometrical properties of building elements are clearly distinguished within the classification system [42] as they undergo different interpretations. The interpretation part defines the relations between domain-specific classification systems, including the semantical and geometrical interpretations. The interpretations support the transition from one to another domain-specific classification system and corresponding data. This process can be fully or partially automated. The classification and interpretation parts take place in central storage and are not dependent on proprietary software tools. Finally, the automation part implies automatic communication between the domain-specific models on the central database with the proprietary models and software tools. The concept of the new framework can be compared to the IFC-based data exchange with, however, several key differences: classification is developed as domain-specific and interpretations take place between multiple centrally-stored domain-specific models, while the popular IFC subschemas called model view definitions (MVD) and IFC involve multiple domains, and the interdisciplinary interpretations are not formalized. Proprietary domain-specific tools in our concept communicate with the domain-specific models. The idea is similar to the MVDs which have not been developed as domain-specific and the interpretations between them have not been considered [6]. An additional difference is that the data exchange is not file-based. Figure 1 depicts different parts within the framework.

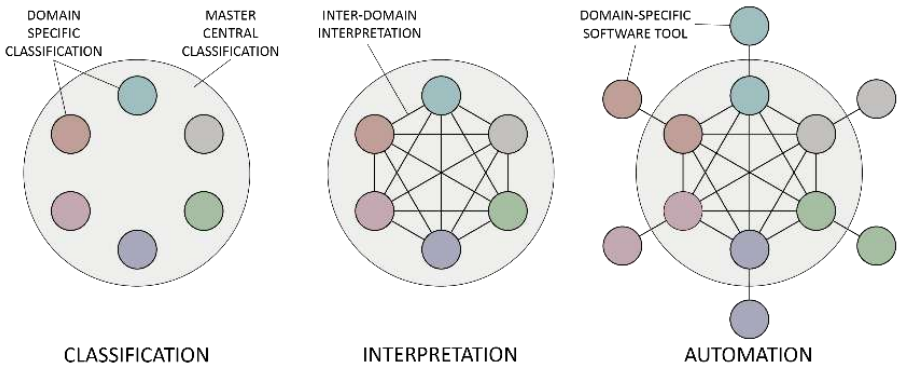

Figure 1. Framework schema (from [9]).

4.2. System Architecture

A digital system comprising software tools, schemas and geometry kernels is developed to support the above presented framework. The system architecture incorporates all three parts: classification, interpretation and automation, and in that order it will be described.

Models can be connected in asynchronous or static and synchronous or dynamic way. Synchronous connection means that a storage (containing a model) or a software tool can be subscribed to another storage or tool and the changes made in the native tool or storage are recognized and updated in the receiving one. On the other hand, asynchronous connection does not allow automatic information updates, and the exchange process must be repeated in order to display the changes. In the described system, synchronous connection represents a connection via an API (application programming interface), while file-based exchange is considered asynchronous. A non-proprietary IFC building model is a starting point in the data exchange framework. A corresponding flexible system architecture can be used with all software tools supporting export to IFC (Figure 2a). However, it does not provide

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a synchronous connection between the native model in Revit or architectural model in IFC and the central storage, and some data losses and inconsistencies take place during the export from native to IFC models.

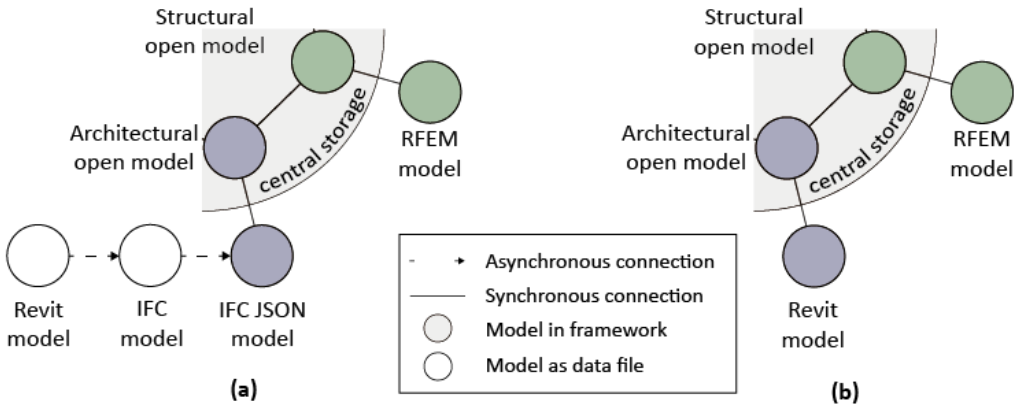

Figure 2. Building models within the (**a**) implemented and (**b**) optimal system architectures.

An optimized, software-specific system architecture with synchronous connection between Revit and a central model can provide fully synchronous exchange (Figure 2b). The system architecture where Revit is directly coupled with the central storage uses Revit API. This work considers one-directional exchange. With the use of APIs and fully synchronous connection, it is possible to extend the exchange to both directions, which is a future work, and requires the investigation of interpretations in the other direction. In order to leave the option of using other architectural tools than Revit open, a suboptimal flexible exchange with IFC is implemented at this stage of the research.

4.2.1. Classification

Classification defines an underlying structure of building models, in this case architectural and structural building models. We opted for MongoDB and JSON, deeming it appropriate for the heterogeneous building models. MongoDB uses documents and groups them in various collections. A data-exchange workflow would benefit from the clear distinction between geometrical and semantic data [42]; therefore, these two types of data are treated separately within the JSON document. The main shared characteristics are that they describe the same building element and both are defined with the JSON format. An example of a building element is presented in Figure 3.

```
{
    "_id": "1000",                                  mandatory attribute building element ID
    "type": "COLUMN",                               mandatory attribute entity type
    "load_bearing": true,                           optional* attribute load-bearing property
    "material": "concrete",                         optional* attribute material
    "cross_section": {                              optional* attribute cross section
        "type": "RECTANGLEPROFILEDEF",              *required for structural analysis
        "width": 20,
        "height": 20
    }
    "geometry": {                                   mandatory attribute geometry
        "BRepBuilderAPI_Transform": [...],          OC class name: array of parameters for the class initialization
        "methods": ["Shape"],                       array of methods for the OC class
    }
}
```

Figure 3. Example of a building element with JSON serialization.

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1. Semantic information

Information necessary for a data exchange between physical and analytical models, besides geometric information, is information about the element ID, type, load-bearing property, cross section for linear elements and material. This amount of information is sufficient to properly define a model in a structural analysis software tool. Mandatory properties for each data exchange are element type, ID and geometry, and specific for the exchange to structural analysis are load-bearing properties and material, as well as cross section details for linear elements. The majority of terms used to define the semantic information originate from the IFC 2x3 schema.

Terms defining building element types are: IfcColumn, IfcWall, IfcSlab, IfcBeam and IfcOpeningElement. Element types in a structural model are IfcStructuralCurveMember or IfcStructuralSurfaceMember and StructuralSurfaceMemberOpening.

The element ID originates from IFC JSON, except that the prefix '#' is removed since it is not supported in MongoDB. The ID remains the same in the structural collection after the interpretation.

Load-bearing properties of building elements are MongoDB boolean values. Only the elements which are not "load-bearing: false" are relevant for structural models.

Cross sections for linear elements are defined based on their profile description in the IFC geometrical definition and the corresponding parameter. The cross-section property is a JSON object consisting of a type description and optionally a parameters array.

Materials are defined with a name string, which does not follow any particular standard. SAF project standardizes the format for exchange between various structural analysis software [43], and defines materials: "concrete", "steel", "timber", "aluminium", "masonry" and "other". The architectural model defines the materials mainly for visualization purposes, the structural models and software tools provide more detailed material description with the structural performance properties. Structural materials are assigned by referencing a commonly used material type, for instance "C30/37" for each material named "concrete" in the architectural model.

- Geometric information

OC was used for geometry definitions to enable significant editing and complex interpretation processes. Each building element has its geometry defined in the form {class: parameters array and methods: parameters array}. In such a way, geometries can be automatically retrieved with the help of recursive methods. A similar approach with OC and linked data is developed within SCOPE project [44]. If the geometry definitions are valid, they result in OC topological shapes. The geometries exported after the interpretation are performed are also defined with the OC kernel, in the same form as the geometries of elements in the central architectural representation.

4.2.2. Interpretation

Prior to implementation of interpretation, implicit structural engineering knowledge has to be documented according to specific project requirements and building element typologies, in order to be codified. The documented knowledge results in algorithms which relate the two domain-specific models and are suitable for coding and automation.

To implement the interpretations, we created the *redDim* (*red*uce *Dim*ensionality) program, using the C# programing language. *redDim* provides multiple functionalities to read the architectural model, edit it and write a new structural model. *redDim* is able to read the existing geometrical and non-geometrical information, filter the load-bearing building elements, interpret semantic information, perform multiple methods for interpretation of geometric information, assign additional material properties for the structural model and finally export the structural model to the MongoDB structural collection.

The greatest advantage of *redDim* is the interpretation of geometrical information on the central storage, since the interpretations are the greatest challenge in conversion from architectural to structural analysis models. The interpretations take place with the

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OC geometry definitions with the help of OC methods. The resulting model is an open structural analysis model, which can be imported by mapping the information to the structural analysis software tool. In that way, the geometry interpretations are not anymore part of the problematic software import.

4.2.3. Automation

Automation part allows coupling of proprietary software with the central storage. As mentioned, IFC building models are used in the system architecture. Programs *IFCtoJSON*, *strucToRISE*, *redDim* and *RFEMimporter* are developed to support the framework (Figure 4). An IFC model is reformatted to a JSON format with a software tool *IFCtoJSON*, and placed on MongoDB as "ifc_json" collection. *strucToRISE* extracts and restructures "ifc_json" information, and creates a central architectural open model. IFC geometry is mapped to OC geometry with *strucToRISE* by using similar classes and preserving parametric element representation (e.g., extrusions, see Figure 13). IFC models contain less information than the native building models—in the case that the IFC export does not suffice, a direct connection with the native model is needed. The architectural model is used for the interpretations and creation of a structural central model. The structural central model can be mapped to any software tool that provides an API. For test purposes and to achieve a full exchange, the resulting structural model was transferred to Dlubal RFEM structural analysis program using a program *RFEMimporter*, with the help of an RFEM API.

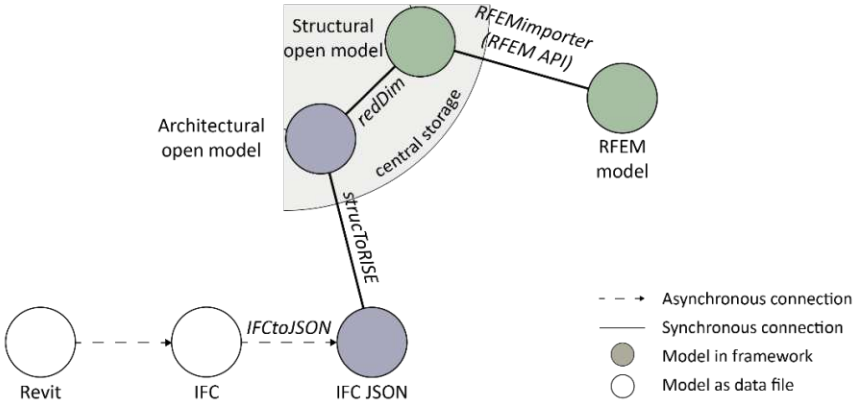

Figure 4. System architecture.

IFCtoJSON, *strucToRISE* and *RFEMimporter* will be described in the follow-up.

- *IFCtoJSON*

In order to use the IFC file on the MongoDB, it is reformatted to the JSON syntax with a self-made converter [45]. All IFC entities and properties are reformatted using the IFC 2x3 schema. In such a way, "key: value" combinations are defined with JSON syntax. A result of the conversion is a JSON file that can be placed on the MongDB. This Mongo collection, named "ifc_json", is a starting point of the novel data exchange.

- *strucToRISE*

From the "ifc_json" collection a central open architectural model is created. Geometry defined in IFC is converted to OC classes and non-geometrical building element properties are restructured (ID, building element type, load-bearing property, cross section and material). The building elements are filtered from "ifc_json" based on the element type.

Load-bearing properties are defined with IfcRelDefinesByProperties; load bearing property is a boolean value defined with an IfcPropertySingleValue. Material is related to the building element with IfcRelAssociatesMaterial; the material is defined as IfcMaterial, IfcMaterialLayerSetUsage or IfcMaterialLayerSet, depending on whether it is a single or multi-layered building element, and if it occurs multiple times in the model. Material

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names originate from the native software tool Revit and do not follow any standardized terminology. Material naming on central storage follow the naming of SAF (2020) recommendation. However, the conventions for the material terminology are needed so they would not cause interoperability problems.

All the geometries were separately treated and converted to OC classes. Proprietary software that converts STEP to OC exists; however, in this work it was not closely investigated.

- *RFEMimporter*

The RFEM Dlubal API is called RF-COM. IFC classes StructuralCurveMember, StrucutralSurfaceMember and StrucutralSurfaceMemberOpening are defined in RFEM as member, surface and opening elements respectively. Geometric information is transferred to RFEM without any complex interpretation, primarily by reassigning the existing information between OC and internal RFEM kernels. RFEM internally describes cross sections as a single string, e.g., "RECTANGLE 100/200", which was created based on the existing cross-section information. Materials are also defined as a single string. For instance, all concrete elements are defined as "C30/37" or in RFEM terminology "NameID | C30/37@TypeID | CONCRETE @NormID | EN 1992-1-1". If a material does not exist in the standard RFEM library it needs to be defined manually. The element ID is kept in RFEM as a comment which can be assigned with the RFEM API.

Figure 5 depicts an exemplary building element through different steps in the data exchange process. Table 3 lists the created software tools with their specific performing tasks used to realize the proposed framework:

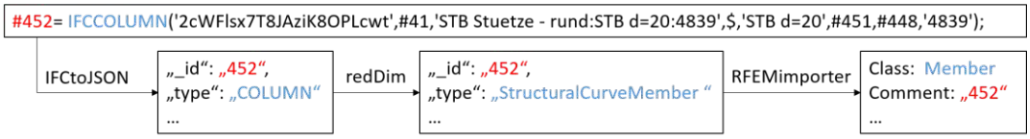

Figure 5. Object ID and type during the data exchange.

Table 3. Summary of developed applications.

Name	Task
IFCtoJSON	Refactors IFC files and IFC schema to JSON format
strucToRISE	Filters and restructures building elements and uses only necessary attributes mainly with IFC terminology, converts IFC geometry definitions to OC
redDim	Core program that performs non-proprietary interpretations between architectural design and structural analysis models
RFEMimporter	Maps the centrally stored structural analysis model to Dlubal RFEM, converts OC geometry and non-geometrical properties to software-specific objects

5. Proof of Concept: Data Exchange Implementation

The following section presents implementation of the novel data exchange framework. The proof of concept builds on the system architecture as presented in Figure 4 to entirely automate the interpretation of the prototype building model (PM). *IFCtoJSON* reformats all IFC files, independent of the building model. However, the other three programs: *strucToRISE*, *redDim* and *RFEMimporter* are developed with the PM. The complete workflow implemented with the PM, from its IFC representation, original and interpreted model in *redDim* and finally resulting import in RFEM Dlubal, is presented in Figure 6.

5.1. Methodology

The PM is a model of the iconic Villa Savoye by Le Corbusier (Table 4). It represents the modernist work of architecture, where concrete columns define the main support system

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with concrete slabs. Additionally, basement walls and staircase walls on the roof terrace are part of the structural system. This building is chosen primarily as its structural system is commonly used in practice, and involves both load-bearing columns and walls; it also consists of a rich set of standard geometrical forms, mainly polygons extruded in different directions with straight and curved segments, defining multiple building element types. Some geometries such as columns with square cross sections and rectangular walls are already addressed in the literature (Table 1), but a suitable geometry-specific algorithm for performing interpretations has not been found.

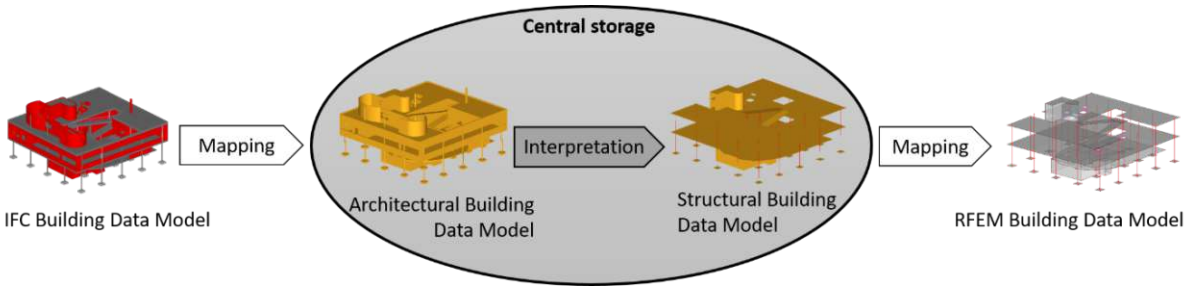
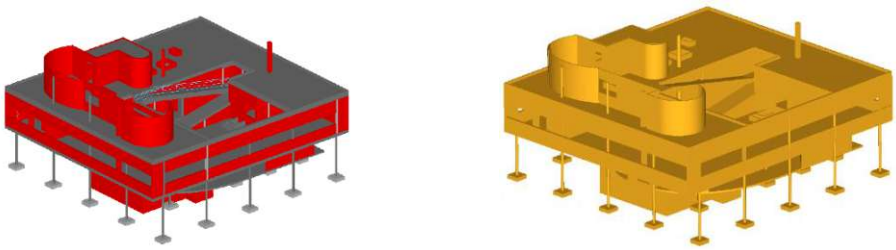


Figure 6. Overview of the PM workflow.

Table 4. Screenshots of PM architectural models.



(a) PM in Solibri (b) PM in *redDim*

5.2. Classification

strucToRISE creates the central open architectural model from the "ifc_json" collection, which follows the previously described classification. The PM architectural collection consists of 421 building elements: walls, openings, columns and slabs, all having properties: element type, ID, material and geometry, and only the linear elements cross-section. The load-bearing property is not defined in 26% of building elements, while 27% of the rest have value "true". Materials of load-bearing elements are "concrete" and "masonry", whereas building materials of non-load bearing elements are not focus of this work. All geometries are defined with OC definitions, and the resulting shapes are automatically created. These properties within the architectural model suffice for data exchange purposes.

The structural model consists of 125 building elements: StructuralCurveMembers, StructuralSurfaceMembers and StructuralSurfaceMemberOpenings, with the corresponding properties. This data is mapped and rendered as structural model in RFEM Dlubal.

5.3. Interpretations

Before the implementation of interpretations, necessary implicit knowledge needs to be documented in such a way that it can be codified, computationally readable and automated. The interpretation algorithms originating from implicit knowledge depend on project properties and building elements. Hereby proposed algorithms will be verified with additional models in order to evaluate their standardization potential.

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5.3.1. Documentation of Implicit Knowledge

The geometry interpretation methods for the data exchange from the physical into an analytical model, developed and applied within the framework, include linearization, planarization, reconnecting elements and perimeter adjustment. The methods are based on the previous literature review (e.g., [20,22]), and were chosen in order to support specific geometries present in the PM, such as columns with round and rectangular cross section, straight and curved one-layered walls with uniform thickness, horizontal and tilted uniform-thickness slabs and single foundations.

- Linearization

Linear elements in the PM are columns with round and square cross sections. They are represented as OC topological shapes cylinders and boxes. A single algorithm converts the shapes to edges, consisting of several steps (Figure 7): (i) top and bottom faces are identified by analyzing and comparing all the faces constituting the shape; in the case of non-vertical linear elements (such as beams) two parallel faces with the smallest area can be identified; (ii) vertices defining the centers of mass of the faces is found; and (iii) an edge is created between the vertices representing the linear element.

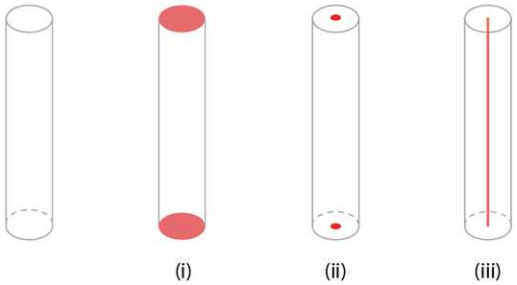

Figure 7. Linearization of building elements.

- Planarization

Planar elements in PM are walls and slabs (including flat roof), both represented as topological shapes of OC, some containing openings. The planarization method involved (Figure 8): (i) largest face of the shape is located; (ii) the element thickness is found by analyzing distances from the central face vertex to its projection on the neighboring surfaces; and (iii) the largest face is offset for half of the thickness to the inner part of the topological element. The result is a planar element axis as the OC face. Analytical representation of openings is an intersection between the physical opening geometry and planarized host element, so it would be coplanar with the host element surface.

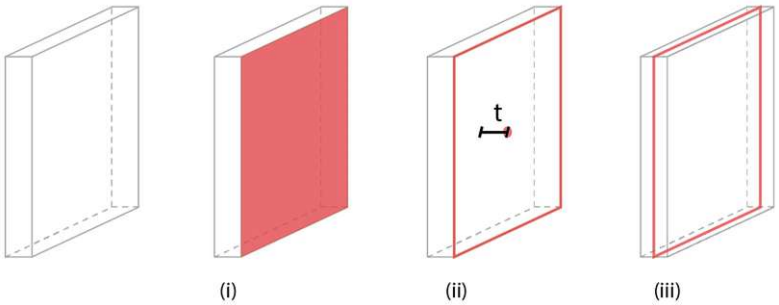

Figure 8. Planarization of building elements.

- Reconnecting Elements

Physical building elements are investigated for their neighboring elements. Based on the results, the analytical elements are reconnected. Reconnect elements consists of (Figure 9): (i) finding neighboring elements in the physical model by checking the minimum

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distance between elements, and considering the element type (e.g., columns cannot be reconnected to other columns or walls, but can to slabs) and inclination (tilted slabs); (ii) addressing each element and their neighbors in analytical representation; depending on whether an element is linear or planar: (iii)(a) linear elements or edges in OC are extended until the intersection point with the neighboring planar element; (iii)(b) the planar elements are extended or trimmed: the closest edges are projected, adjacent edges extended or trimmed and the remaining edges unchanged. Vertical planar elements are connected both to horizontal and vertical neighboring planar elements. Openings are reconnected to the neighboring elements, and the complex geometry of hosts with openings is updated.

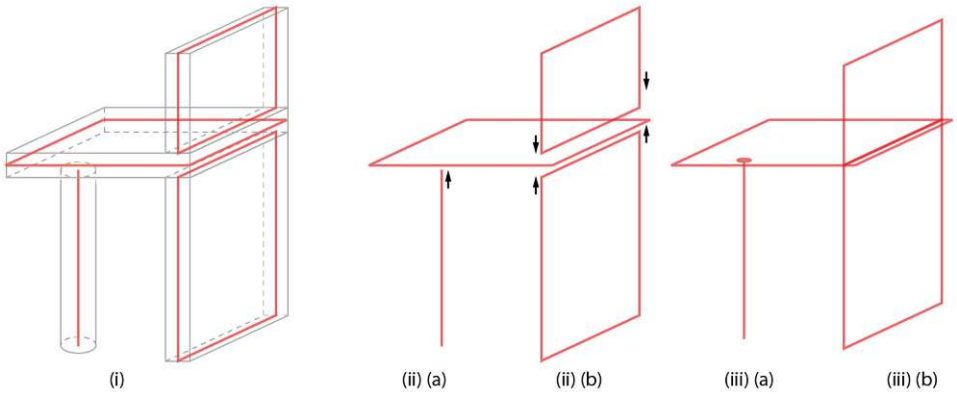

Figure 9. Reconnecting elements in structural representation.

- Perimeter Adjustment

The information about the neighboring building elements is used in order to adjust the perimeter of horizontal planar elements. The edges of horizontal planar elements are adjusted to the building elements supporting them. The elements near the perimeter edges are identified, and linear vertical elements connected to the two closest vertical load-bearing elements on the same side of the slab and in the same neighbor list to create *load-bearing fronts*. These *fronts* determine if the slab edge should be adjusted to the underlying columns. For perimeter adjustment the following steps are applied (Figure 10): (i) vertical elements close to the perimeter in the analytical model are found; (ii) "load-bearing fronts" are created from the vertical linear elements; (iii) planar vertical elements and "*fronts*" are projected on the horizontal planar element; (iv) depending on the distance between intersection and the edge of the slab, and the tolerance, some neighbors are eliminated; parallelism of the edges and the projections is checked; and (iv) the face is extended or trimmed to the edges which fulfill the conditions from (iii).

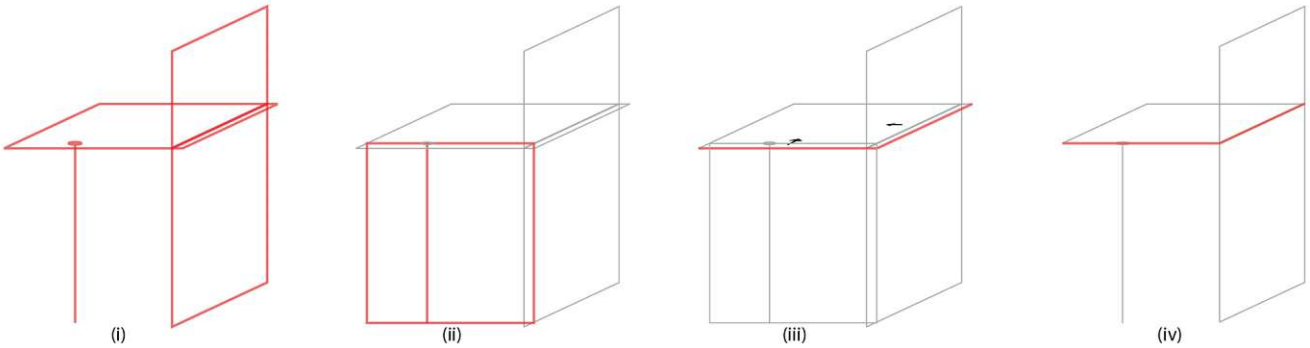

Figure 10. Perimeter adjustment of horizontal structural elements.

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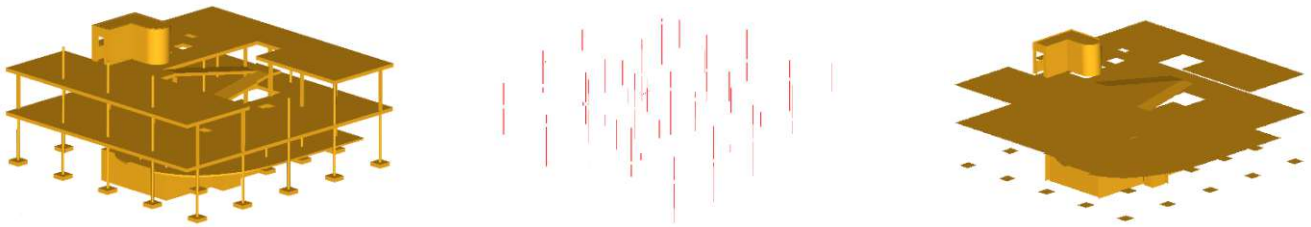
5.3.2. redDim

redDim program is developed for the PM of Villa Savoye with all necessary interpretation methods. The architectural model available on MongoDB is read with MongoDB API and NET framework. OC libraries are required to create and edit OC classes. *redDim* provides the method "original" showing the original geometry found in the architectural model. This geometry includes all elements, irrelevant of their load-bearing properties. Since *strucToRISE* and *redDim* were created for PM, validation was not required. *redDim* is able to read the complete model geometry (Table 4b). The method "filtered" renders all elements which do not have the load-bearing property "false" (Table 5a). This model is the working model for the geometry interpretations. Semantic interpretations take place on the go with geometric interpretations. The interpretations follow the implicit knowledge: linearization, planarization, reconnecting elements and perimeter adjustment.

Table 5. Results of *redDim* methods.



(a) Filtering result (b) Linearization result (c) Planarization result

Linearization affects the columns (Table 5b). Two smallest faces of the topological shape are found with ShapeExplorer and tested for parallelism. Centers of mass for both faces are determined with BRepGProp surface properties method, resulting with two points. The edge is created with the two points, describing a linear building element. The element type is redefined as a structural curved member.

Planarization reduces dimensionality of slabs and walls (Table 5c). The openings, both in slabs and walls, are planarized separately. The largest face of each slab and wall is found with ShapeExplorer and BRepGProp. The parallel face is found by comparing normal directions of underlying surfaces. The central point of largest face is projected to the parallel face and the distance between the points is found, defining the thickness of the building element. The largest face is offset for half of element thickness, creating the structural representation of the building element. Planar elements, such as walls and slabs, change their building element type to structural surface member in the structural representation. Since openings are dependent on their host elements, they are planarized by finding an intersection of the planarized host element representation and physical geometry of an opening.

Linearization and planarization reduce dimensionality of all load-bearing elements. Elements are reconnected in their structural representation with reconnect elements and perimeter adjustment. *redDim* tests all elements for the distance in the physical model, and each element is assigned a neighbor list. Each building element is connected to their neighboring elements: columns are extended to the slabs by redefining edges in their structural representation with an intersection point and a more distant edge point; Walls are extended to each other and to the slabs by identifying the edge closest to the neighbor and its adjacent edges, finding the intersection line between two planar surfaces, defined by the wall and the neighbor, identifying the intersection points of curves of adjacent edges and neighboring surface, using these points to define an edge on the intersection line, and extending or trimming adjacent edges (similar to linear elements). This method is used to extend walls, openings belonging to the walls and ramps. Horizontal slabs are interpreted with the adjust perimeter method (Figure 11).

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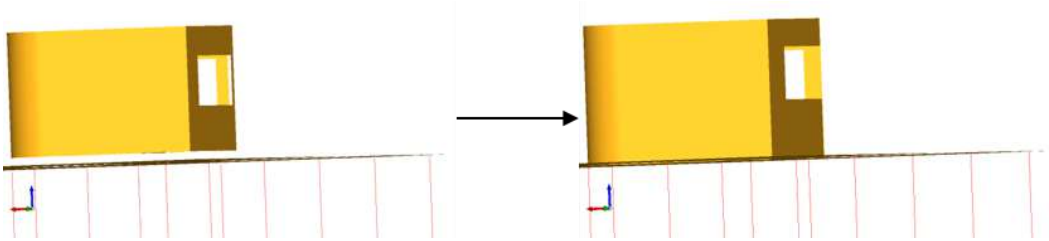

Figure 11. Before and after reconnecting elements.

Slabs and openings belonging to slabs are treated with perimeter adjustment method, using already defined lists with neighbors (Figure 12). Only the neighbors close to the perimeter, which is a wire of a face defining the structural representation, are filtered. Each column in the list of neighbors is connected to the two closest elements in the same list, which are on the same side of the slab, creating "load-bearing fronts". These columns are hereafter considered as planar "load-bearing fronts" and not as linear elements. Intersection lines between the slab and the planar neighbor are analyzed. Slab edges are adjusted to the ones satisfying the closeness and parallelism conditions. Elements with curved edge had to be specially treated. If an edge neighbors a curved edge, a curved edge is not extended. The curved edge is defined on the intersection line between the two surfaces; its end points are designated as an intersection of a line passing through the center point of the arc and the original end point intersection with the neighboring surface. The adjacent edges are adjusted to these intersection points.

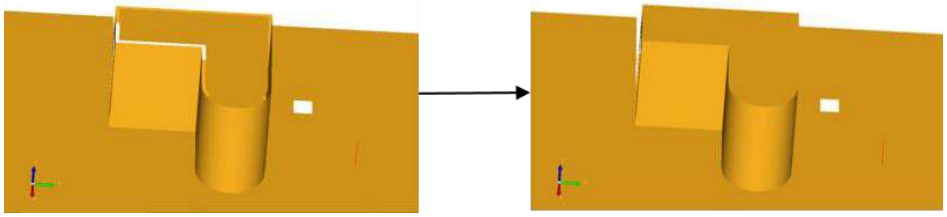

Figure 12. Before and after perimeter adjustment.

Last method in *redDim* exports the structural model. Exported are OC classes and methods defining the geometry, and additional parameters such as ID of building element, entity type, thickness calculated within *redDim* and profile cross section for linear elements from the architectural model. All load-bearing elements in their structural representation are available in a new collection on MongoDB.

5.4. Automation: StructToRISE and RFEM Importer

The central database contains architectural design and structural analysis models, which are related to the external domain-specific models. IFC in JSON format is used as the external architectural model, and RFEM Dlubal contains the external structural analysis model. *structToRISE* accesses the IFC model and defines the "ifc_json" collection to central architectural collection, creating 421 building elements from 20046 entities in the "ifc_json" collection. For each building element its reference number or ID and its entity type is transferred to the MongoDB. Geometries existing in the original model such as IfcMappedItem, IfcExtrudedAreaSolid, IfcBooleanClippingResult, IfcFacetedBrep, IfcHalfSpaceSolid and IfcPolygonalBoundedHalfSpace are identified by "body" representations of building elements. These geometries are redefined as OC classes. *RFEMimporter* maps the central structural building model to RFEM internal model with all the necessary properties, merely by mapping the geometries and properties to the RFEM internal classes. Converting OC to RFEM classes is a simple procedure compared to geometry interpretations. As an example, Figure 13 shows extruded area solid in its IFC and OC representations, where the focus is on geometry information.

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```
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#19=    IFCDIRECTION((0.,0.,1.));
#23=    IFCDIRECTION((1.,0.));
#31=    IFCAXIS2PLACEMENT3D(#6,$,$);
#32=    IFCLOCALPLACEMENT(#33320,#31);
#35=    IFCPERSON($,'','***@hotmail.com',$,$,$,$,$);
#37=    IFCORGANIZATION($,'','',$,$);
#38=    IFCPERSONANDORGANIZATION(#35,#37,$);
#41=    IFCOWNERHISTORY(#38,#5,$,.NOCHANGE.,$,$,$,1591271314);
#94=    IFCAXIS2PLACEMENT3D(#6,$,$);
#95=    IFCDIRECTION((6.123031769111189E-17,1.));
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#102=   IFCGEOMETRICREPRESENTATIONSUBCONTEXT
        ('Body','Model',*,*,*,*,#97,$,.MODEL_VIEW.,$);
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#141=   IFCLOCALPLACEMENT(#32,#140);
#239=   IFCCARTESIANTRANSFORMATIONOPERATOR3D($,$,#6,1.,$);
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#992=   IFCMAPPEDITEM(#989,#239);
#994=   IFCSHAPEREPRESENTATION(#102,'Body','MappedRepresentation',(#992));
#996=   IFCPRODUCTDEFINITIONSHAPE($,$,(#994));
#998=   IFCAXIS2PLACEMENT3D(#6,$,$);
#999=   IFCLOCALPLACEMENT(#141,#998);
#1000=  IFCCOLUMN('2cWFlsx7T8JAziK8OPLcZu',#41,'STB St\X2\00FC\X0\tze –
        rund:STB d=20:5288',$,'STB d=20',#999,#996,'5288');
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#33320= IFCLOCALPLACEMENT($,#33319);
```

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        "BRepBuilderAPI_Transform": [{
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            "methods": ["Shape"] }, {
            "gp_Trsf": [],
            "methods": [{
                "SetTransformation": [{
                    "gp_Ax3": [{
                            "gp_Ax2": [{
                                "gp_Pnt": [] }, {
                                "gp_Dir": [0, 0, 1] }, {
                                "gp_Dir": [1, 0, 0] }] }],
                        "methods": [{
                    "SetLocation": [{
                            "gp_Pnt": [-136, 610, 0] }] }] }, {
                "gp_Ax3": [{
                    "gp_Ax2": [{
                            "gp_Pnt": [] }, {
                            "gp_Dir": [0, 0, 1] }, {
                              "gp_Dir": [1, 0, 0] }] }] }] },
        false],
        "methods": ["Shape"] }, {
        "gp_Trsf": [],
        "methods": [{
            "SetTransformation": [{
                "gp_Ax3": [{
                        "gp_Ax2": [{
                            "gp_Pnt": [] }, {
                            "gp_Dir": [0, 0, 1] }, {
                            "gp_Dir": [1, 0, 0] }] }],
                "methods": [{
                        "SetLocation": [{
                            "gp_Pnt": [0, 0, 0] }] }] }, {
                  "gp_Ax3": [] }] }] },
    false],
    "methods": ["Shape"] }
```

Figure 13. IFC (**left**) and OC (**right**) geometry definition.

6. Verification

An additional aim of this work is to test the applicability of the demonstrated approach to external models (created by various modelers). Since the application is still conceptual and a work in progress, debugging was not considered as model-related change (e.g., error handling was done on the go), but rather new and changed interpretation methods which were required for the new models.

6.1. Methodology

The interpretations defined with the PM are tested on additional two building models. Two new exports of IFC models from Revit are created and used in the novel framework—Verification Building Model 1 (VM1) and Verification Building Model 2 (VM2) (curtesy of STRABAG AG). Native Revit models originate from a different planner or planners, where a company specific workflow and standards were implemented. The models, as real use cases, are provided by a structural engineering company and display a similar structural system as in the PM. "ifc_json" models are imported to MongoDB. *strucToRISE* supported all geometries for creating the architectural model. *redDim* is adapted to the new building elements and geometries (Section 6.2). *RFEMimporter* created for the PM was sufficient for the proper import of the new models. The methods defined for the PM were tested on complete automation of the building model interpretations. The methodology primarily involved software testing and visual checks of the resulting model. The imported structural models in RFEM Dlubal are, the same as PM, verified by authors and the external structural engineer.

VM1 is a three-story building with concrete load-bearing walls. VM2 is a five-story building with an underground garage and structural system as a combination of load-bearing walls and columns. IFC models and the corresponding OC representations of verification models are shown in Table 6.

The verification models extend implicit knowledge documented for the PM, and the previously described methods are updated.

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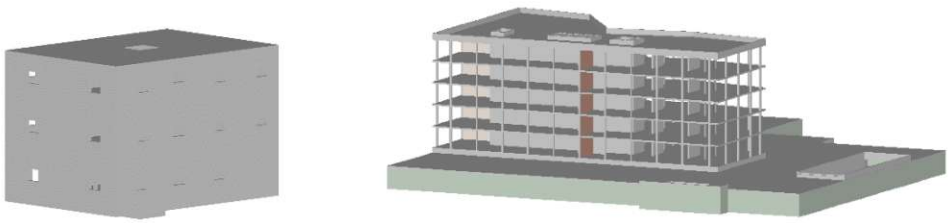
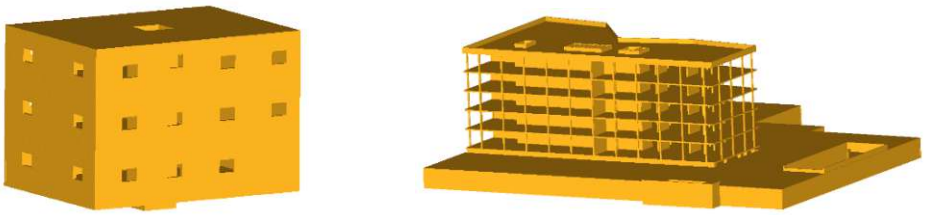
Table 6. Screenshots of VM1 and VM2 architectural models.



(a) VM1 in Solibri (b) VM2 in Solibri



(c) VM1 in *redDim* (d) VM2 in *redDim*

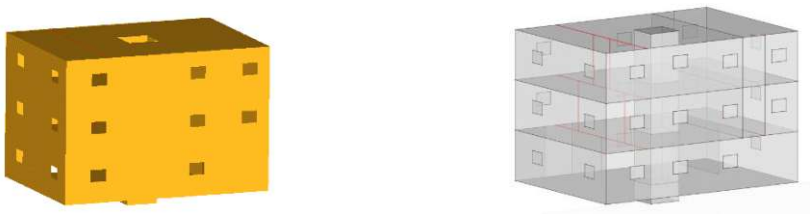
6.2. Results

The interpretations defined with the prototype building covered more than 80% of building elements of the VM1. The VM2 had only a few additional adjustments, after the changes for the VM1 were implemented. VM1 has 84 architectural and 83 structural, while VM2 has 613 architectural and 366 structural building elements. Results show a great potential in standardizing the majority of interpretations for the most common geometries and building elements.

6.2.1. Verification Model 1 (VM1)

The geometry of the VM1 was supported entirely by *strucToRISE* and *RFEMimporter*. *redDim* behaved unexpectedly and it was adjusted to the new interpretations. With the adjustments it was able to automatically create a structural model (Table 7a), which could be imported to RFEM Dlubal with *RFEMimporter* (Table 7b).

Table 7. Screenshots of VM1 structural model.



(a) VM1 in *redDim* (b) VM1 in RFEM

Differences in VM1 compared to the PM were identified as follows:

- Continuing walls

The intersections of parallel walls with the same thickness do not exist (Table 8a). However, parallel walls were present in the lists with neighbors and since it is a standard modelling approach *redDim* required an extension—the neighbors are tested for their parallelism and divided into two groups. Linear elements are parallel if their main directions are same, and planar if their normals to the face are parallel. Linear and planar neighbors are considered parallel if the direction of linear element is orthogonal to the normal of the planar face.

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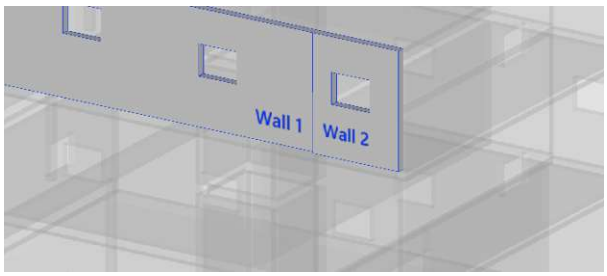
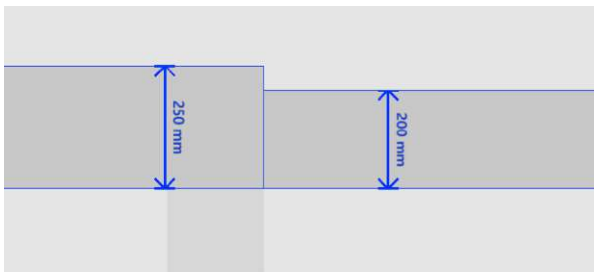
Table 8. Building elements which required additional methods in VM1.



(a) Continuing walls



(b) Continuing slabs

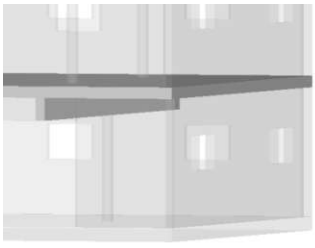
- Aligning continuing slabs with varying thickness

Neighboring building elements with varying thicknesses were not part of PM. The staircase slab is a neighboring standard floor slab, and their thicknesses are 20 and 25 cm respectively (Table 8b). The slabs have their bottom faces aligned, however, after planarization; the resulting faces display a 2.5 cm distance between each other. Parallel neighbors which are not in the same plane after the planarization need to be aligned. Thus, as an addition to the reconnecting elements method, in fact, as its first step, an alignment of neighboring structural faces is performed. The smaller face, area-wise, is moved to be coplanar with the larger one. An additional connectivity problem was found due to the varying slab thicknesses: the underlying wall is modelled as a single element, and connected only to one of the two slabs. If the alignment is performed as the first step, this problem is avoided. The eccentricity of the slab was added as additional information based on the distance between the original and final position.

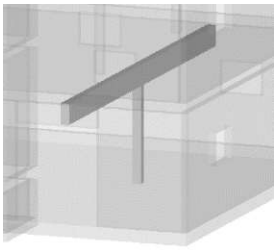
- Aligning beam to slab

In the PM there were no beams; however, in the VM1 beams supporting slabs were present (Table 9a). When the beam is linearized, it loses its connection to the slab in its structural representation. The beam is aligned to the slab from the neighbor list. The distance between the beam and the slab is added as the eccentricity of the beam, when the beam is translated to the face which represents the structural representation of slab.

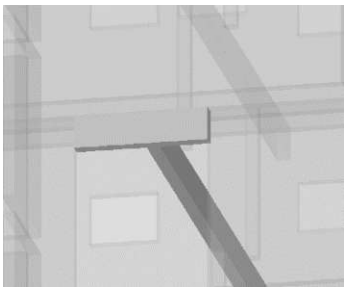
Table 9. Building elements which required additional methods in VM1.



(a) Beam supporting slab



(b) Column supporting beam



(c) Beam neighboring beam

- Extending column to beam

In the VM1, a column-supporting a beam exists (Table 9b). The column is reconnected to the beam after the beam is aligned with the slab. For checking the extension distance, beam eccentricity is considered, since the beams have previously been aligned with the slab.

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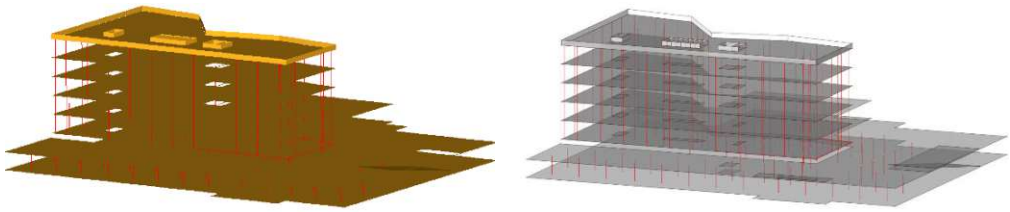
- Extending beam to beam

Since there were no beams in the PM, there were also no connections between two beams. In VM1, two beams supporting the same slab are neighboring each other (Table 9c). Both beams are aligned to the face of the corresponding slab in its structural representation, which made them coplanar. Because of that there was no problem in finding the beam intersection.

6.2.2. Verification Model 2 (VM2)

Changes in *redDim* to completely automate the interpretation of the physical into analytical model involved addressing the issues of linearization of beams with non-parallel smallest faces and walls with multiple connectivity options. After the changes in *redDim*, a structural model could be successfully created (Table 10a) and imported to RFEM (Table 10b).

Table 10. Screenshots of VM2 structural model.



(a) VM2 in *redDim* (b) VM2 in RFEM

VM2 building was addressing additionally the issues of:

- Linearization of beams with non-parallel smallest faces

Linearization was finding two smallest faces of a shape to create the linear element representation. The method additionally involved checking if the faces were parallel to each other. This approach did not work for beams found in VM2 since there were beams that were not orthogonally connected to each other and therefore their smallest faces were not parallel (Table 11a). Parallelism was excluded as a condition for linearization and the method worked properly for the PM and VM1 without it.

Table 11. Building elements which required additional methods in VM2.

(a) Beams with non-parallel smallest faces (b) Walls with multiple connectivity options

- Reconnecting walls with multiple connectivity options

In the VM2, some walls had multiple neighbors that were satisfying the connectivity relations from the previous two models (Table 11b). Due to this, a wall was not trimmed to the correct neighbor, whereby it lost connection to the neighbor closest to the edge. Therefore, an additional condition was added, which checks if the cut-off or extended part is within the tolerance range. The tolerance is defined as the area calculated with the intersection and thickness of the neighbor, with the consideration of the angle between the elements. This approach eliminated the wrong connections and worked with the previous models as well.

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7. Discussion

The research question of "*how to define and realize open interpretations for the transfer of architectural design to structural analysis building models*?" is answered by implementing a novel data exchange framework, demonstrating it with a prototype building and verifying it with two additional building models. Thereby, a complete development of a new data exchange approach—from the novel framework implementation, to proof of concept and verification—was presented. The new approach shows potential in overcoming misinterpretations that are the state of the art in data exchange practices. The focus of the paper is set on the open geometrical interpretations which can be understood, edited and expanded to satisfy heterogeneous workflows, and currently pose a main challenge for a seamless data exchange.

Four interpretation methods were initially proposed based on the geometrical elements of the PM. The four methods cover some common building elements and relatively simple but commonly present geometries such as columns with constant cross-sections and walls and slabs with constant thickness. The interpretations take place during the conversion of a physical model to an analytical model. They have not been standardized nor documented for the existing workflows, which causes inconsistencies in the data exchange practices between the architectural design and structural analysis domains. The interpretation methods are implemented with a novel framework, which is described in the previous work [9].

After the verification of the implemented exchange with two additional external building models, VM1 and VM2, a great similarity is found between the interpretations. More than 80% of both verification models were successfully interpreted with the methods defined for the PM. After the automated exchange is achieved for all three building models, the geometrical interpretations can be summarized in two method groups: reducing dimensionality and reconnecting elements. In the PM, reconnecting elements and perimeter adjustment were recognized as separate methods, while in the verification models, alignment of building elements was also required. All three methods, reconnecting elements, perimeter adjustment and alignment, are actually different approaches for reconnecting elements. Which method is to be applied depends on the neighbors and their position compared to the element to be extended or trimmed. Further analysis can be performed and additional verification models tested to obtain more detailed results. However, the approach until now has shown significant potential for the interpretation automation.

The overview of the interpretations and final summary is presented in Figure 14. The required interpretations can be categorized into two groups: dimensionality reduction and reconnection of elements. Dimensionality reduction is defined with linearization and planarization. We also previously recognized the need for punctualization (marked with *), where 3D elements are represented as points; however, this method was not present in the tested models. On the other hand connections between the elements need to be reestablished. In the analyzed models, three reconnection methods were identified: aligning parallel building elements, simple reconnection of elements with low number of neighboring elements and complex reconnection (or in PM perimeter adjustment) where each edge of the building element is tested individually. This overview gives the final proposal for the geometrical interpretations between physical and analytical models. As the main motivation is to realize the non-proprietary interpretations, the methods allow editing and extending if other workflows or geometries require changes. However, based on the verification results, the proposed methods cover most building elements and geometries found in building models.

The main advantage of the novel framework is that it moves the procedural steps for interpretation from single software tools (either architectural design or structural analysis) to the central database. Interpretation methods are facilitated with the open source geometry kernel on the central database. Therefore, the end users (or coordination/BIM managers) have insight into the methods taking place, understand the model behavior and can adjust it to their workflows if needed. This is currently in practice mostly impossible

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since the import or export procedures work as "black-boxes" defined in the proprietary software tools.

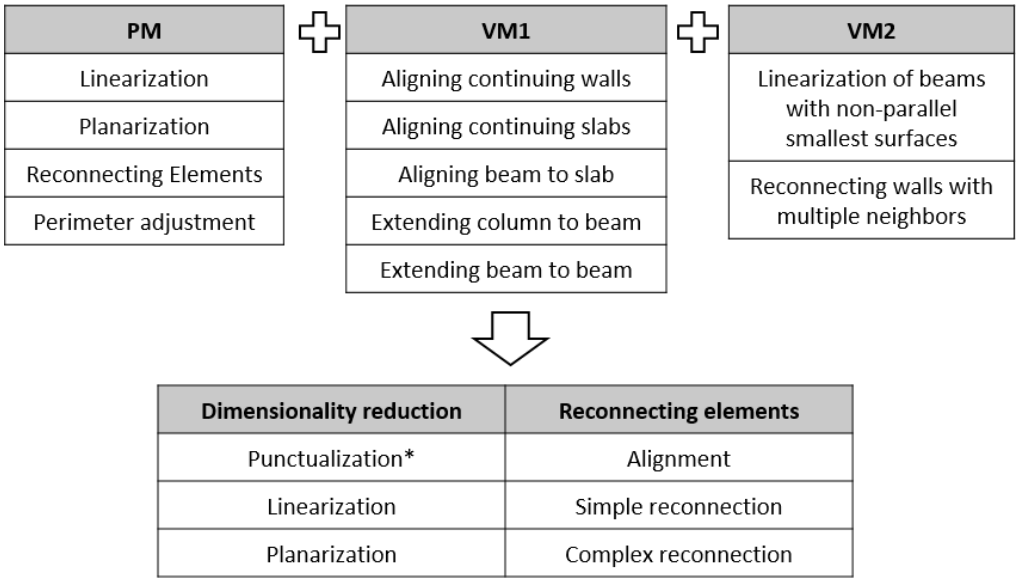

Figure 14. Summary and overview of results.

The innovative aspects of this research lie primarily in the documentation and codifying of intuitive interpretation rules based on implicit expert knowledge, making it explicit, thus enabling editing, expanding and automation via other software tools or geometry kernels. Additionally, the implementation of the interpretations in the novel open exchange framework making them comprehensible to end users represents further innovative contribution.

All building elements in the use-case building have been successfully interpreted, through application of methods for dimensionality reduction and reconnecting elements. Some interpretations were more elaborate to automate than the others, partly because of the complexity of the traditional intuitive interpretation process and partly because of the technical reasons such as geometry kernel suitability and predefined methods in the kernel. The level of difficulty depended on several factors: (a) difficulty of translating IFC to OC geometry; (b) understanding the traditional implicit interpretation process; and (c) difficulty in bridging the gap between the traditional implicit knowledge and explicit method.

8. Conclusions

This paper aims to bridge a knowledge gap through documenting and codifying the implicit interpretations of architectural design models for structural analysis models. This knowledge is found to be a requirement in overcoming the data exchange difficulties between architectural design and structural analysis building models.

Methods required to perform geometrical interpretation are dimensionality reduction and reconnecting elements. Although the described geometrical interpretations represent only a small part of numerous possibilities and undocumented knowledge taking place during the information exchange between physical and analytical models, the geometries present in the PM, namely vertical columns with a constant cross section and walls and slabs with constant thickness, can often be found in building models. After the approach was verified with two additional building models, where new elements such as beams and different spatial relations between the building elements were introduced, interpretations methods defined with PM were not able to cover only several building elements. Hence, it is possible to predefine the majority of geometrical interoperations in such a way. The openness of the proposed methods distinguishes the framework from proprietary solutions

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and allows for changes which might be required for various practices. Automating the interpretations might significantly simplify the data exchange process by avoiding the most common and repetitive tasks, leaving a small portion of building elements, geometries and interpretations to structural engineers to manually deal with.

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

Next steps will include the optimization of the system architecture together with the application of interpretation steps in order to get the direct open exchange model from Revit. The framework, after being enhanced with additional methods, will be tested on the models from design offices. In that way the scalability of the current approach will be tested. The usefulness and usability of the novel software can be tested only after a user-friendly interface is provided, which is also one of the future steps, where the engineers can tackle a single element and gain better control over the interpretations. Structural analysis feedback is not part of the investigated data exchange, since additional structural analysis information is required. Reaching automated structural feedback after the data exchange is investigated in [46] and will be extended with the future investigations. Additionally, a bidirectional exchange will be tested, including data transfer from the analytical to physical model.

Author Contributions: Conceptualization, G.S.; methodology, G.S.; software, G.S. and V.P.; validation, G.S., I.K. and W.S.; formal analysis, G.S.; investigation, G.S.; resources, W.S.; data curation, G.S. and V.P.; writing—original draft preparation, G.S.; writing—review and editing, G.S., I.K. and W.S.; visualization, G.S. and V.P.; supervision, I.K. and W.S.; project administration, I.K.; funding acquisition, I.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was conducted as part of the Doctoral College "Computational Design" on TU Wien (TUW) and as part of the project DATAFILTER which was funded by Strabag SE.

Data Availability Statement: The data presented (developed software tools) in this study are available on request from the corresponding author. The data are not publicly available due to privacy issues. Building models were obtained from Züblin AG and are available from the authors with the permission of Züblin AG.

Acknowledgments: The authors wish to express their appreciation to Theodor Sansakrit Strohal for his support and contribution to the research on the side of Strabag SE, and Dario Bubalo and the department "Technische Dienste—Konstruktion und Technologie" from Züblin, subsidiary of Strabag SE, for providing the building data models. Open Access Funding by TU Wien.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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PUBLICATION 4:

Goran Sibenik, Iva Kovacic, Valentinas Petrinas, Wendelin Sprenger, Dario Bubalo and Nikola Ruzicic:

"Automated preprocessing of building models for structural analysis", *Gradjevinar*, Volume 74(3), (2022)

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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

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Subject review

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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

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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

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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

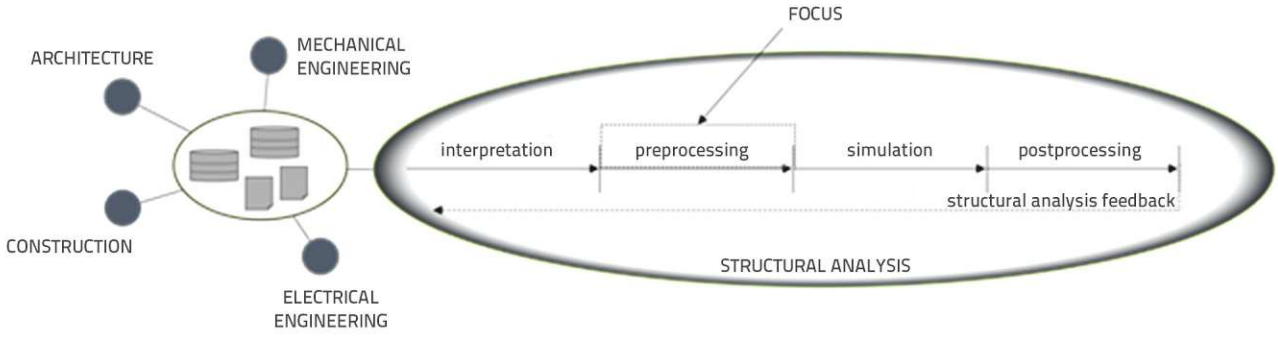

Figure 1. Focus of research within BIM environment

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

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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

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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.

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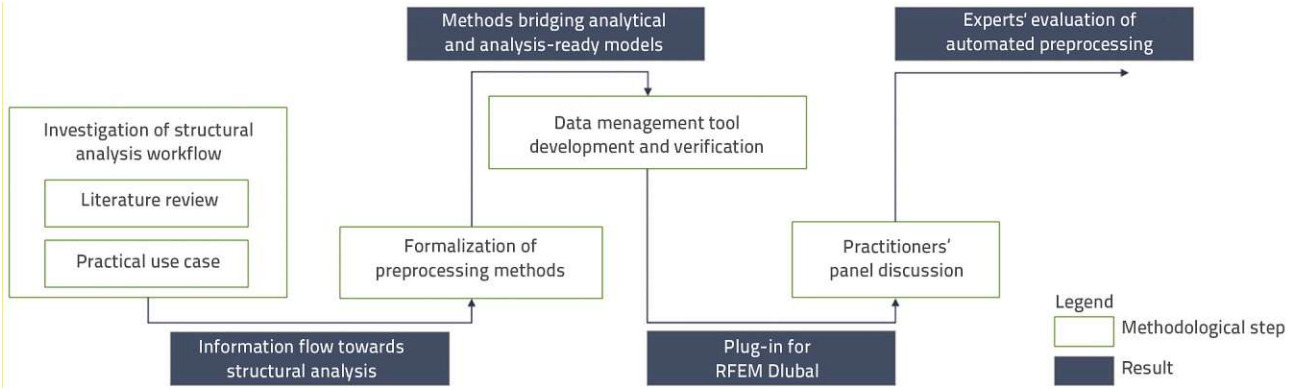

Figure 2. Methodological steps and corresponding deliverables

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

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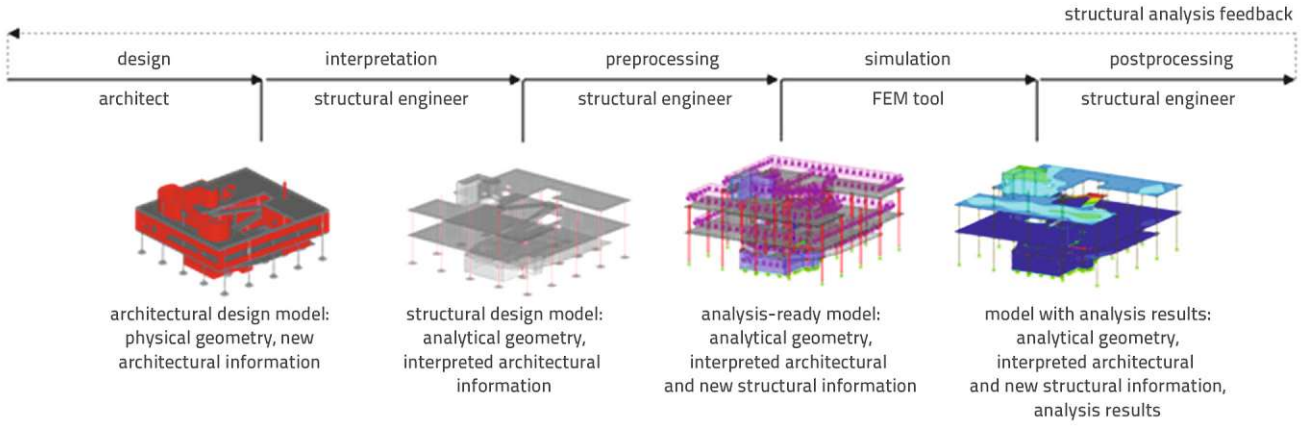

Figure 3. Procedures leading to structural analysis feedback

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

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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.

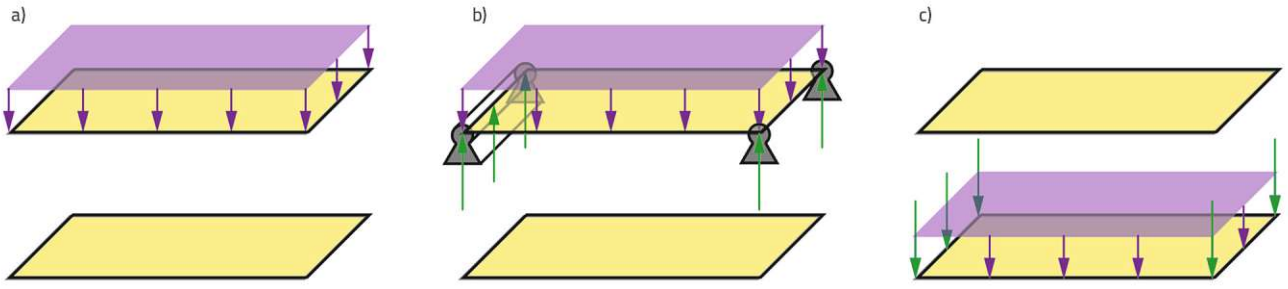

Figure 4. Workflow in 2,5D analysis

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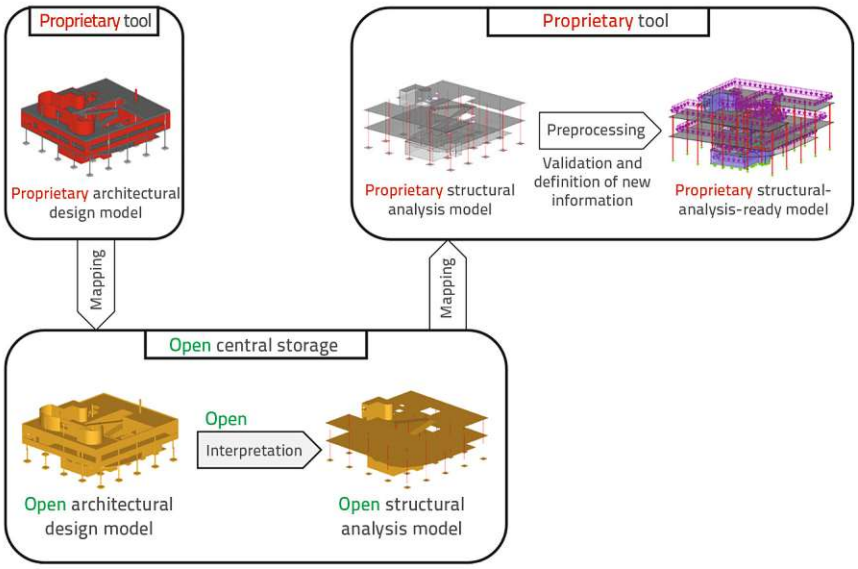

Figure 5. Overview of novel workflow

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

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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

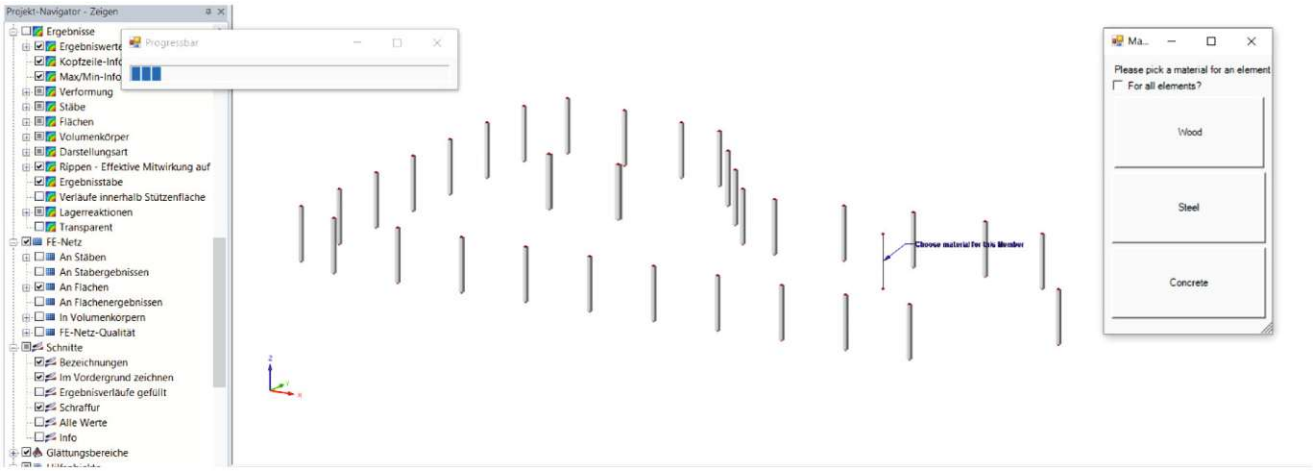

Figure 6. Material assignment after validation

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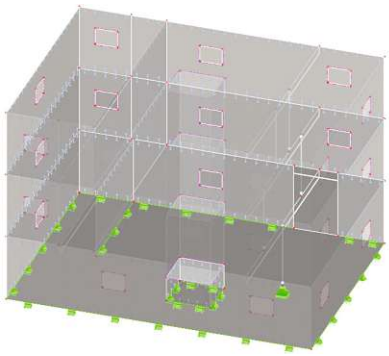
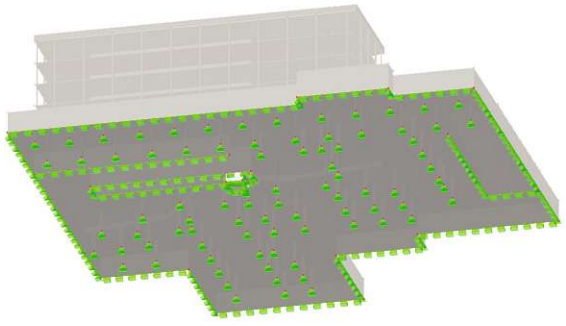
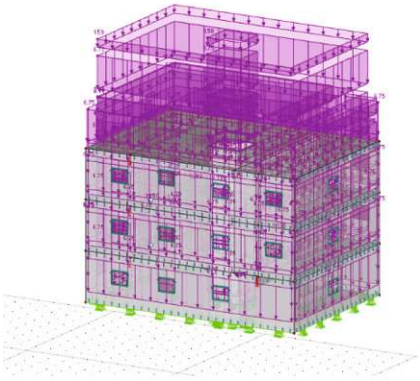
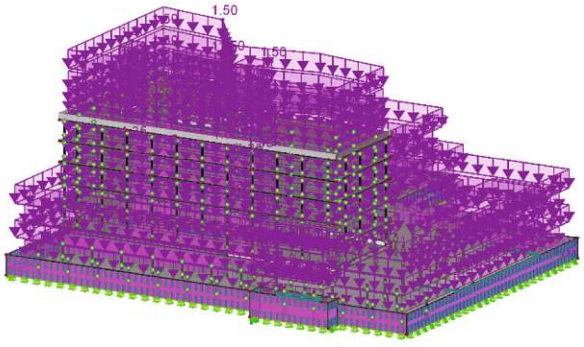
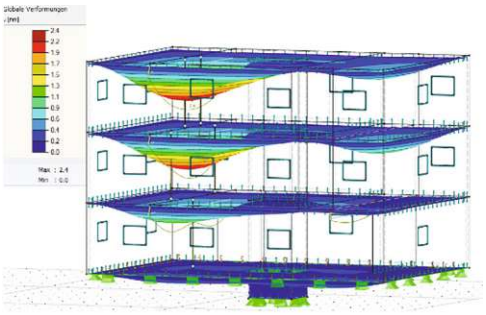
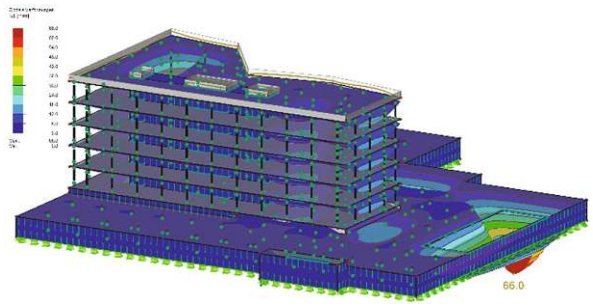
Table 3. Screenshots of results of preprocessing methods and analysis

	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.

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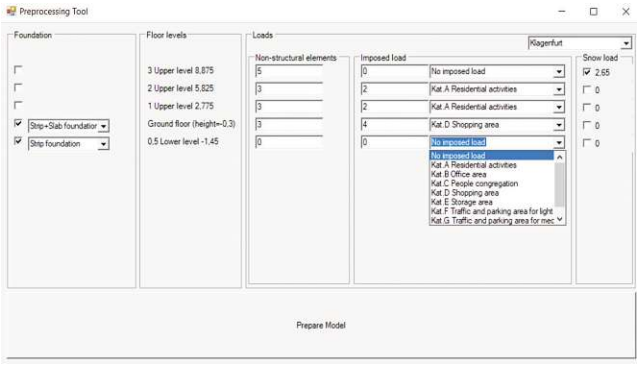


Figure 7. Plug-in screenshot

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.

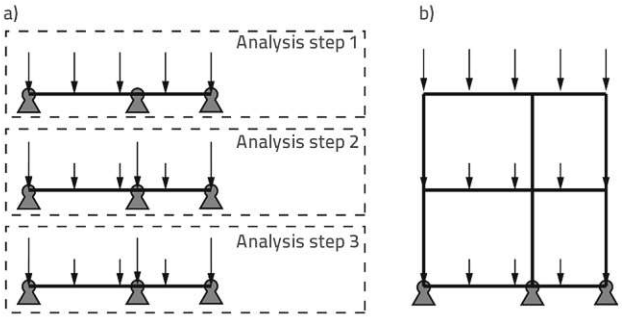


Figure 8. Schematic comparison of a) 2,5D analysis and b) 3D analysis

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

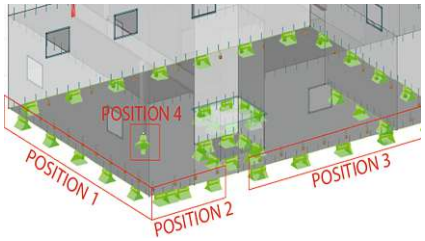
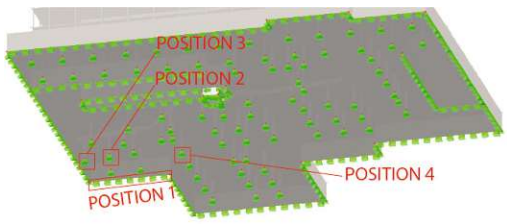
	Screenshot with foundation positions	Position	2.5D	3D	Diff. [kN]	Diff. [%]
Pilot model 1		1	185.71 kN/m	170.21 kN/m	15.5	8.35
		2	117.38 kN/m	134.40 kN/m	-17.0	14.50
		3	170.84 kN/m	179.51 kN/m	-8.7	5.07
		4	876.49 kN	657.25 kN	219.2	25.01
Pilot model 2		1	3.16 kN/m	3.58 kN/m	-0.42	13.29
		2	83.73 kN	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

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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

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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.

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