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Chair of Computational Modeling and Simulation

A Knowledge-Driven Automated Method for Detecting Load-bearing Walls in As-Built Digital Building Models

Master thesis

For the Master of Science Course Civil Engineering

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Abstract

Digital building models are crucial in various applications, including planning, monitoring energy performance simulation, and structural and energy analyses. However, creating and utilizing such models remains challenging. Manual methods for generating digital building models are time-intensive and error-prone. In contrast, automated methods, such as laser scanning and point cloud technologies, provide raw environmental data but lack essential structural usage information for building elements.

This research addresses these limitations by developing a systematic method to identify and classify wall elements based on their structural functionality. Such classification is pivotal for accurately interpreting the as-built condition of structures and has significant practical implications. For instance, it can assist in building renovation projects by identifying critical load-bearing elements that require preservation or reinforcement. Furthermore, these insights support redesign efforts by facilitating efficient modifications or extensions while ensuring structural integrity.

To achieve these objectives, this thesis undertakes a comprehensive review of international building standards and explores the need for automated tools in the Architecture, Engineering, and Construction (AEC) industry. A wide array of parameters influencing the identification of wall structural functionality is investigated, moving beyond basic practical considerations such as wall thickness or width. This holistic approach incorporates diverse factors to enable a reliable and comprehensive classification of wall functionalities within digital building models.

The proposed methodology was systematically evaluated using as-built digital building models, demonstrating promising performance. When assessed against Eurocode and International Building Code standards, the classification pipeline achieved an average accuracy of 73.91% and a recall of 94.39%. This study introduces a framework for categorizing wall elements within digital building models into distinct structural categories, including load-bearing and non load-bearing walls, based on their functional roles. The findings establish a foundation for enhancing digital modelling practices and advancing the integration of structural functionality into automated classification systems.

Zusammenfassung

Digitale Gebäudemodelle sind für verschiedene Anwendungen von entscheidender Bedeutung, z. B. für die Planung, die Überwachung der Energieleistung, Simulationen sowie Struktur- und Energieanalysen. Die Erstellung und Nutzung solcher Modelle bleibt jedoch eine Herausforderung. Manuelle Methoden zur Erstellung digitaler Gebäudemodelle sind zeitintensiv und fehleranfällig. Im Gegensatz dazu liefern automatisierte Methoden, wie z. B. Laserscanning und Punktwolken-Technologien, zwar rohe Umweltdaten, aber keine wesentlichen Informationen über die strukturelle Nutzung von Gebäudeelementen.

Die vorliegende Forschungsarbeit setzt an diesen Grenzen an und entwickelt eine systematische Methode zur Identifizierung und Klassifizierung von Wandelementen auf der Grundlage ihrer strukturellen Funktionalität. Eine solche Klassifizierung ist von zentraler Bedeutung für die genaue Interpretation des Ist-Zustands von Bauwerken und hat erhebliche praktische Auswirkungen. So kann sie beispielsweise bei Gebäudesanierungsprojekten helfen, indem sie kritische tragende Elemente identifiziert, die erhalten oder verstärkt werden müssen. Darüber hinaus unterstützen diese Erkenntnisse die Neugestaltung von Gebäuden, indem sie effiziente Änderungen oder Erweiterungen ermöglichen und gleichzeitig die strukturelle Integrität gewährleisten.

Um diese Ziele zu erreichen, wird in dieser Arbeit eine umfassende Überprüfung der internationalen Baunormen vorgenommen und der Bedarf an automatisierten Werkzeugen in der Architektur-, Ingenieur- und Bauindustrie (AEC) untersucht. Es wird eine breite Palette von Parametern untersucht, die die Identifizierung der strukturellen Funktionalität von Wänden beeinflussen und über grundlegende praktische Überlegungen wie Wanddicke oder -breite hinausgehen. Dieser ganzheitliche Ansatz bezieht verschiedene Faktoren mit ein, um eine zuverlässige und umfassende Klassifizierung von Wandfunktionalitäten in digitalen Gebäudemodellen zu ermöglichen.

Die vorgeschlagene Methodik wurde systematisch anhand von digitalen Gebäudemodellen im Ist-Zustand evaluiert und zeigte vielversprechende Ergebnisse. Bei der Bewertung anhand von Eurocode- und International Building Code-Normen erreichte die Klassifizierungspipeline eine durchschnittliche Genauigkeit von 73,91 % und eine Wiedererkennung von 94,39 %. Diese Studie führt einen Rahmen für die Kategorisierung von Wandelementen in digitalen Gebäudemodellen in verschiedene strukturelle Kategorien ein, einschließlich tragender und nichttragender Wände, basierend auf ihrer funktionalen Rolle. Die Ergebnisse bilden eine Grundlage für die Verbesserung digitaler Modellierungsverfahren und die Integration struktureller Funktionen in automatisierte Klassifizierungssysteme.

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List of Abbreviations

AEC	Architecture, Engineering, and Construction
BIM	Building Information Modeling
IBC	The International Building Code
IFC	Industry Foundation Classes

1 Introduction

1.1 Preface

Digital building models are crucial in various applications, including structural and energy analyses. However, creating and utilizing such models remains challenging. The use of digital methods in the built environment is frequently constrained by the lack of up-to-date real-world data regarding the current conditions of the construction site. (Noichl, Lichti, & Borrmann, 2024). Manually creating as-built digital models with up-to-date data on current conditions for buildings would be very time-consuming. On this issue, laser scanning technology has become crucial to capture the real environment in digital form. Existing capturing technologies such as laser scanning make it possible to efficiently collect point clouds that contain geometric information about the as-is state in the built environment (Pan, Braun, Borrmann, & Brilakis, 2023). These point clouds are then processed into as-built digital building models. However, since laser scanning technology provides data as a raw representation of the physical environment, these models lack information on building semantics and the structural functionality of the building elements (Liu, Eybpoosh, & Akinci, 2012).

Information on the structural functionality of the building elements is required for structural analysis. In the Architecture, Construction, and Engineering (AEC) industry, digital models are being used as input for structural analysis processes for all types of construction projects. This lack of information creates a need to attach the label information about the structural usage of building elements like walls to the digital building models. Civil engineers spend time and effort to obtain the structural usage information for building elements by making multiple site visits, considering the local and international building standards, building observations, conducting destructive and non-destructive tests, and reviewing existing technical drawings. This manual process that has limitations as manual work, time consumption, and is prone to errors, creates a need to develop a tool that automatically attaches the label information about the structural usage of wall elements in a building.

1.2 Research Objectives

This study aims to develop an automatic method to identify and classify wall elements based on their structural functionality with the purpose of being used in construction projects. This thesis undertakes a comprehensive review of international building standards and explores the need for automated tools in the Architecture, Engineering, and Construction (AEC) industry. A wide array of parameters influencing the identification of wall structural functionality is investigated, moving beyond basic practical considerations such as wall thickness or width. This holistic approach incorporates diverse factors to enable a reliable and comprehensive classification of wall functionalities within digital building models.

1.3 Outline of Thesis

The rest of the thesis is structured as follows: Chapter 2, State of the Art, an extensive literature review on the developed methods for creating digital building models using point cloud data. Chapter 3, Methodology, offers a comprehensive theoretical exposition of the developed methodology. Chapters 4 and 5, Implementation and Results, present several case studies to substantiate the feasibility of the proposed approach. Lastly, Chapter 6, Conclusion, discusses the primary findings of the research and outlines the potential avenues for future research directions within the field.

2 State of the Art

2.1 Digital building models

Digital building models are characterized by building components represented by digital objects that know what they are and can be associated with computable graphics, data attributes and parametric rules, components that include data that describe how they behave, and consistent non-redundant data so changes are propagated to all views and the presentation of all views of the model are coordinated (Sacks, Eastman, Ghang, & Teicholz, 2018). Digital models contain valuable information for construction projects, such as the building geometry and relationships between building elements and materials. The digital building models mainly have two different forms: “as-designed” and “as-built”.

"As-designed" building models contain detailed information about the original design of a building. These models are created during the early stages of a construction project and include data on the building's structural and architectural features, as well as its mechanical, electrical, and plumbing systems. They also illustrate the relationships between different systems within the building. However, the current functionality and condition of buildings can change from their as-designed state due to alterations in building use, renovations, and extensions.

“As-built” building model is a term used to describe the BIM representation of a building concerning its state at the moment of survey. This would inform about the state of conservation of historic buildings. It is usually a manual concept that involves three aspects: firstly, the geometrical modelling of the component, then the attribution of categories and material properties to the components and, finally the establishing of relations between them (Hichri, Stefani, De Luca, Veron, & Hamon, 2013). The as-built digital building models created by using laser scanning technology have the geometrical models and the relations between them, but they lack the information on material properties and structural usage (Pa˘tra˘ucean, et al., 2015).

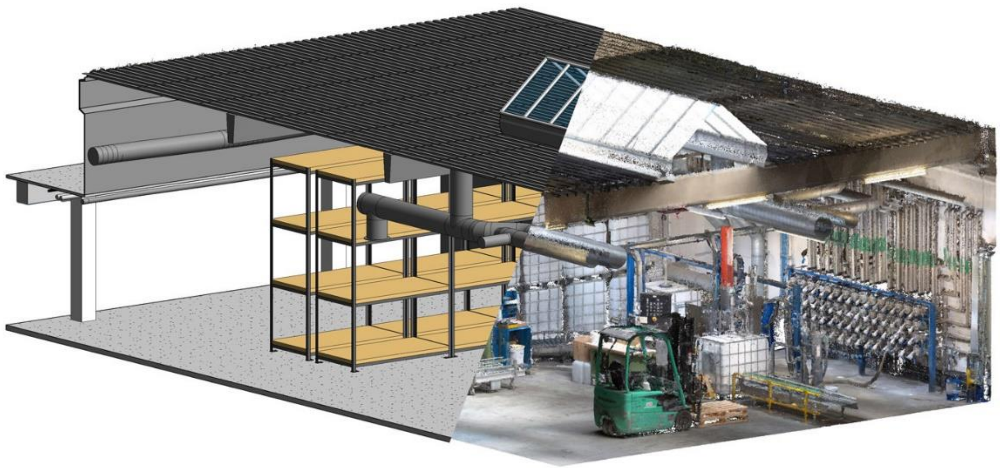

Figure 1: An example for as-built digital models (NavVis GmbH, 2022).

2.2 Identification of structural functionality of walls

Understanding the structural role of walls, such as distinguishing between load-bearing and non-load-bearing elements, is a critical aspect of engineering and construction. Load-bearing walls are essential to a building's stability as they support structural components like floors and roofs, as well as additional loads from occupancy and environmental factors. Conversely, non-load-bearing walls primarily serve as partitions and do not contribute to the structural framework. Accurate identification of these roles is fundamental to ensuring the safety, functionality, and adaptability of buildings.

In renovation and reuse projects, recognizing the structural function of walls is essential. Renovation often requires altering internal layouts, where modifying or removing load-bearing walls without proper reinforcement could compromise the building's stability, leading to severe safety risks. Reuse, which repurposes older buildings for modern functions, relies on an accurate understanding of structural roles to make cost-effective and safe modifications that align with new usage requirements. This knowledge helps retain the building's structural integrity while accommodating design changes. Structural retrofitting also benefits significantly from understanding wall functionality (Ma, Cooper, Daly, & Ledo, 2012). As buildings age or face increased demands due to changes in environmental conditions or updated safety codes, retrofitting ensures their continued performance. Identifying critical load-bearing elements enables engineers to prioritize reinforcement efforts, such as adding bracing or supports, to enhance the building's resilience. Such practices are particularly important in risk-prone areas, where retrofitting load-bearing walls can mitigate vulnerabilities to seismic, flood, or wind-induced loads. Similarly, accurate classification of wall roles supports effective risk assessment and safety planning. Knowledge of load-bearing walls aids in evaluating a building's overall vulnerability, especially in disaster-prone areas (Naito & Wheaton, 2006). Furthermore, understanding the structural function of walls facilitates efficient redesign and building extensions. When altering or expanding a building, correctly identifying load-bearing elements ensures integration of new components with the existing structural framework. It also enables the allocation of resources by focusing reinforcement and design efforts where they are most needed, thus optimizing both costs and construction timelines.

Incorporating this understanding into digital modelling processes further enhances its practical value. Automated identification of structural functionality of walls within Building Information Modeling (BIM) tools can streamline workflows by improving accuracy in structural simulations and project planning. This is especially beneficial in large-scale projects or when reconstructing models from scanned data, where manual classification would be impractical, time consuming and error-prone.

Existing techniques for identifying the structural functionality of walls leverage a combination of geometric, material, and contextual factors to distinguish between load-bearing and non load-bearing elements. Traditional methods often rely on manual analysis of architectural and structural drawings, where engineers assess parameters such as wall thickness, material composition, and placement within the structural framework. Thickness, for instance, is a critical indicator, as load-bearing walls are typically thicker to support additional loads. Material properties, such as concrete, masonry, or reinforced composites, are also essential since certain materials are more commonly associated with structural roles.

Automating the identification of structural roles of walls in digital building models faces challenges due to the variability in building designs, inconsistencies in digital models, and the lack of standardized classification systems. Building designs differ widely based on function, era, and regional practices, making it difficult to develop universal methods that accommodate this diversity. Furthermore, digital models often contain inaccuracies or incomplete data, whether from manual drafting, BIM, or automated scanning methods. These inconsistencies complicate the identification of structural roles.

Finally, the structural role of walls is intrinsically linked to legal and regulatory compliance. Building codes often dictate specific requirements for load-bearing walls, such as material standards and dimensional thresholds. Proper identification and classification of these elements ensure adherence to such regulations, avoiding legal complications and mitigating risks of structural failure.

2.3 Methods for classifying walls

Various approaches have been developed to classify walls in building systems, including rule-based systems, machine learning models, and hybrid methods. Each approach leverages different methodologies to address the complexities of distinguishing load-bearing walls from non-load-bearing ones, with varying degrees of accuracy and scalability.

Rule-based systems rely on predefined criteria, such as wall thickness, material type, and spatial relationships, to classify walls (Grosan & Abraham, 2011). These systems are typically built on heuristic rules derived from building codes or engineering expertise. For example, a rule-based system might classify walls exceeding a certain thickness and directly connected to beams or slabs as load-bearing. While these methods are straightforward and interpretable, they often struggle with edge cases or complex architectural designs that fall outside the predefined criteria. Moreover, rule-based systems depend heavily on the accuracy and consistency of input data, limiting their applicability to poorly documented or irregular structures. As an example model, Qiu et al. have proposed a building element identification scheme using a segmentation-aggregation strategy termed EI-SA. The purpose of the strategy was to address the element-level sketches in digital building models. The innovation of the study was to propose a building element identification scheme using IFC (Qiu, et al., 2021). The segmentation step divides the BIM model into geometric representations based on IfcShapeModel and predefined rules for identifying slices of shapes. This step relies on explicit, structured rules for segmentation and the geometric relationships among components. The aggregation step groups geometric representations using logical rules to form meaningful elements. The rules dictate when and how individual representations combine to create a complete element.

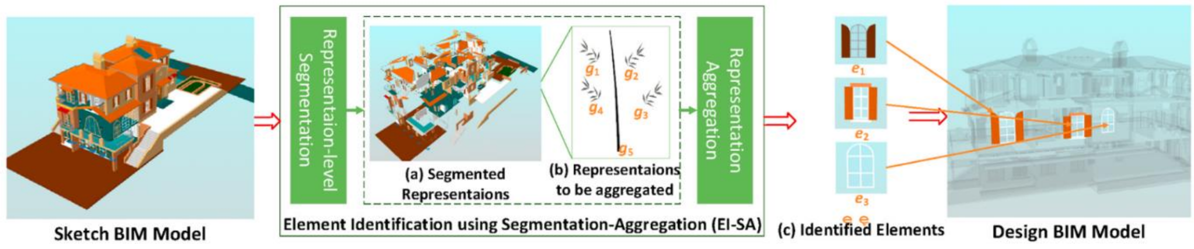

Figure 2: The overall framework of Element Identification (Qiu, et al., 2021).

Macher et al. have developed a rule-based approach that has two parts. Based on indoor point clouds, the first part consists in several segmentations into spaces and planes and in the classification of points into several categories. The second part of the approach deals with the reconstruction of walls and slabs of buildings from the element point clouds extracted in the first part. At the end of the approach, a file in a BIM format is generated and reconstructed walls and slabs can be opened in BIM software (Macher, Landes, & Grussenmeyer, 2017).

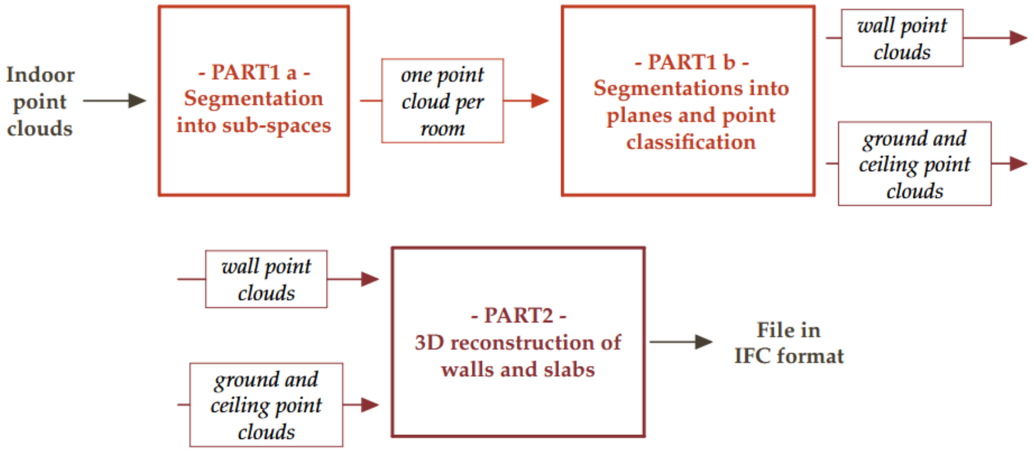

Figure 3: Overview of the developed approach (Macher, Landes, & Grussenmeyer, 2017).

Xiong et al. proposes a knowledge-driven automated indoor as-built BIM reconstruction method based on structural knowledge of buildings by reasoning more stringent sets of constraints at three levels: geometry, topology, and semantics. Initiation of the method involves the segmentation of 3D data into individual rooms through the application of wall constraints. The proposed method focuses on single-story indoor environments under Manhattan assumption (Xiong, et al., 2023). Wang and Cho introduced a method to create 3D building models and to recognize building components as individual objects from point cloud data collected by 3D laser scanners using the boundary estimation method and building component recognition methods (Wang & Cho, 2014). The method uses a rule-based approach to identify building elements.

Machine learning models, in contrast, use data-driven approaches to identify structural functionality. These models are trained on labelled datasets containing examples of load-bearing and non load-bearing walls, learning to recognize patterns across a range of features such as geometry, material properties, and connectivity. However, machine learning models require large and diverse datasets for training, and their performance can be impacted by biases or inconsistencies in the data. Furthermore, the "black-box" nature of some machine learning techniques can make their decision-making process less interpretable compared to rule-based systems. Perez et al. have proposed a deep learning method to classify building components including walls (Perez-Perez, Golparvar-Fard, & El-Rayes, 2021). The proposed method is a data-driven approach that relies on deep learning models to classify point cloud data, and make predictions without explicit rules or assumptions.

Hybrid methods aim to combine the strengths of rule-based and machine learning approaches to improve classification performance. These methods often use rule-based criteria to preprocess data or provide initial classifications, which are then refined using machine learning algorithms. For example, a hybrid system might use rules to filter out non-structural walls based on obvious characteristics (e.g., thin drywall partitions) before applying a machine learning model to evaluate more ambiguous cases. By integrating expert knowledge with data-driven insights, hybrid methods can achieve greater accuracy and robustness, particularly when dealing with noisy or incomplete data. However, they also require careful calibration to balance the contributions of each component and avoid conflicting outputs. Xiong et al. developed an automatic 3D reconstruction framework that used the voxelized point cloud to recognize patches such as walls, ceilings, or floors based on boundary limits (Xiong, Adan, Akinci, & Huber, 2013). Their framework uses a hybrid approach by having a rule-based component where they work with the minimum Euclidean distance between boundaries, and they are also using machine learning for feature generation. Vega Torres et al. proposed a pipeline to extract the vertical elements in dense building point clouds using domain knowledge, deep learning, image processing and computer vision techniques (Vega Torres, et al., 2021). The pipeline uses rule-based approaches for the earlier steps and have data-driven approaches for the further learning tasks like formwork classification.

Each of these approaches has distinct advantages and limitations, making their suitability dependent on the specific context of the project. Ongoing advancements in computational power, data availability, and algorithmic innovation continue to enhance the capabilities of these methods, paving the way for more reliable and efficient classification of walls in digital building models.

In digital approaches, Building Information Modeling (BIM) and point cloud processing have introduced semi-automated techniques for wall functionality identification. BIM-based methods utilize embedded metadata to extract information on material type, dimensions, and connectivity. Similarly, point cloud data can be analysed to detect spatial relationships between walls and other structural elements. For example, the position of a wall within the building's layout and its connection to floors, beams, or columns are crucial contextual factors. While these techniques represent significant advancements, they remain reliant on the accuracy and completeness of input data, which can vary depending on the source and method of model creation.

2.4 Limitations and research gap

Current research on element identification for digital building models focuses mainly on object recognition. The existing methods provide great capabilities for the structure recognition of natural objects, but they are not well-suited for estimation of structural usage of building elements like walls. An accurate automated tool is needed to estimate the structural usage of wall elements to decrease the amount of time and work spent on this issue in the AEC industry.

Gimenez et al. have investigated the issue of a lack of digital building models for renovation projects, especially including old buildings. The motivation of the study was that only limited parts of the digital building model generation processes were being addressed. They address the fact that many building elements are still to be recognized automatically, the incompleteness of digital building models in the areas of structural usage and semantics (Gimenez, Hippolyte, Robert, Suard, & Zreik, 2015).

Current methods for identifying the structural functionality of walls in digital building models face several limitations, primarily in scalability, semantic integration, and reliance on manual input. Methods often fail to integrate semantic information, limiting their ability to provide comprehensive insights into the functional roles of building elements. Scalability remains a challenge, as these techniques are frequently tailored to specific use cases, such as single-story environments or specific building types, and may not generalize effectively to more complex or diverse structures.

Based on our understanding and the latest research, there is a research gap in addressing the automatic identification of the structural usage of wall elements within building models. This thesis provides a literature review on international building codes and proposes a pipeline designed to address this issue.

3 Methodology

This chapter outlines the primary concepts and proposed framework to establish the essential parameters needed for identifying load-bearing walls within as-built digital models of buildings. It focuses specifically on buildings constructed according to building codes implemented from the year 2000 onward, exploring various factors that could influence the structural properties of wall instances within these models.

The research for this thesis began with a comprehensive literature review focused on the Eurocode (European Comission, 2024), the German National Annexes (DIN, 2024), and the International Building Code (IBC) (International Code Council, 2023). These codes are essential in civil engineering and architecture, as they provide guidelines and standards for construction, especially within Europe and the United States. The purpose of this review is to examine the critical characteristics of wall assemblies within these regulatory frameworks, with an emphasis on factors affecting structural functionality.

In these standards, several key characteristics influence the structural properties of wall assemblies, including:

Continuity of the wall throughout the building's height: Structural walls are typically continuous across multiple stories to ensure effective vertical load transfer from the superstructure to the foundation.

Wall thickness and position: This includes the wall’s thickness, whether the wall is internal or external, and consistency in thickness throughout the wall's height.

Presence of regularly spaced openings: Openings at regular intervals can affect the structural integrity and load distribution of the wall.

In this thesis, wall thickness is chosen as the primary focus of study due to its significant role in determining structural properties. Thickness is one of the most critical indicators for load-bearing walls, which are generally thicker than non-load-bearing decorative walls. This increased thickness supports their load-carrying function and often accommodates steel reinforcements, requiring a greater cross-sectional area in concrete buildings. Other characteristics identified as influencing structural properties will be examined and discussed following sections.

The minimum thickness requirements for various wall types are specified according to building codes. These codes define minimum thickness standards for wall assemblies in both masonry and concrete structures. Minimum wall thicknesses are categorized by load-bearing and non-load-bearing wall types. These values are considered threshold ranges to help determine the structural properties of wall assemblies in as-built models of different buildings.

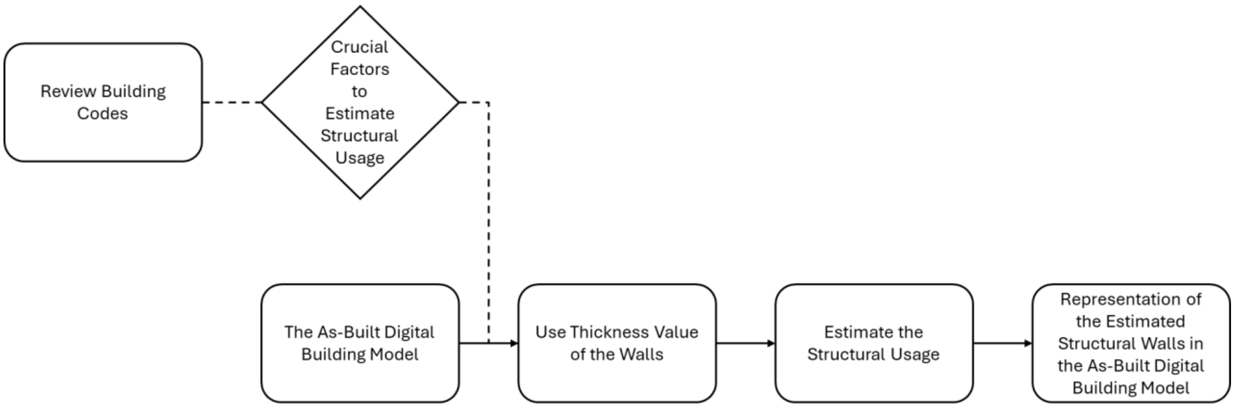

Figure 4: Workflow of the thesis study.

3.1 Eurocode

The EN Eurocodes are a series of 10 European Standards, EN 1990 - EN 1999, providing a common approach for the design of buildings and other civil engineering works and construction products (European Commission, 2024).

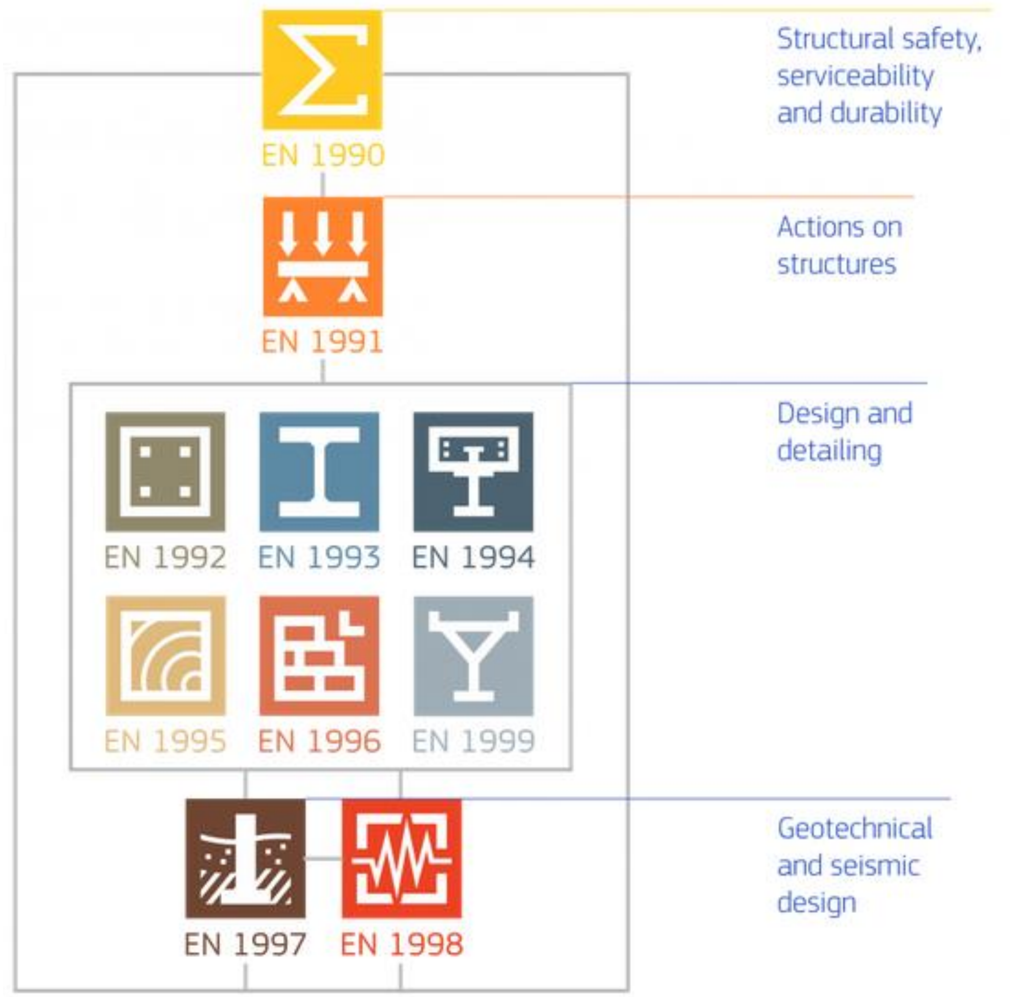

Figure 5: Eurocodes, European Union, 2021

The Eurocodes include the basis of structural design (EN 1990), actions on structures (EN 1991), the design of concrete (EN 1992), steel (EN 1993), composite steel and concrete (EN1994), timber (EN 1995), masonry (EN 1996) and aluminium (EN 1999) structures, geotechnical design (EN 1997), and the design, assessment and retrofitting of structures for earthquake resistance (EN 1998).

3.1.1 Specified minimum thickness values

After reviewing the ten Eurocodes and corresponding National Annexes for each standard for Germany, relevant minimum thickness values were determined for load-bearing and non load-bearing walls in concrete and masonry type buildings.

For concrete buildings, the following values are specified in the Eurocodes:

Table 1: Specified minimum wall thickness values for concrete buildings, Eurocode.

Topic	Code	Load-Bearing	Non Load-Bearing
Concrete	**EN 1992.1.2**	110 mm (interior) 130 mm (exterior)	60 mm

The required minimum thickness value for non load-bearing walls in concrete buildings is specified as 60 mm in the standard EN 1992.1.2.2004, Chapter 5.4.1, Table 5.3 (The European Commission, 2004).

The required minimum thickness value for load-bearing solid walls in concrete buildings is specified as 110 mm for interior walls and 130 mm for exterior walls in the standard EN 1992.1.2.2004, Chapter 5.4.2, Table 5.4 (The European Commission, 2004).

For masonry buildings, the following values are specified as required minimum thickness value in the Eurocodes:

Table 2: Specified minimum wall thickness values for masonry buildings, Eurocode.

Topic	Code	Load-Bearing	Non Load-Bearing
Masonry	**EN 1996.3**	-	50mm (interior)
Earthquake	**EN 1998.1.1**	350 mm (unreinforced, natural stone) 240 mm (unreinforced, any) 170 mm (unreinforced, low seismicity) 240 mm (confined masonry) 240 mm (reinforced masonry)	-

The required minimum thickness value for interior non load-bearing walls in masonry buildings is specified as 50 mm in the standard EN 1996.3.2006, Annex B. (The European Commission, 2006)

The required minimum thickness value for load-bearing walls in masonry buildings is specified as 350 mm for unreinforced, with natural stone masonry, 240 mm for unreinforced, with any other masonry units, 170 mm for unreinforced, with any other masonry units and in cases of low seismicity, 240 mm for confined masonry, and 240 mm for reinforced masonry in the standard EN 1998.1.1.2004, Chapter 9.3, Table 9.2. (The European Commission, 2004)

3.2 International Building Code (IBC)

The International Building Code (IBC) is the foundation of the complete Family of International Codes. It is an essential tool to preserve public health and safety that provides safeguards from hazards associated with the built environment. It addresses the design and installation of innovative materials that meet or exceed public health and safety goals. The International Building Code is in use or adopted in 50 states in the USA, the District of Columbia, Guam, Northern Marianas Islands, New York City, the U.S. Virgin Islands and Puerto Rico. (International Code Council, 2015)

3.2.1 Specified minimum thickness values

After reviewing the International Building Code, relevant minimum thickness values are determined for load-bearing and non load-bearing walls in concrete and masonry type buildings.

For concrete buildings, the following values are specified in the International Building Code:

Table 3: Specified minimum wall thickness values for concrete buildings, IBC.

Topic	Code	Load-Bearing	Non Load-Bearing
Concrete	**2024 IBC**	190 mm	-

There were no specified minimum thickness values for non load-bearing walls in concrete buildings as per the standard 2024 International Building Code.

The required minimum thickness value for load-bearing walls in concrete buildings is specified as 190 mm in the standard 2024 International Building Code, Chapter 19, Section 1905.6.2. (International Code Council, 2023)

For masonry buildings, the following values were specified in the International Building Code.

Table 4: Specified minimum wall thickness values for masonry buildings, IBC.

Topic	Code	Load-Bearing	Non Load-Bearing
Masonry	**2024 IBC**	254 mm (exterior, one-story building) 203 mm (interior)	-

There were no specified minimum thickness values for non load-bearing walls in masonry buildings as per the standard 2024 International Building Code.

The required minimum thickness value for load-bearing walls in masonry buildings is specified as 254 mm for exterior walls in one-story buildings and 203 mm for interior walls in the standard 2024 International Building Code, Chapter 21, Section 2109.2.4.4 (International Code Council, 2023).

3.3 Parameters for Identifying Structural Functionality

3.3.1 Wall thickness

The wall thickness value is one of the most important indicators for load-bearing wall in-stances. Load-bearing walls have more thickness than non load-bearing decorative walls in general due to their structural properties, their load-carrying role, and usually containing steel reinforcements, which require more cross-sectional area for walls in concrete buildings.

The study of this thesis work focuses on as-built digital building models instead of as-design digital building models. In as-built digital building models, there usually is a lack of information compared to the as-design models due to changes in building elements or building functionality through the lifetime of the structure. These changes are often not reflected in the as-design models and drawings that are already present. As-built digital building models are either manually prepared or are the results of laser scanning projects from the building renovation or construction site. That makes the digital models susceptible to errors due to either complications in digital building model generation processes from point cloud data or human error (Jung, et al., 2014). Common challenges include having multiple elements instead of the original one due to errors in the calibration of the scanning equipment, having “pseudo walls” in the as-built digital building model due to mislabelling the elements during the model creation from the point cloud data phase, and more.

Taking these possible errors into account, the wall thickness value is among the most usable and reliable information in as-built digital building models. For that reason, the wall thickness parameter in as-built digital building models was chosen as the focus of this thesis's studies. While rest of the parameters also influence the determination of the structural usage of the wall instance, they were left out of the scope of this study for future work due to the complications in the implementation phase and the lack of more complex digital building models.

3.3.2 Persistence of the wall element across multiple floors

Load-bearing walls carry the vertical load of the building in addition to their own weight (Designing Buildings Ltd., 2022). They act as structural elements like columns, beams, and trusses. The load-bearing walls are usually present in multiple storeys of the building and on top of each other to provide continuity for vertical load transfer from the top floor to the foundation of the building. The presence or non-presence of a similar wall instance on multiple floors would be an indication of load-bearing type of wall instances in the building.

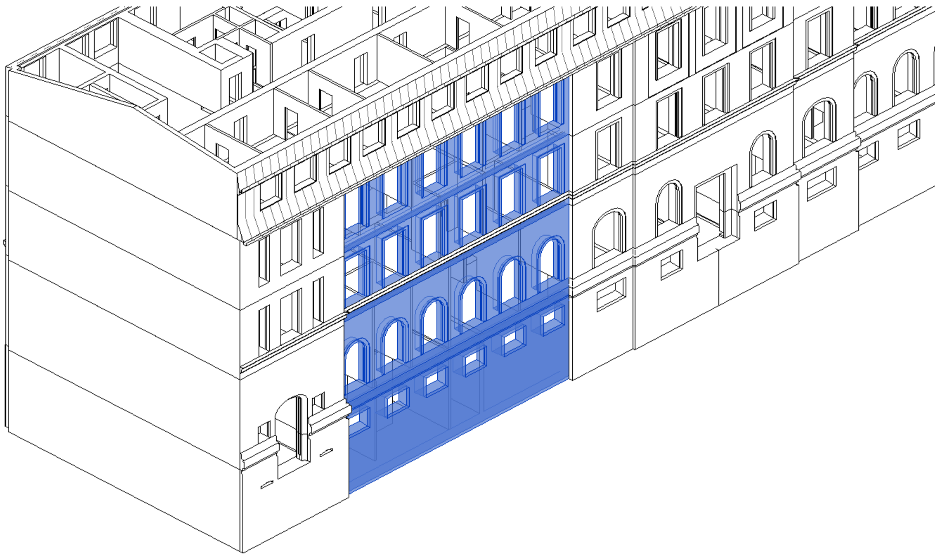

Figure 6: A load-bearing wall system being present on multiple storeys.

3.3.3 The classification of walls as external or internal

Building standards specify different requirements for internal and external load-bearing walls. The minimum thickness values in the building standards for external load-bearing walls are typically greater than those for internal load-bearing walls (International Code Council, 2023). In typical residential buildings, this difference in thickness and the location of the wall instance can help distinguish load-bearing walls from non-load-bearing walls in as-built digital building models.

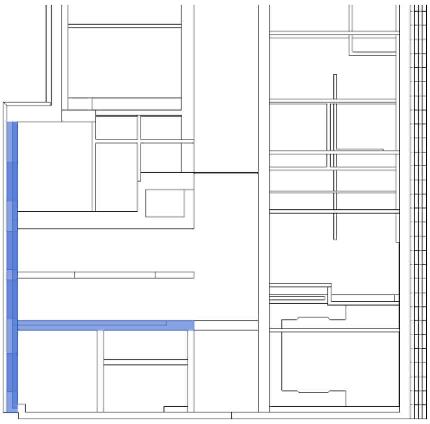

Figure 7: Variety of thickness values for external and internal load-bearing wall instances.

3.3.4 Constant wall thickness

Load-bearing walls typically maintain a consistent thickness throughout their height due to their load-bearing function. A uniform cross-section allows for continuous load transfer, reducing the likelihood of critical failure points within the structure. Additionally, consistent wall thickness simplifies the design of steel reinforcement along the wall's length.

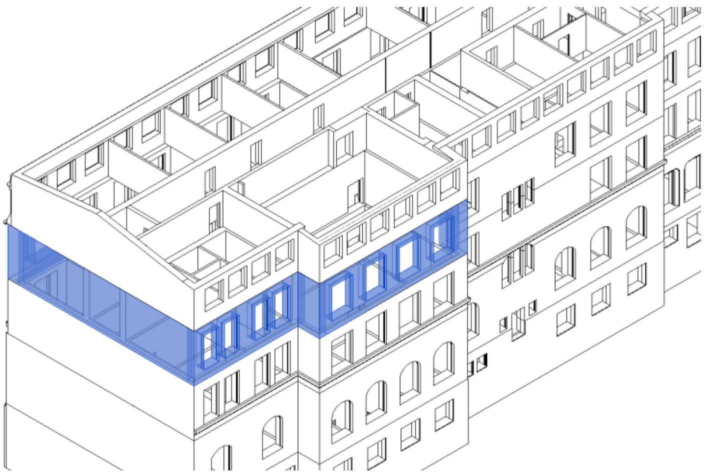

Figure 8: Constant wall thickness throughout the load-bearing wall instance.

3.3.5 Irregular openings

Irregular openings in the wall instances cause irregular cross-sectional parts, which decrease the load-carrying capacity and create critical failure points in load-bearing walls. Since continuous load transfer is an important aspect of the safety of the building, these characteristics are often not desired in load-bearing walls. The presence of irregular openings in the wall instance could indicate a non load-bearing wall in buildings.

3.4 Summary

The minimum wall thickness values outlined in the standards were compiled into a table as part of the literature review and methodology processes. The figure illustrates the findings from the literature review concerning the Eurocode and the International Building Code standards. The Eurocodes are categorized by their respective topics in the first two columns. The table consolidates various minimum wall thickness values for different types of walls, with each value corresponding to a specific wall type and the standard in which it is specified. Additionally, this table is included in Appendix A of the thesis.

Topic	Code	Masonry Wall	Timber Wall	Fire Wall	Load Bearing Wall	Non Load Bearing Wal	Basement Wall	Shear Wall	Ductile Wall
Structural Design	**EN 1990**								
Actions on Structures	**EN 1991.1.7**	150mm							
Concrete	**EN 1992.1.1**								
Concrete	**EN 1992.1.2**			200mm (unreinforced) 140mm (reinforced, LB) 120mm (reinforced, NLB)	110mm (interior) 130mm (exterior)	60mm			
Steel	**EN 1993.1.1**								
Composite	**EN 1994.1.1**								
Timber	**EN 1995.1.2**		8mm (panel thickness)						
Masonry	**EN 1996.1.1**	85mm							
Masonry	**EN 1996.1.2**								
Masonry	**EN 1996.3**					50mm (interior)	200mm		
Geotechnics	**EN 1997.1.1**								
Earthquake	**EN 1998.1.1**	350mm (unreinforced, natural stone) 240mm (unreinforced, any) 170mm (unreinforced, low seismicity) 240mm (confined masonry) 240mm (reinforced masonry)	3d (d: nail diameter <3,1mm)					200mm (composite steel plate, one side) 100mm (composite steel plate, both sides)	{150mm, hs/20[m]} 200mm (confined part)
Aluminium	**EN 1999.1.1**								
	2024 IBC	Exterior Wall 254mm (one story building) Interior Load Bearing Wall 203mm	Exterior Wall 102mm Interior Load Bearing Wall 102mm		190mm				

Figure 9: Specified minimum wall thickness values in the building standards.

4 Implementation

4.1 Digital building models

As-built digital building models were used to implement and test the proposed methodology. The digital building models were provided by the Technical University of Munich and used from a public resource library of the NavVis GmbH.

4.2 Implementation Tools

The implementation was done in the Autodesk Revit BIM authoring tool using pyRevit extension. Revit is a design and documentation platform that supports the design, drawings, and schedules required for building information modeling (BIM). (Autodesk, 2024) Revit software was used in this study to visualise and work on the digital building models. pyRevit is a Rapid Application Prototyping (RAD) environment for Autodesk Revit. It helps you quickly sketch out your automation and add-on ideas, in whichever language that you are most comfortable with, inside the Revit environment and using its APIs. It also ships with an extensive set of powerful tools that showcase its capabilities as a development environment. (Iran-Nejad, 2024) The pyRevit add-on was utilized to execute a script on digital building models, aiming to implement the methodology, visualize the results, and calculate error margins for the methodology. Visual Studio Code is a streamlined code editor with support for development operations like debugging, task running, and version control. It aims to provide just the tools a developer needs for a quick code-build-debug cycle and leaves more complex workflows to fuller featured IDEs. (Visual Studio Code, 2024) Visual Studio Code was used to develop a computational script that would run by pyRevit on digital building models in Revit to implement the methodology, visualize the results, and calculate error margins for the methodology.

4.3 Implemented pipeline

The developed script implements the methodology to automate the process of analysing and visualizing wall elements in an as-built digital building model based on their thickness values. It identifies walls that meet specified thickness thresholds according to the building standards, checks whether they are marked as structural to calculate the performance metrics and assigns distinct colours to differentiate between structural and non-structural walls. The script calculates precision, recall, and accuracy performance metrics to evaluate how effectively structural walls are identified and coloured. The results, including metrics and counts, are displayed in a dialogue box for straightforward interpretation by the user.

4.4 Code flow

4.4.1 Setup

- Import required Revit API modules.
- Define parameters like *thickness_values* and conversion factor (*feet_to_mm*).

```
"""Assign colors to walls based on their thickness in mm in the Revit model.
Additionally, check the 'Structural' property and calculate metrics based on
the number of colored structural walls."""

from Autodesk.Revit import DB
from Autodesk.Revit.UI import TaskDialog

doc = __revit__.ActiveUIDocument.Document

# Define thickness threshold
thickness_values = [110]  # in millimeters

# Conversion factor from feet to millimeters
feet_to_mm = 304.8
```

4.4.2 Collect walls

- Use *FilteredElementCollector* to retrieve all wall instances.
- Initialize counters for tracking metrics.

```
# Collect all wall elements from the model
wall_collector = DB.FilteredElementCollector(doc)\
                   .OfCategory(DB.BuiltInCategory.OST_Walls)\
                   .WhereElementIsNotElementType()\
                   .ToElements()

# Initialize counters
walls_colored_count = 0
structural_colored_count = 0
total_structural_count = 0
total_wall_count = len(wall_collector)  # Total number of walls
```

4.4.3 Start transaction

- Begin a transaction to allow modifications in the Revit model.

```
# Start a transaction to modify the Revit model
transaction = DB.Transaction(doc, "Change Wall Surface Colors Based on Width
and Structural Property")
transaction.Start()
```

4.4.4 Iteration over wall instances

- For each wall:
    - Check Parameters: Retrieve Width and Structural properties.
    - Classify:
        - Structural or non-structural.
        - Thickness threshold comparison.
    - Assign Colours:
        - Apply green (structural) or red (non-structural) colour based on classification.
        - Use *OverrideGraphicSettings* for colour and fill patterns.
    - Update Counters:
        - Increment counters based on classification.

```
try:
    # Iterate over walls and assign colors based on width (converted to mm)
    for wall in wall_collector:
        if isinstance(wall, DB.Wall):
            wall_type = wall.WallType
            width_param = wall_type.LookupParameter("Width")  # Get width pa-
rameter
            structural_param = wall.LookupParameter("Structural")  # Check
Structural property

            if width_param and width_param.HasValue and structural_param:
                width_in_feet = width_param.AsDouble()
                width_mm = width_in_feet * feet_to_mm

                # Check if the wall is structural
                is_structural = structural_param.AsInteger() == 1
                if is_structural:
                    total_structural_count += 1  # Count all structural walls

                # Check width and assign color
                if width_mm >= thickness_values[0]:
                    if is_structural:
                        wall_color = DB.Color(0, 255, 0)  # Green for struc-
tural walls
                        structural_colored_count += 1
                    else:
```

```
                    wall_color = DB.Color(255, 0, 0)  # Red for non-struc-
tural walls

                # Apply color to wall surface
                ogs = DB.OverrideGraphicSettings()
                ogs.SetSurfaceForegroundPatternColor(wall_color)

                # Use a solid fill pattern for surface coloring
                fill_pattern_collector = DB.FilteredElementCollector(doc)\
                                            .OfClass(DB.FillPatter-
nElement)\
                                            .ToElements()
                solid_fill = next((fp for fp in fill_pattern_collector if
fp.GetFillPattern().IsSolidFill), None)

                if solid_fill:
                    ogs.SetSurfaceForegroundPatternId(solid_fill.Id)  #
Set solid fill pattern

                doc.ActiveView.SetElementOverrides(wall.Id, ogs)
                walls_colored_count += 1

    transaction.Commit()
```

4.4.5 Commit or roll back

- Commit the transaction if all walls are processed without error.
- Roll back changes if an error occurs.

```
except Exception as e:
    transaction.RollBack()
    error_dialog = TaskDialog("Error")
    error_dialog.MainInstruction = "An error occurred"
    error_dialog.MainContent = str(e)
    error_dialog.Show()
```

4.4.6 Error calculation

- Compute Precision, Recall, and Accuracy metrics using the counters.
    - Precision: Fraction of coloured walls that were structural.
        - $Precision = \frac{Structural\ Walls\ Coloured\ (TP)}{Walls\ Coloured\ (TP+FP)}$
    - Recall: Fraction of structural walls that were correctly coloured.
        - $Recall = \frac{Structural\ Walls\ Coloured\ (TP)}{Total\ Structural\ Walls\ (TP+FN)}$
    - Accuracy: Fraction of all walls that were correctly identified.
        - $Accuracy = \frac{Correctly\ Identified\ Walls\ (TP+TN)}{Total\ Walls}$

```
# Calculate metrics, ensuring they are floats to handle decimals in IronPython
precision = float(structural_colored_count) / float(walls_colored_count) if
walls_colored_count > 0 else 0
recall = float(structural_colored_count) / float(total_structural_count) if
total_structural_count > 0 else 0
accuracy = (float(structural_colored_count) + (float(total_wall_count) -
float(total_structural_count) - float(walls_colored_count) + float(struc-
tural_colored_count))) / float(total_wall_count) if total_wall_count > 0 else
0
```

4.4.7 Display results

- Use a *TaskDialog* to display the results, including metric values and counts.

```
# Show the result in a TaskDialog
task_dialog_result = TaskDialog("Wall Color Update")
task_dialog_result.MainInstruction = "Wall Color Assignment Complete"
task_dialog_result.MainContent = (
    "{} total walls in the model.\n"
    "{} walls had their colors changed based on thickness.\n"
    "{} structural walls were colored.\n"
    "{} total structural walls.\n"
    "Precision: {:.2f}%\n"
    "Recall: {:.2f}%\n"
    "Accuracy: {:.2f}%".format(
        total_wall_count,
        walls_colored_count,
        structural_colored_count,
        total_structural_count,
        precision * 100,
        recall * 100,
        accuracy * 100
    )
)
task_dialog_result.Show()
```

5 Results

The proposed pipeline was applied to the as-built digital building models that contain structural information. The results of the process were visualized using different colours to distinguish between correct and incorrect estimations. The performance metrics precision, recall, and accuracy were calculated to present the effectiveness of the proposed pipeline.

The as-built digital building models used in this thesis were created using laser scanning products to obtain the point cloud data for the digital model and then by using software tools to process the point cloud data and create the as-built digital building model from the point cloud data. The structural information for the as-built digital building models was only available for the first three models. The first three models were used to evaluate the proposed methodology. The rest of the models lacked the structural information, so they were only used to visualise the methodology and to test the implementation on various models.

The as-built digital building models were then assessed according to their wall thickness values and the Eurocode and International Building Code (IBC) standards. The results of the assessment were presented in green and red colours. Walls that were correctly estimated as load-bearing walls were coloured green, whereas walls that were incorrectly estimated as load-bearing walls were coloured red. In the dialogue box, the performance metrics precision, recall, and accuracy were also presented.

Load-bearing walls in the as-built digital building models were visualised by a simple script. In the following figures, blue-coloured walls are the actual load-bearing walls in the structures. The additional as-built digital building models with no structural information were used to visualise the proposed pipeline. The estimated possible load-bearing walls were coloured in yellow.

5.1 TUM building 1

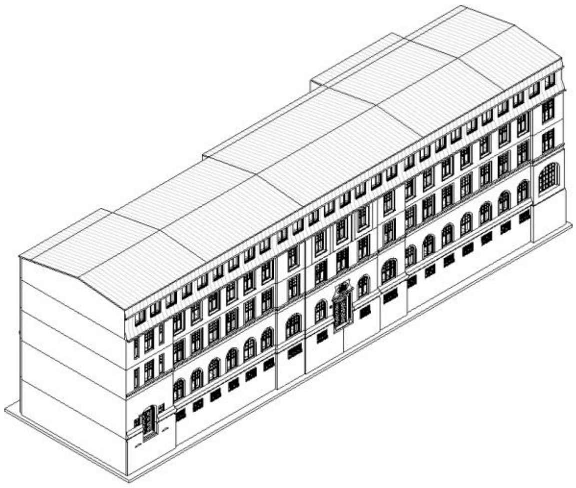

Figure 10: Model (1) - TUM building 1 data.

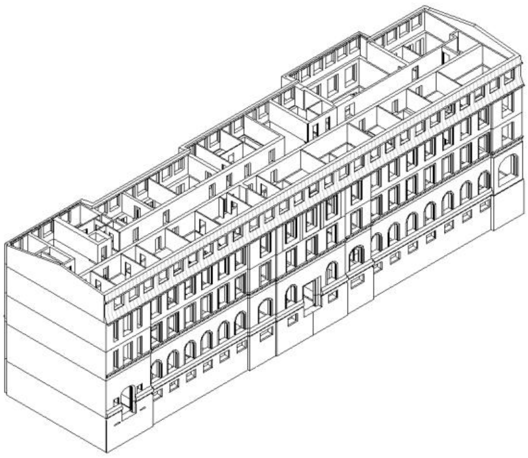

Figure 11: Model (1) - TUM building 1 data (wall elements).

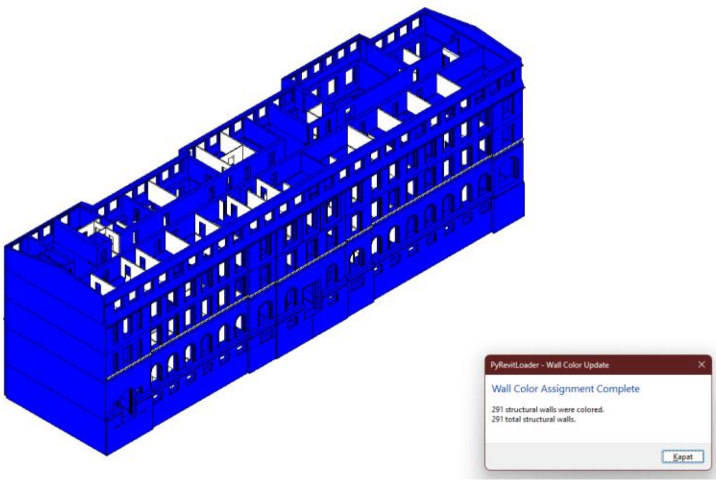

Figure 12: Model (1) - Load-bearing walls.

5.1.1 Results

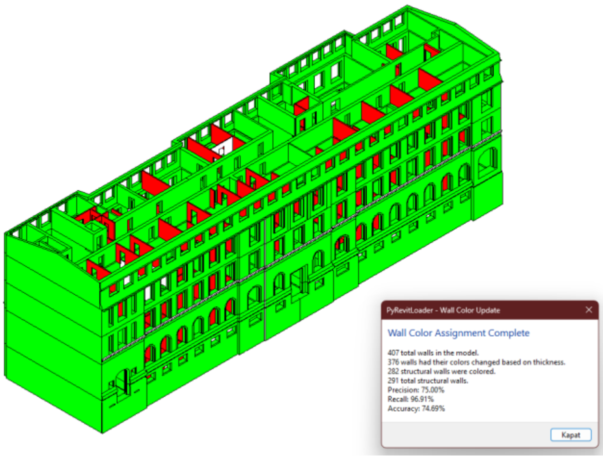

Figure 13: Model (1) - Results, Eurocode.

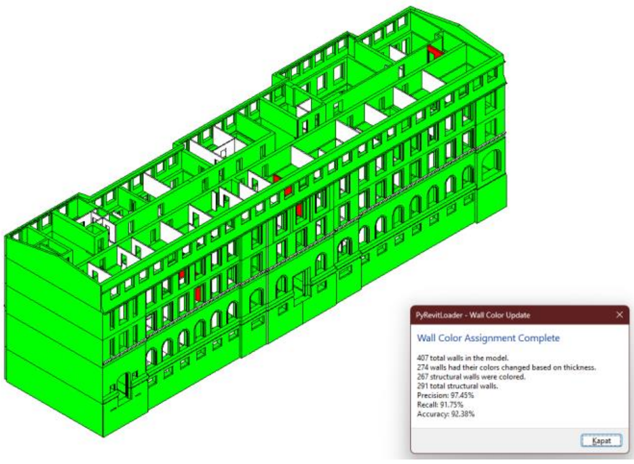

Figure 14: Model (1) - Results, IBC.

Table 5: Results for Model (1).

	Eurocode	IBC
Total number of walls	407	407
Coloured walls	376	274
Coloured structural walls	282	267
Total structural walls	291	291
Precision	75,00%	97,45%
Recall	96,91%	91,75%
Accuracy	74,69%	92,38%

5.2 TUM building - Mensa

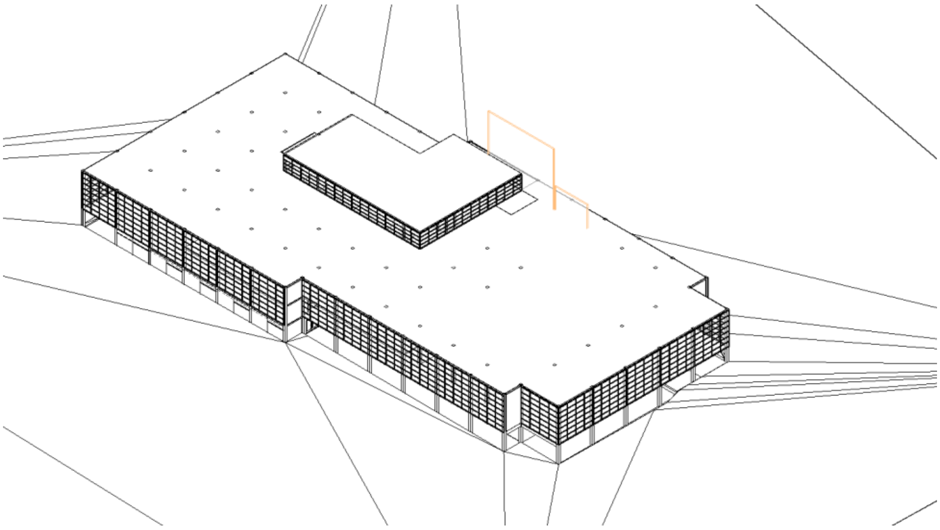

Figure 15: Model (2) - TUM building – Mensa data.

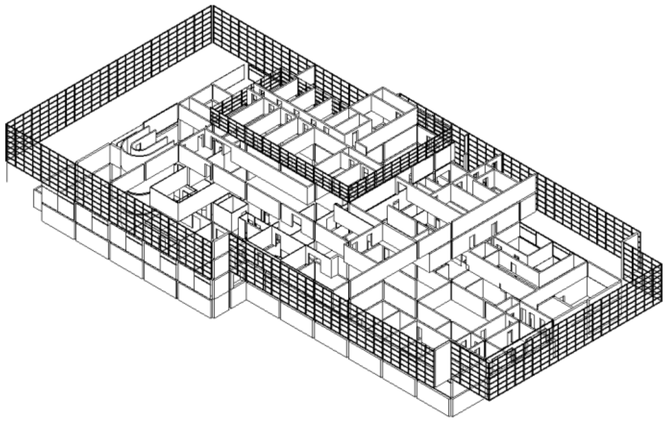

Figure 16: Model (2) – TUM building – Mensa data (wall elements).

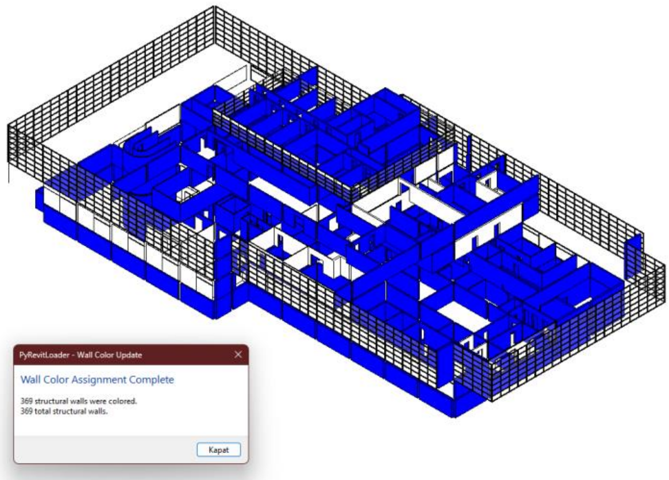

Figure 17: Model (2) - Load-bearing walls.

5.2.1 Results

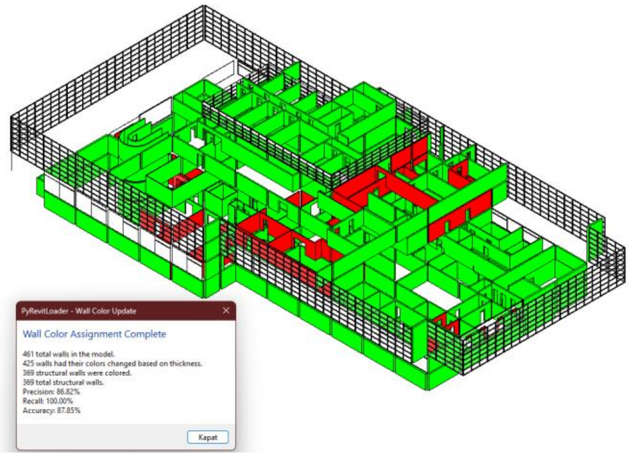

Figure 18: Model (2) - Results, Eurocode.

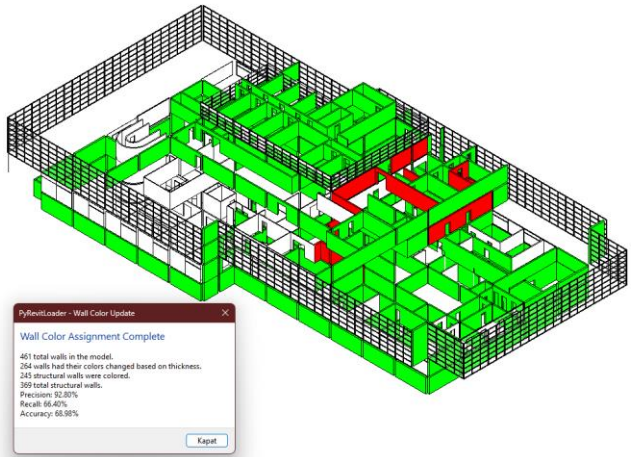

Figure 19: Model (2) - Results, IBC.

Table 6: Results for Model (2).

	Eurocode	IBC
Total number of walls	461	461
Coloured walls	425	264
Coloured structural walls	369	245
Total structural walls	369	369
Precision	86,82%	92,80%
Recall	100,00%	66,40%
Accuracy	87,85%	68,98%

5.3 Residential building complex

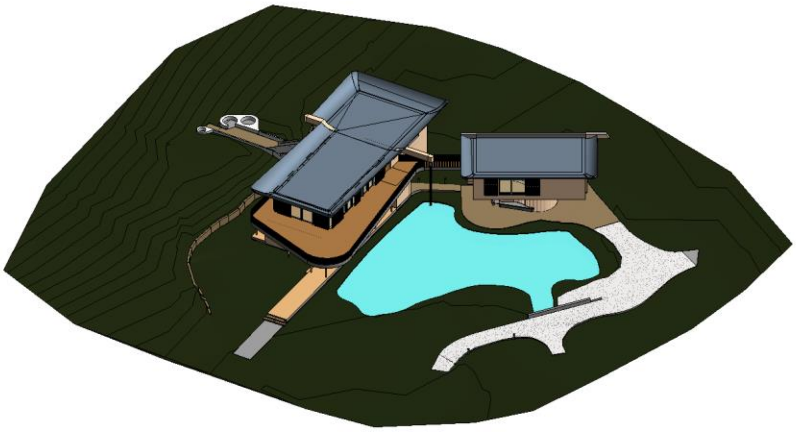

Figure 20: Model (3) - Residential building complex data.

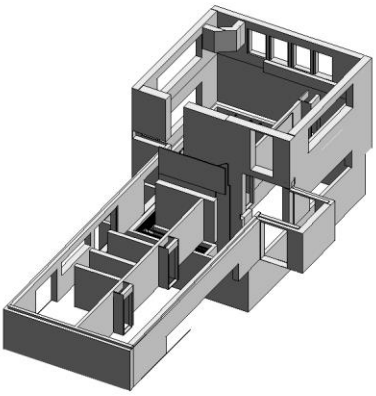

Figure 21: Model (3-1), Residential building complex data (wall elements).

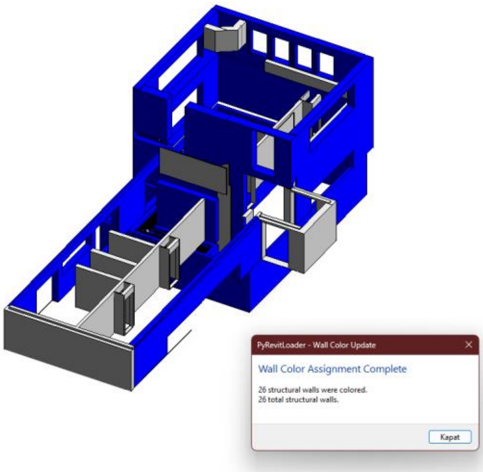

Figure 22: Model (3-1) Load-bearing walls.

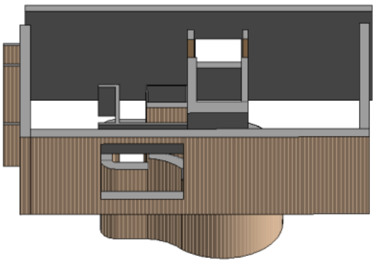

Figure 23: Model (3-2), Residential building complex data (wall elements).

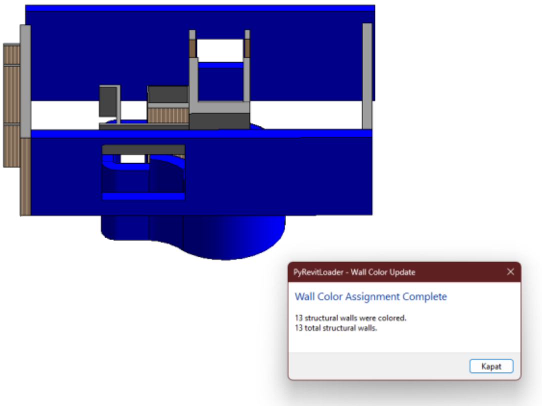

Figure 24: Model (3-2) Load-bearing walls.

5.3.1 Results, Model 3-1

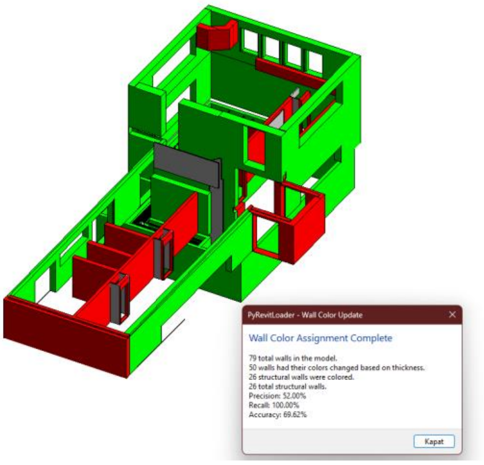

Figure 25: Model (3-1) - Results, Eurocode.

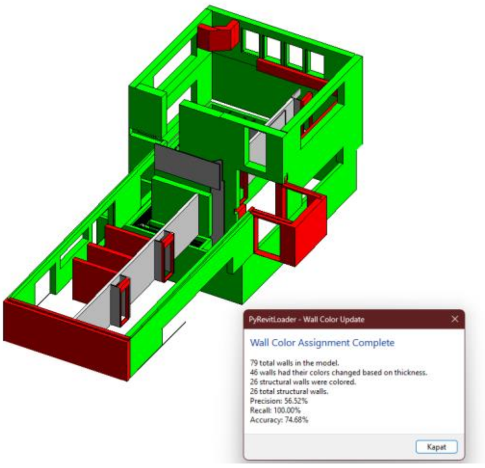

Figure 26: Model (3-1) - Results, IBC.

Table 7: Results for Model (3-1).

	Eurocode	IBC
Total number of walls	70	70
Coloured walls	50	46
Coloured structural walls	26	26
Total structural walls	26	26
Precision	52,00%	56,52%
Recall	100,00%	100,00%
Accuracy	69,62%	74,68%

5.3.2 Results, Model 3-2

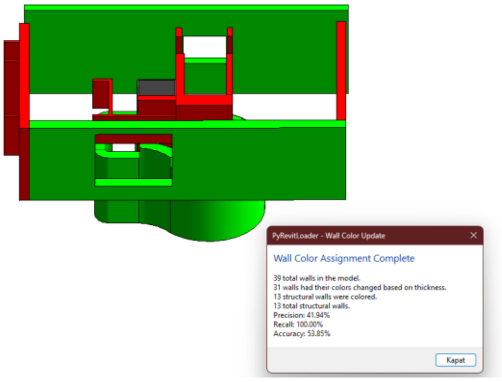

Figure 27: Model (3-2) - Results, Eurocode.

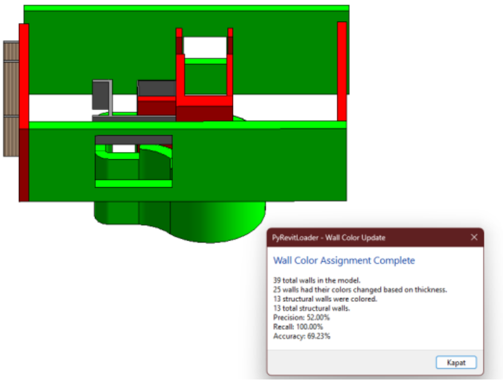

Figure 28: Model (3-2) - Results, IBC.

Table 8: Results for Model (3-2).

	Eurocode	IBC
Total number of walls	39	39
Coloured walls	31	25
Coloured structural walls	13	13
Total structural walls	13	13
Precision	41,94%	52,00%
Recall	100,00%	100,00%
Accuracy	53,85%	69,23%

5.4 Residential multi-storey house

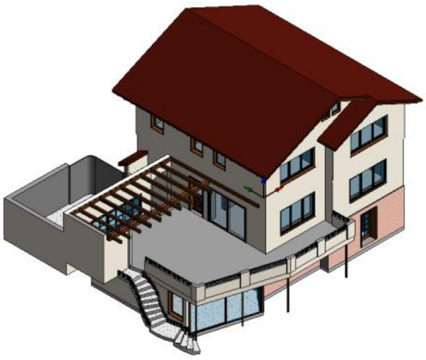

Figure 29: Model (4) - Residential multi-storey house data.

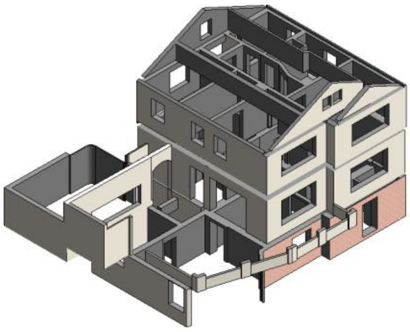

Figure 30: Model (4) - Residential multi-storey house data (wall elements).

5.4.1 Results

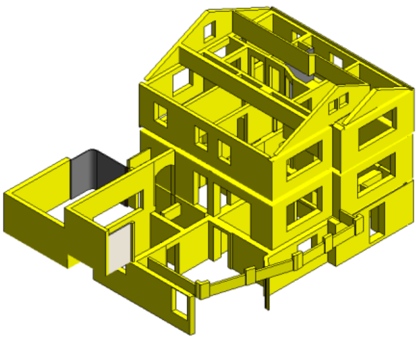

Figure 31: Model (4) – Results, Eurocode.

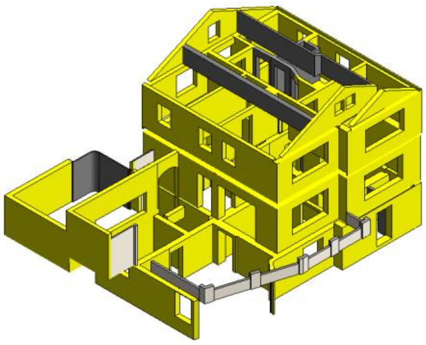

Figure 32: Model (4) – Results, IBC.

5.5 Office building

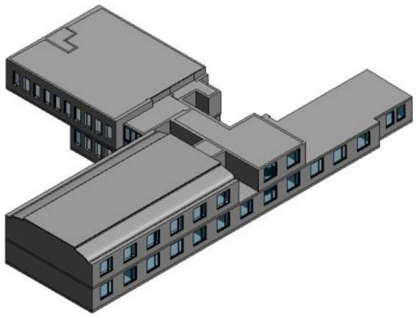

Figure 33: Model (5) - Office building data.

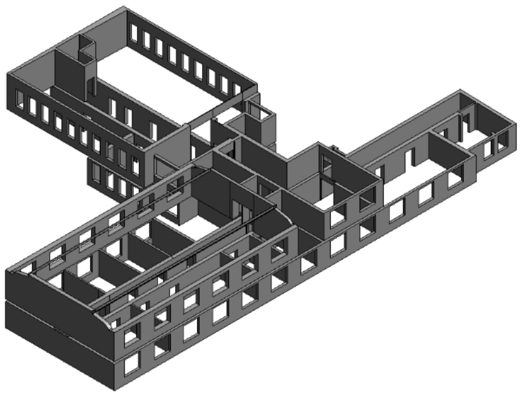

Figure 34: Model (5) - Office building data (wall elements).

5.5.1 Results

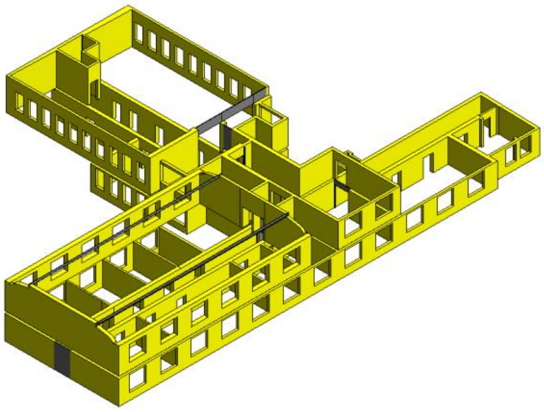

Figure 35: Model (5) – Results, Eurocode.

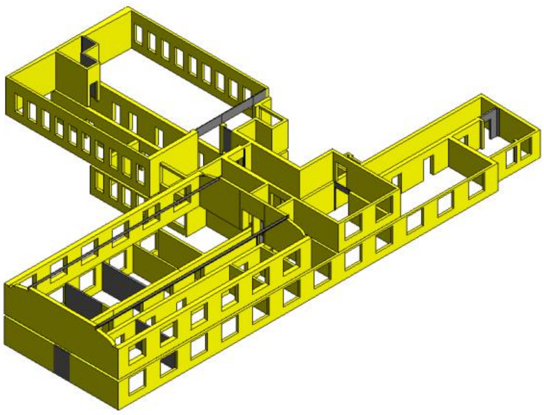

Figure 36: Model (5) – Results, IBC.

6 Conclusion

6.1 Contribution

The contribution of this thesis is by conducting extensive literature research on international building standards and introducing a knowledge-based method for identifying load-bearing walls in as-built digital building models. This method is based on the Eurocode and the International Building Code (IBC) standards. The primary use case involves classifying wall instances according to their structural function, enabling the automatic identification of load-bearing walls in as-built digital building models. This process is designed to reduce the time and effort civil engineers in the architecture, engineering, and construction (AEC) industry spend on creating these models, while also providing an accurate approach aligned with international building standards.

The state-of-the-art process of element identification in as-built digital building models consists of a lot of manual and time-consuming work. A significant research gap exists in automating this process for various construction scenarios. As a result, designers and engineers are making many site visits, requiring original technical drawings of the buildings, which may not be available in some cases, conducting destructive or non-destructive tests on-site, and manually picking and labelling wall instances on as-built digital building models.

This study introduces a framework to automate the identification of structural usage of wall instances in as-built digital building models using the Eurocode and the International Building Code (IBC) standards. The relation between the specified minimum load-bearing wall thickness values in the international building standards and the structural property of the wall instances in as-built digital building models was analysed.

The proposed pipeline has been successfully implemented in various digital building models. The key factors that affect the structural usage of walls are the wall thickness, the continuous presence of the wall instance in multiple storeys, the wall instance being external or internal, wall thickness being constant throughout the wall instance, and the presence of irregular openings. For the implementation of the proposed pipeline, the thickness values of the wall instances were compared to the specified values in the Eurocode and the International Building Code (IBC) standards to determine the structural usage of the same wall instance. After the evaluation, the average values for the performance metrics were calculated as follows: for the Eurocode 63,94% precision, 99,23% recall, and 71,50% accuracy; for the International Building Code (IBC) 74,69% precision, 89,54% recall, and 76,32% accuracy.

Table 9: Average performance metrics of the proposed pipeline according to the Eurocode and the IBC standards.

Performance Metrics, Average	**Eurocode**	**IBC**
Precision	63,94%	74,69%
Recall	99,23%	89,54%
Accuracy	71,50%	76,32%

6.2 Limitations

The proposed pipeline has been successfully implemented in various as-built digital building models, demonstrating its accuracy and effectiveness. However, there are a few limitations that need to be considered.

The used as-built digital building models are prone to having errors in them. These errors include having double walls, pseudo-walls, or misshaped walls instead of having the same geometry as the original ones. These errors often arise when processing the point cloud data into a digital building model or when human error is involved while creating the digital model. Therefore, the accuracy values for the implementation of the proposed pipeline would be affected by the accuracy of the as-built digital building model that was used.

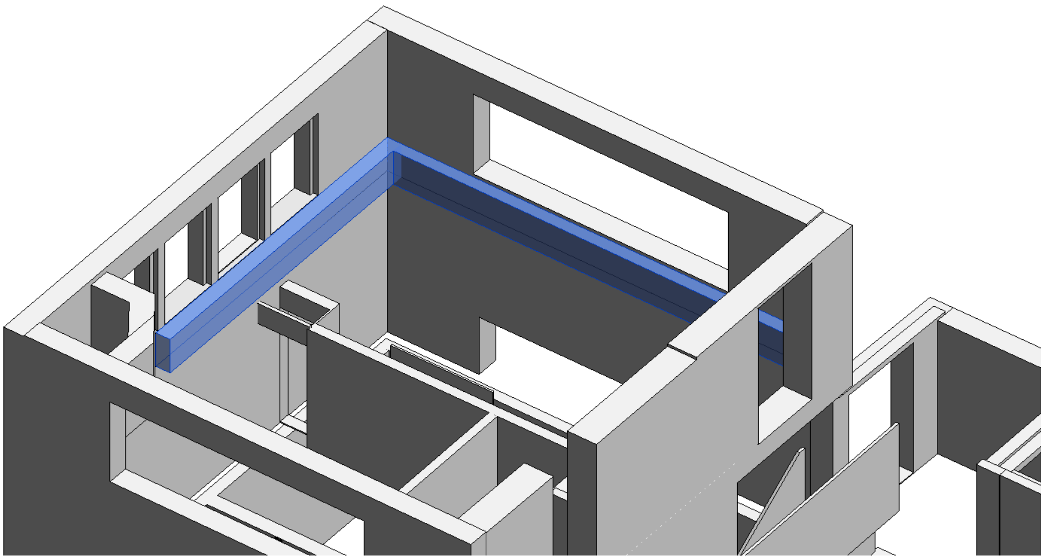

Figure 37: A mislabelled pseudo-wall instance on Model 3-1.

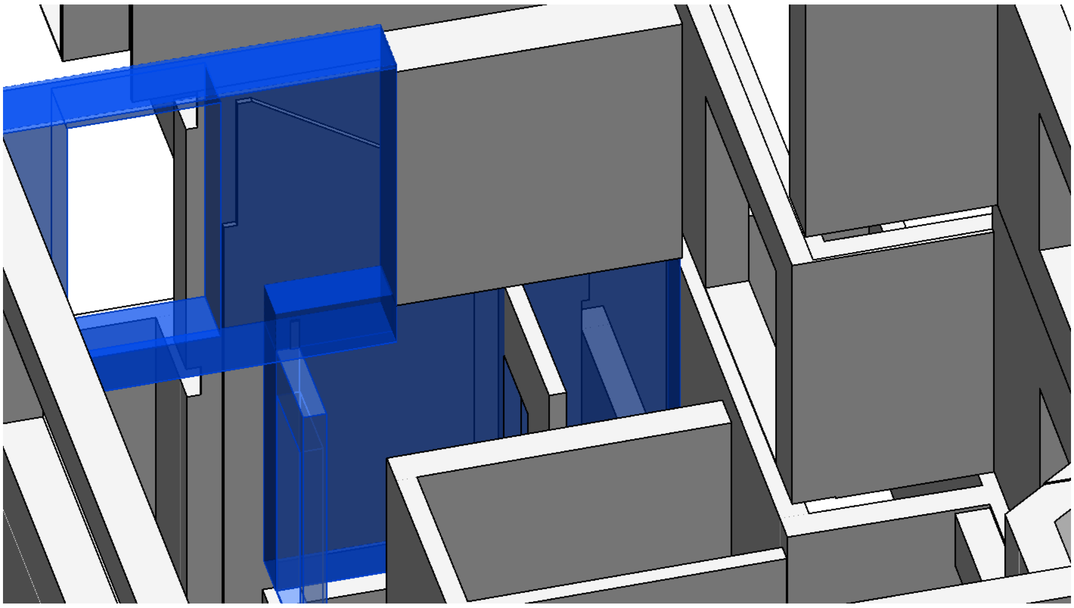

Figure 38: Overlapping wall instances in Model 3-1.

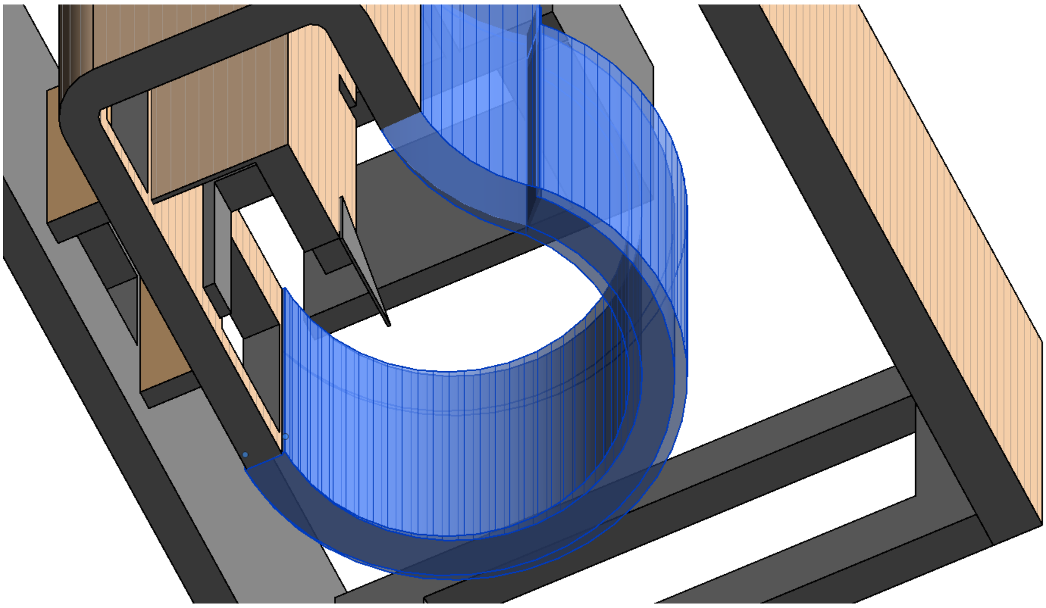

Figure 39: Double walls in Model 3-2.

Among all the factors influencing the identification of the structural functionality of the walls, the thickness parameter was used to estimate the structural property of the wall instances. However, in real scenarios where structural engineers identify the structural property of wall elements in a building, they consider more properties like continuous presence of the wall in multiple storeys, the walls being internal or external, the wall thickness being constant throughout, etc.

6.3 Future work

There are possible improvements to be implemented through which the proposed pipeline and accuracy in classifying wall instances based on their structural usage can be further enhanced.

In the scope of this thesis, only the thickness value of the wall instance was used as a basis for estimating the structural property of the wall element. There could be more parameters like the continuous presence of the wall instance in multiple storeys, the wall instance being external or internal, the wall thickness being constant throughout the element, or if there are irregular openings present in the wall element to include to the estimation process. The proposed approach could be improved in future work by implementing these parameters to the proposed pipeline. The parameters that were investigated to be relevant to estimating the structural usage of wall instances were already discussed in Chapter 3 of this study. Implementation of these parameters would increase the accuracy of the proposed pipeline while estimating the structural usage of the wall instances.

To expand the compliance of the proposed pipeline with different building standards, more literature reviews on different building standards and implementation of the specified minimum thickness values could be done.

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Appendix A

Topic	Code	Masonry Wall	Timber Wall	Fire Wall	Load Bearing Wall	Non Load Bearing Wal	Basement Wall	Shear Wall	Ductile Wall
Structural Design	**EN 1990**								
Actions on Structures	**EN 1991.1.7**	150mm							
Concrete	**EN 1992.1.1**								
Concrete	**EN 1992.1.2**			200mm (unreinforced) 140mm (reinforced, LB) 120mm (reinforced, NLB)	110mm (interior) 130mm (exterior)	60mm			
Steel	**EN 1993.1.1**								
Composite	**EN 1994.1.1**								
Timber	**EN 1995.1.2**		8mm (panel thickness)						
Masonry	**EN 1996.1.1**	85mm							
Masonry	**EN 1996.1.2**								
Masonry	**EN 1996.3**					50mm (interior)	200mm		
Geotechnics	**EN 1997.1.1**								
Earthquake	**EN 1998.1.1**	350mm (unreinforced, natural stone) 240mm (unreinforced, any) 170mm (unreinforced, low seismicity) 240mm (confined masonry) 240mm (reinforced masonry)	3d (d: nail diameter <3,1mm)					200mm (composite steel plate, one side) 100mm (composite steel plate, both sides)	{150mm, hs/20[m]} 200mm (confined part)
Aluminium	**EN 1999.1.1**								
	2024 IBC	Exterior Wall 254mm (one story building) Interior Load Bearing Wall 203mm	Exterior Wall 102mm Interior Load Bearing Wall 102mm		190mm				

Figure 40: Specified minimum wall thickness values in the standards.

Affirmation

Hereby I declare to have written the Master thesis autonomously. Only the cited sources and means have been used. Verbally or semantically transferred intellectual property I distinguished as such.

Further I assure not to have handed in the Thesis for another examination.

München, 25. December 2024

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