Application of Data-driven Methods for Multidisciplinary Design Coordination Through Avoidance

by

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Application des méthodes basées sur les données pour la coordination de la conception multidisciplinaire par évitement

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RÉSUMÉ

Atteindre l'efficacité et l'économie demeure une quête constante pour l'industrie de la construction. Cependant, des obstacles au sein de la coordination multidisciplinaire basée sur la modélisation des informations du bâtiment (BIM), associés à un nombre significatif de conflits détectés dans le modèle fédéré, entravent l'optimisation des pratiques BIM et nuisent aux avantages collaboratifs découlant de cette technologie. Divers groupes de chercheurs ont identifié les obstacles les plus impactant à la coordination BIM et les causes des conflits, recommandant différentes approches pour les atténuer. Ce travail représente une étape naturelle pour accroître l'efficacité dans l'industrie de la construction en identifiant le cadre de solution le plus efficace pour éviter ces obstacles de coordination, réduisant ainsi le nombre de conflits à résoudre. Des propositions consolidées des cadres de solution ont été formulées, établissant des liens entre les obstacles et les causes des conflits, leurs solutions, et les phases de coordination BIM où ils ont le plus d'effet. La vérification de l'applicabilité des cadres proposés à l'industrie de la construction est cruciale pour assurer l'impact optimal d'une stratégie proactive d'évitement élaborée et proposée dans ce cadre.

La thèse valide les propositions précédentes en utilisant les opinions d'experts en BIM. Les experts confirment que l'application des leçons apprises et des meilleures pratiques dès les premières phases de la coordination BIM est primordiale pour éviter les conflits. De plus, les règles de conception et les meilleures pratiques dérivées des experts en BIM promettent de réduire le nombre de conflits dans la phase de création du modèle BIM. Cette étude présente un système intégré d'assistance basé sur des règles conçues pour les outils de création BIM, visant à aider les concepteurs à identifier et éviter les conflits. Le travail démontre le cadre proposé et présente un prototype développé pour évaluer l'efficacité de cette solution novatrice.

Cette recherche est pionnière en sollicitant l'avis d'experts canadiens en BIM sur les règles de conception et les meilleures pratiques pour éviter les conflits dans la coordination BIM. Le système d'évitement des conflits basé sur des règles devrait contribuer significativement à la gestion proactive des conflits dans la coordination BIM, offrant une perspective nouvelle sur cette approche relativement moins explorée dans la littérature scientifique.

Mots-clés : Modélisation des informations du bâtiment (BIM), Coordination multidisciplinaire, Gestion des conflits, Évitement des conflits, Construction Lean

Application of Data-driven Methods for Multidisciplinary Design Coordination through Avoidance

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ABSTRACT

Achieving efficacy and economy is an ongoing pursuit for the construction industry. However, obstacles within Building Information Modelling (BIM)-based multidisciplinary coordination, coupled with a significant number of detected clashes in the federated model, impede the optimization of BIM-based practices and hinder the collaborative benefits derived from this technology. As the first step in resolving this problem, different groups of researchers have pointed out the most impactful obstacles to BIM coordination and the causes of clashes. Other investigators have recommended different approaches for mitigating the identified obstacles and causes of clashes. This work constitutes the natural next step for increasing efficiency in the construction industry and identifying the most effective solution framework to avoid these coordination obstacles, thus reducing the number of clashes to be resolved. Consolidated overviews of solution frameworks were formulated so as to draw connections between the obstacles and causes of clashes, their solutions, and the phases of BIM coordination where they have the most expected effect. The next step of this work is verifying whether the proposed frameworks apply to the construction industry in its current state. This is necessary to ensure that any proactive avoidance strategy implemented based on the proposed framework will be optimally impactful for the industry.

This thesis validates the proposed frameworks presented in previous works, using BIM experts' opinions. Industry experts confirm that the importance of the application of lessons learned and best practices during the earliest phases of BIM coordination is paramount for clash avoidance. Furthermore, the design rules and best practices derived from the BIM experts promise to reduce the number of clashes in the BIM model creation phase. Drawing on expert opinions, this study introduces an integrated rule-based assistance system designed for BIM authoring tools. The purpose is to aid designers in identifying and resolving clashes during the creation of BIM models. The work outlines the proposed framework and presents a prototype constructed to assess the effectiveness of this innovative solution.

This study is the first of its kind that seeks the opinions of experienced BIM professionals regarding design rules and best practices to avoid clashes in BIM coordination. The proposed rule-based clash avoidance system contributes tremendously to the existing body of knowledge regarding clash management and sheds light on the relatively less explored proactive clash avoidance approach in BIM-based coordination.

Keywords: Building Information Modelling (BIM), Multidisciplinary coordination, Clash management, Clash avoidance, Lean construction

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LIST OF ABREVIATIONS

AEC	Architecture, Engineering, and Construction
AI	Artificial Intelligence
AIA	American Institute of Architecture
API	Application programming interface
BIM	Building Information Modelling
BEP	BIM Execution Plan
BMP	BIM Management PlaN
CDE	Common Data Environment
DSR	Design Science Research
GA	Genetic Algorithm
HVAC	Heating, ventilation, and air conditioning
LOD	Level of Development/Detail
MEP	Mechanical, Electrical, and Plumbing
NLP	Natural Language Processing
OWL	Web Ontology Language
RL	Reinforcement Learning
UI	User Interface
VPN	Virtual Private Network
VR	Virtual Reality
USACE	United States Army Corps of Engineers
UML	Unified Modeling Language

INTRODUCTION

The construction industry continually strives to attain both efficiency and cost-effectiveness. Building Information Modeling (BIM) has played an integral role in the construction industry's pursuit of this goal for an extended period. BIM's expansive and evolving role within the construction industry starts with schematic designs and it influences the entire lifecycle of a building. This encompassing involvement goes beyond the construction phase, stretching into the building operation, management, and even the eventual deconstruction of structures. BIM's comprehensive integration allows it to serve as a critical tool for seamless coordination and optimization throughout the entire spectrum of a building's life.

Within the construction process, the utilization of BIM for multidisciplinary coordination stands as a pivotal and intricate procedure. Its overarching purpose is to validate that the various constituents of the building systems are impeccably defined, devoid of any potential conflicts or clashes, and aligned with the full spectrum of project criteria. Thus, the process of BIM coordination demands flawless teamwork and collaboration from all involved stakeholders, encompassing not only designers and engineers but also contractors and owners (Meem & Iordanova, 2022a). This particular demand presents significant challenges to the traditional construction industry, which is often characterized by its historical reluctance to embrace change and innovation. The challenges and impediments encountered in BIM-based multidisciplinary coordination span a wide spectrum. They encompass technical shortcomings, including the absence of adequate support for managing clashes, ensuring interoperability, and fostering collaboration through a common data environment. Additionally, these challenges extend into the organizational domain, where issues related to corporate culture and team dynamics come into play, such as the presence of trust deficits and uncertainties regarding BIM-related roles and responsibilities (Meem & Iordanova, 2022a).

Moreover, within the BIM-based multidisciplinary coordination process, a prominent and progressively pressing concern revolves around the increasing number of identified clashes. These clashes arise from the intricate interplay between various systems and components representing different disciplines involved in a construction project, such as architectural, structural, mechanical, and electrical systems. The clashes, when left unaddressed, can lead to delays, increased costs, and inefficiencies, which can potentially compromise the overall quality of the project. Thus, the clashes or conflicts within the production system can be aptly characterized as inefficiencies and bottlenecks in the construction process (Tommelein & Gholami, 2012). Consequently, mitigating and resolving these clashes has become a pivotal focus among researchers in ensuring seamless integration of these diverse elements within the construction process.

In the quest to address obstacles and clashes within BIM coordination, researchers have taken the important initial step of identifying their underlying causes. Recent years have witnessed a concentrated effort to not only pinpoint these issues but also to develop dependable solutions for overcoming the obstacles in multidisciplinary coordination. This endeavor has been accompanied by an increase of innovative tools for automatic clash detection and the implementation of strategic approaches to filter and manage clashes effectively. Following the initial identification of the causes of coordination obstacles and clashes, the next important stage of this effort focused on determining the most effective framework for proactively avoiding clashes. Proactive clash avoidance can streamline the coordination process, enhance project efficiency, and reduce the associated time and resource burdens that arise from addressing clashes during construction projects.

In this work, comprehensive summaries of solution frameworks have been meticulously constructed. These frameworks establish meaningful linkages between the obstacles in BIM-coordination and the root causes of clashes, their corresponding solutions, and the specific phases within the BIM coordination process where they exert the most impact (Meem & Iordanova, 2022a, 2022 b).

The subsequent phase of this endeavor involves a critical assessment to ascertain the applicability of the proposed frameworks within the current state of the construction industry. This evaluation seeks to gauge how effectively these frameworks align with the industry's contemporary needs and dynamics, ensuring their relevance and potential for practical implementation. This work will provide a comprehensive account of the validation process for the frameworks initially identified in the early stages of this research (Meem & Iordanova, 2022a, 2022 b). Furthermore, it will delve into defining clash avoidance and the meticulous procedure of assembling crucial design guidelines or rules to serve as the foundation for the development of the BIM model to achieve clash avoidance.

Generally, research endeavors aimed at identifying the challenges or obstacles within the BIM coordination process and the management of clashes typically involve the acquisition of data from seasoned BIM practitioners. This data acquisition process focuses on evaluating the effectiveness of the proposed findings and solutions. Nevertheless, this particular methodology has thus far failed to yield a successful clash management solution, primarily because it treats BIM coordination as an isolated phase distinct from the initial planning and design stages of the project. This study stands as an innovative venture in this domain, as it seeks to pioneer the discovery of the optimal approach for discerning a highly efficient clash avoidance strategy via Design Science Research (DSR) methodology. This strategy aims to be not only effective but also readily applicable within the current context of the construction industry. The insights and expertise gathered from seasoned professionals in the construction industry will serve as a cornerstone in this work. The key stakeholders within the construction process participating in this study encompass a wide spectrum of experienced professionals and experienced professionals. These individuals, with a role not limited to, comprise architects, mechanical, electrical, and plumbing (MEP) engineers, structural engineers, BIM coordinators, BIM managers, and various other significant contributors in the domain.

This methodology is poised to establish a comprehensive framework, fostering a proactive approach to clash avoidance right from the initial stages of formulating the BIM execution plan and design. The goal of this strategy is to go beyond the fragmented and reactive clash management techniques that currently dominate the industry and research landscape.

Research objectives

The goal of this research is to propose a method streamlining the multidisciplinary coordination by proactively avoiding clashes (i.e., interferences between BIM models) in the construction industry digital landscape. It is to be noted that this work does not focus on time clashes. The primary objective of this endeavor is to enhance the efficiency of the specialty BIM model generation phase by proactively preventing clashes. This proactive approach is anticipated to result in a reduction in the overall number of clashes identified during the BIM coordination process. To achieve this overarching goal, several specific objectives have been outlined, which can be succinctly summarized as follows:

- **Identification of research gaps in clash management and proactive clash avoidance within the context of BIM-based multidisciplinary coordination.**

The first overarching objective seeks to systematically uncover and delineate the areas where our current understanding and practices in clash management and proactive avoidance within BIM in the context of multidisciplinary coordination fall short. This will involve a thorough examination of the existing body of knowledge to pinpoint where further investigation is needed.

- **Identification and assessment of key obstacles to BIM coordination and causes of clashes impacting BIM-based multidisciplinary coordination.**

The second objective focuses on the intricate task of identifying and assessing the most influential challenges or obstacles and factors that give rise to clashes in BIM-based multidisciplinary coordination. This entails a comprehensive examination of the root causes, encompassing technological, process-related, and human factors, which contribute to inefficiencies and clashes.

- **Development of an effective methodology for crafting a proactive clash avoidance strategy.**

The third primary objective involves the formulation of a robust and systematic methodology based on Design Science Research for devising a proactive strategy to prevent clashes. This methodology will be a our main contribution, outlining step-by-step procedures and protocols that practitioners can employ to minimize the occurrence of clashes before they become problematic.

- **Identification and codification of design rules and best practices acquired from BIM experts for clash prevention.**

The fourth objective centers on the acquisition, formalization, and encoding some sample design rules and best practices from the wealth of insights gathered through consultations with seasoned consultants, engineers, and BIM experts. These rules and practices are essential to inform and guide the design, modeling, and coordination processes to proactively mitigate clashes.

- **Proposal of an integrated system for BIM authoring tools, aiding adherence to design rules and best practices.**

The final objective seeks to advance the field of BIM-based multidisciplinary coordination by proposing a comprehensive and integrated system, specifically designed to work in tandem with the BIM authoring tools. This system will serve as a supportive mechanism, facilitating the practical implementation of the design rules and best practices, enhancing the effectiveness of clash prevention measures.

Through the pursuit of these interrelated objectives, this thesis endeavors to make a significant contribution to the field of BIM-based multidisciplinary coordination by filling the research gaps, addressing obstacles, and providing practical methodologies and tools for the proactive avoidance of clashes, ultimately promoting more efficient and effective construction projects.

Thesis structure

This thesis unfolds through a structured narrative composed of eight chapters. Its inaugural segment, the introduction, serves as a foundational framework. In this chapter, the research is situated within its broader context, casting a spotlight on the fundamental goals and objectives that underscore this work. In this chapter, the research question is carefully crafted, and the related objectives are clearly outlined in a brief manner. In chapter one, a deep dive is taken into the background and history related to the research topic. The current practices in the industry and the latest research in the field of BIM-based coordination and clash management were carefully examined. This exploration helps to provide a solid foundation for understanding the following chapters and connects this research to the changing landscape of the field. Chapter two explores the primary factors leading to clashes in BIM models, alongside a thorough examination of proactive clash avoidance strategies that researchers have thus far investigated. Chapter three delves into the comprehensive exploration of the research methodology employed in this thesis. Subsequently, in chapter four, a detailed analysis is provided for the process of designing and conducting semi-structured interviews with AEC professionals. This chapter also unveils the results and insights obtained from these interviews. Chapter five shows the conceptual design of the proposed clash avoidance system in light of the insights collected from industry experts. This chapter also shows the development of the clash avoidance system prototype in detail. Finally, the discussion and conclusion sections delve into the discussion about the key findings from this work including the research limitations and future possibilities of expanding and refining this work.

CHAPTER 1

LITERATURE REVIEW

In this chapter, a comprehensive literature review was conducted to assess the present status of research, to identify prominent challenges, and to explore future possibilities within the relevant subject matter. Addressing the obstacles or challenges for effective BIM-based multidisciplinary coordination has emerged as a vibrant focus of research. The existing body of literature proposes several solution frameworks targeted at improving the overall efficiency of multidisciplinary collaboration within the industry to decrease unanticipated obstacles and expenses in construction processes. In this chapter, a comprehensive synthesis of these effective solutions is offered, with the intent of discerning research gaps and gaining insight into prospective research paths in the domain of BIM-based multidisciplinary coordination. This synthesis establishes a clear connection between the intricacies of multidisciplinary BIM-based coordination workflows, the challenges that impact them, and potential solutions to these challenges.

In this chapter, the terms 'obstacles' and 'challenges' are used interchangeably. The structure of this chapter unfolds as follows: In Section 1.1, the methodology for the literature review is introduced. Then recent research surrounding factors that influence BIM-based collaboration, and the obstacles and challenges that impede meaningful multidisciplinary coordination are explored. The reviewed literature reveals various obstacle categories, including: i) process, ii) actor, iii) task, iv) context, and v) team. Section 1.2 discusses the different category of obstacles in detail and section 1.3 is dedicated to in-depth discussions of the solution frameworks previously explored by researchers which are effective against the identified categories of obstacles. Finally, section 1.4 discusses the relationship between the stages of BIM based multidisciplinary coordination, the identified obstacles and their potential solutions to understand which stages of multidisciplinary coordination are the most affected and where the research gaps exist.

1.1 Methodology for the literature review

For this synthesis a comprehensive "mixed-methods systematic review" was conducted to ensure a thorough analysis of the existing literature, incorporating both quantitative and qualitative approaches to minimize potential bias. As per Pearson et al. (2015), a systematic review employing mixed methods allows for the assessment and interpretation of all pertinent studies. This approach involves synthesizing results derived from quantitative, qualitative, or a combination of both research methods (mixed methods) to address one or more pertinent research questions, subject matters, or a specific area of interest (Pearson et al., 2015). There were three stages to this "mixed-methods systematic review" as shown in table 1.1.

Table 1.1 Stages of mixed-methods systematic review

Stages	**Evaluation criteria**	**Number of collected literature**
Stage 1	Keyword search based on relevance to the field of study.	1,077
Stage 2	Published, open access, journal articles, conference papers, book chapters, Written in English.	357
Stage 3	Studies focused on multidisciplinary collaboration, coordination, and efficiency frameworks.	32

In the first stage of the study, a targeted keyword search within the Scopus database was conducted, yielding a substantial collection of 1,077 relevant pieces of literature. These chosen keywords were thoughtfully selected to align with the study's subject matter. The search encompassed the following keyword string; bim OR "building information model*") AND ("multidisciplinary coordination" OR "real time collaboration" OR barriers OR obstacles OR "clash filtration" OR "clash relevance" OR "clash resolution" OR clash OR "clash management". This approach was carefully designed to ensure a thorough investigation by capturing related ideas and different forms of relevant terms. ‘Construction’ or ‘construction industry’ was not added to this keyword string since not all relevant literature identified construction industry as one of the keywords. In the second stage, the number of literature was narrowed down to 357 selections, considering their publication stage, document type, and source. Specifically, -language, open-access journal articles, conference papers, and book chapters were focused on English for the analysis. Subsequently, VOSviewer was employed to perform a bibliometric analysis of the curated literature. Additionally, a co-occurrence network map was generated for the author keywords as shown in figure 1.1, offering insights into the research topics and their interrelationships within the realm of BIM-based multidisciplinary coordination. The VOSviewer network map employs node circles and lines to depict the strength and significance of connections. Circle size indicates keyword frequency, while node distance signifies closeness. Line thickness reflects the relationship and co-occurrence frequency of keywords. This map highlights common research topics in multidisciplinary coordination and offers insights into potential research avenues. Additionally, the map reveals six unique keyword clusters, each represented by a distinct color. Notably, clusters related to BIM in sustainable construction, barriers in BIM, and BIM-based collaboration are prominently featured.

The map highlights substantial research on identifying barriers in BIM-based collaboration and multidisciplinary coordination with different colors but reveals a gap in comprehensive studies aimed at addressing these obstacles. In the final stage, a qualitative analysis was employed to assess the relevance of the literature. Initially, the focus was on literature directly addressing obstacles in BIM-based coordination and collaboration. These selected papers underwent meticulous scrutiny to extract pertinent information for the subsequent phase. Following this, the papers were categorized according to the specific BIM coordination or collaboration obstacles they examined, offering insights into the depth of research and potential solutions. This process also aided in identifying research gaps. In Stage 3 of the mixed-methods systematic review, a total of 32 papers were shortlisted.

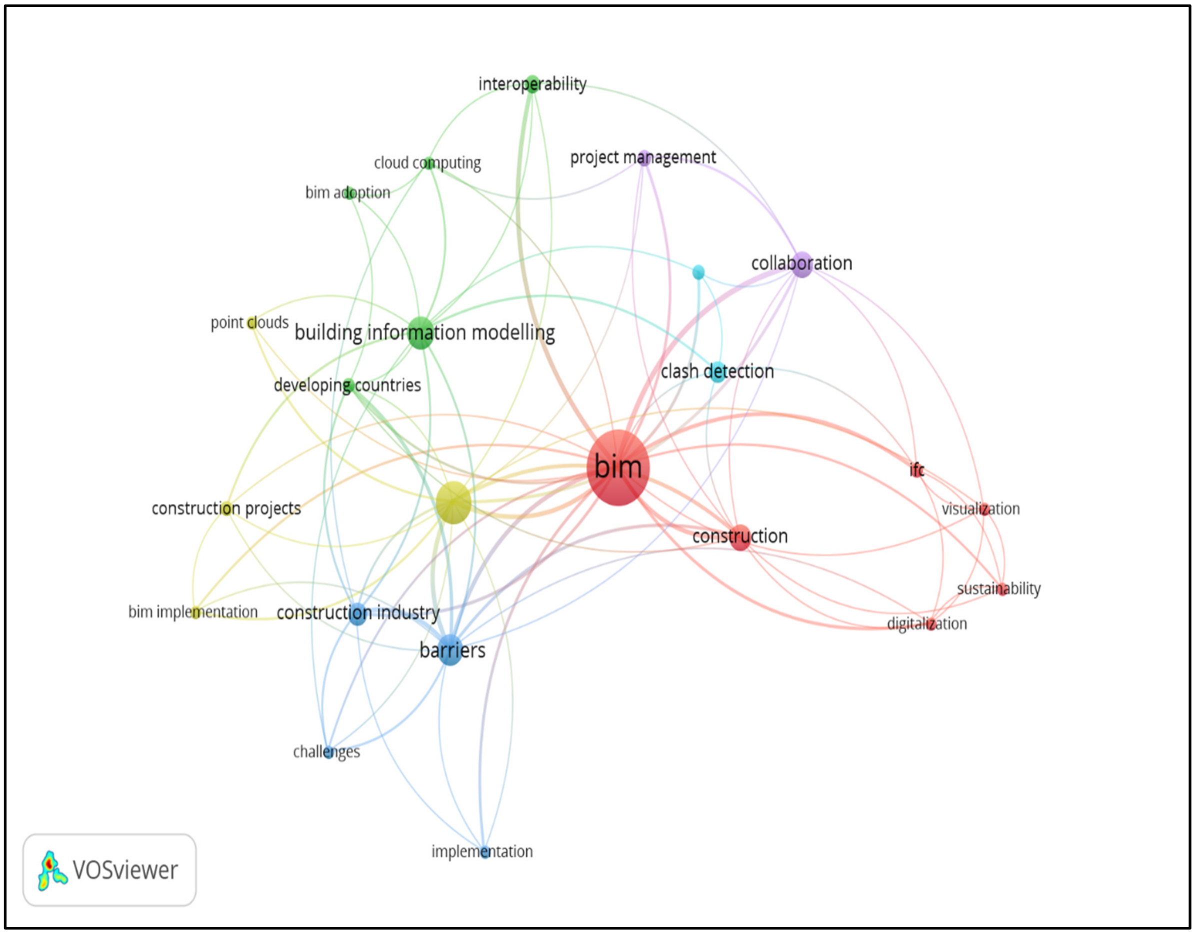

Figure 1.1 VOSviewer network map of research topics and their interrelationships

1.2 Classification of obstacles in BIM-based multidisciplinary coordination

In this section, the most impactful obstacles within BIM-based multidisciplinary coordination are studied as illuminated by numerous existing literatures. BIM is regarded as integrative technology with 'parametric intelligence' able to escalate efficiency in the construction industry (Raja Mohd Noor et al., 2021). In recent years BIM-enabled construction coordination is being increasingly adopted in construction projects to drive productivity (Liu. H et al., 2021). However, efficiently managing a diverse multidisciplinary collaborative network in BIM projects remains a challenge, despite its essential role in BIM-driven projects (Matthews et al., 2018). While considerable research focuses on enhancing BIM-based multidisciplinary coordination, the exploration of obstacles in construction collaboration has been somewhat isolated. An integrated analysis of fragmented studies is necessary to identify the key challenges and barriers.

One of the contemporary studies that address this research gap is a research by Oraee et al., where BIM-based construction networks are viewed as geographically dispersed stakeholders from diverse disciplines and organizations collaborating on project tasks (Oraee et al., 2017). This study adopts the obstacles categories from (Oraee et al., 2017), which was also used as a theoretical lens in (Oraee et al., 2019).These categories are: i) process, ii) actor, iii) task, iv) context, and v) team.

1.2.1 Process-related obstacles

Oraee et al., (2019), note that obstacles related to required resources, essential tools, and professional training in BIM-based collaboration fall into this category. The research highlights that obstacles related to pertinent technologies, collaborative spaces, data security, and appropriate guidelines have the most significant impact according to the literature. These obstacles are further subdivided into 'Tools' and 'Resources,' which will be explored in more detail in this study.

1.2.2 Actor-related obstacles

In (Oraee et al., 2019), it is outlined that challenges linked to individual participants, including the 'knowledge, skills, and abilities' of team members, fall under this category. The importance of the skills and abilities of individual team members was also identified as a pivotal factor influencing social collaboration among BIM participants (Raja Mohd Noor et al., 2021).

1.2.3 Task-related obstacles

This category encompasses the requirement for timely access to pertinent information, encompassing both task demands. It is important to note that 13% of the sample articles investigated (Oraee et al., 2017, 2019) acknowledge the significance of information demand within this context. The subsequent sections will delve into a more detailed exploration of information demands.

1.2.4 Context-related obstacles

Factors tied to organizational culture and environment, including the absence of a collaborative mindset and extensive communication happening outside the BIM framework, are categorized as context-related challenges (Oraee et al., 2017, 2019). Within (Oraee et al., 2021), the authors identify a reluctance to enforce BIM standards and advocate for particular BIM collaboration tools as challenges within the context category.

1.2.5 Team-related obstacles

This category encompasses obstacles associated with team member roles and relationships, as identified by Oraee et al., (2017, 2019). The authors also point out that the lack of complete control and a vague comprehension of the BIM manager's role are significant obstacles within this category (Oraee et al., 2021).

1.3 Potential solution frameworks for obstacles in BIM coordination

This section discusses the potential solution frameworks for different classes of obstacles presented in section 1.2.

1.3.1 Potential solution frameworks for Process-related obstacles

The potential solution frameworks are divided in two sub-sections: i) Resources, and ii) Tools.

1.3.1.1 Resources

As per the conceptual model proposed by Oraee et al., the challenges pertaining to resources include: (i) Lack of a Common Data Environment (CDE) to support collaboration, (ii) lack of guidelines and standards for BIM collaboration, and (iii) data ownership and data privacy concerns (Oraee et al., 2019).

- **Potential framework for improving CDE to support collaboration:**

One of the obstacles, as identified in the literature, is the absence of a CDE that can guarantee seamless and effective collaboration. To address this issue, it is crucial to establish a seamless and resilient integration of CDE access within BIM authoring tools. Preidel et al. introduce the concept of a BIM Integration Framework (BIF) that offers a consistent link to a central online data platform for all team members, irrespective of the specific BIM authoring tools they employ (Preidel et al., 2017). Instead of repeatedly converting the model into IFC format, participants have the option to upload files in their native formats and engage in clash detection and management via compact data packages known as "topics." This approach conserves important resources, including time and computing power. Consequently, this proposed framework offers a promising solution for BIM-based collaboration.

- **Potential frameworks for improving guidelines and standards for BIM collaboration:**

Concerns have been raised by researchers regarding the lack of uniformity in guidelines and standards within BIM-enabled projects. They have also emphasized the significance of establishing clear and comprehensive standards for facilitating multidisciplinary coordination in BIM-based endeavors (Khanzode, 2008.; Oraee et al., 2019). The requirement for all collaborating disciplines to have a complete understanding of each other's actions had been noted by researchers (Khanzode, 2008). They further assert that the coordination model must encompass user-specified detailed facility functions to avert possible rework. Furthermore, it is essential to establish the Level of Development (LOD) of the model prior to initiating the coordination process and obtaining input from all participants. These findings mirror established industry BIM execution planning guidelines, such as the PennState BIM Project Execution Planning Guide and ISO 19650 guidance, which can effectively address the issue of unclear standards.

- **Potential framework for improving data ownership and data privacy concerns:**

Companies and participants frequently harbor privacy and security concerns when it comes to sharing their models on a CDE or any cloud-based collaboration platform, despite the significant collaboration benefits these platforms offer (Oraee et al., 2017, 2019). Controlled information exchange and access during such collaboration may resolve this issue. Akponeware & Adamu suggest an evolving work-in-progress structure to enhance transparency while recognizing the necessity for user-controlled access rights to prevent unauthorized entry and ensure data security (Akponeware & Adamu, 2017). They also advocate for the participation of a built asset security manager who can oversee and regulate role-based access rights, ensuring that access is provided on a need-to-know basis for all pertinent participants.

1.3.1.2 Tools

A substantial part of the challenges associated with tools is attributed to deficiencies in technological support, as indicated by Oraee et al. (Oraee et al., 2019). The majority of commonly employed technologies lack the requisite features for effective BIM collaboration. The specific Tools-related obstacles and potential frameworks that could enhance the existing tools for BIM-based collaboration will be discussed below.

- **Potential frameworks for clash relevance prediction**

The presence of numerous irrelevant clashes during the BIM coordination phase significantly extends the time and expenses of construction projects. Nevertheless, existing clash detection tools lack the essential automation to analyze clash data, thereby requiring manual investigation (Pärn et al., 2018). As a result, the incorporation of clash relevance prediction into BIM coordination tools has emerged as a prominent research focus in recent years. Machine learning techniques, including supervised and unsupervised learning, deep learning, and reinforcement learning, hold the potential to play a pivotal role in improving clash management (Pan & Zhang, 2021).

A significant study aimed at enhancing the clash filtration process was carried out by Hu and Castro-Lacouture. They compared six supervised machine learning algorithms, including Decision trees, Jrip rules, Binary logistic regression, and Bayesian methods, to determine the most effective approach for clash filtration (Hu & Castro-Lacouture, 2019). This study revealed that Jrip-based rule methods, achieving an 80% prediction accuracy, outperformed the alternative algorithms. In a parallel research investigation, the utilization of Bayesian statistical methods, including Naive Bayes, Bayesian networks, and Bayesian probit regression, was explored in the context of predicting clash relevance (Hu & Castro-Lacouture, 2018). The authors determined that the Naïve Bayes method exhibited average precision, with the Bayesian network method being particularly dependable in forecasting irrelevant clashes. On the other hand, Bayesian probit regression, adept at handling small datasets, demonstrated the highest precision when predicting relevant clashes. Nonetheless, the amalgamation of Bayesian methods via a majority rule approach proves to be more dependable and exhibits certain enhancements in the precision of clash categorization. Moreover, an attempt was made to filter clashes using a hybrid approach that combines rule-based reasoning and supervised machine learning, revealing that this hybrid method can boost prediction accuracy by 6% to 17%, surpassing the performance of individual or ensemble learning classifiers (Lin & Huang, 2019).

- **Holistic clash detection and resolution improvement frameworks**

Design coordination and clash detection stand out as the two most influential factors when it comes to affecting design errors (Wong et al., 2018a). As per the research by Hu et al., building components exhibit interconnectedness, forming a network of interdependencies that significantly impact clash outcomes (Hu et al., 2019a, 2019b). These studies by Hu et al . illustrated this relationship through a building component network, primarily focusing on hard clash elements. The practical application of this network in a real project demonstrated a noteworthy reduction of 17% in irrelevant clashes. Furthermore, the network approach successfully facilitated the grouping of pertinent clashes, leading to a substantial reduction in the total number of detected clashes. The authors delved deeper into examining the interdependent relationship between building components and its impact on clash resolution.

They achieved this by analyzing six different types of spatial relations and then devised algorithms to query these relations, utilizing models in IFC format (Hu et al., 2019b). Following the establishment of a spatial network for building components grounded in these relations, the authors put this method to the test in a practical project. They recognized the application of a component-dependent network and graph theory in aiding clash resolutions and seeking globally optimized solutions as a promising direction for future research.

- **Proposed framework for automatic clash resolution**

In recent years, there has been substantial research into automatic clash resolution. The examination of the interdependent relationships among building components in the context of clash resolution was carried out by Hu et al. (Hu et al., 2019a, 2019b), while multiple researchers have explored the effectiveness of individual algorithms in automatic clash resolution. A particular framework utilized a simulated annealing algorithm, integrating it with the Application Programming Interface (API) of a BIM authoring tool. This framework proposed the modification of the arrangement of components implicated in a clash as a strategy to decrease the count of detected clashes (Hsu & Wu, 2019). In addition to methods for addressing MEP clashes, modern researchers are actively exploring techniques for resolving clashes in steel reinforcement. One such endeavor involved the application of a two-step Genetic Algorithm (GA) to automatically optimize the design of reinforcement for a clash-free configuration (Mangal et al., 2021). The feasibility of Multi-Agent Reinforcement Learning (MARL) as discussed by J. Liu et al. (J. Liu et al., 2019), as well as the utilization of Q-learning in the context of BIM, has been explored to achieve practical path-planning for the automatic generation of clash-free rebar designs (J. Liu et al., 2020).

- **Functional requirements in BIM authoring tools**

To offer effective support for collaborative efforts based on Building BIM, BIM authoring tools must possess specific functionalities that encourage and facilitate collaboration. In a recent analysis the bottlenecks in BIM-based design coordination was identified (Mehrbod, Staub-French, & Bai, 2017). They also conducted a benchmark assessment of commonly used BIM tools, evaluating their range of functionalities, which encompassed support for various model formats and the ability to provide comments on model development. The research highlighted that currently prevalent BIM authoring tools lack support for multiple model formats and do not provide the capability to track changes. Solibri was identified as the most compatible BIM tool, as it offers a comprehensive set of essential functionalities (Mehrbod, Staub-French, & Bai, 2017).

1.3.2 Potential solution frameworks for Actor-related obstacles

The team members' deficiencies in collaboration knowledge, skills, and abilities fall into the actor category, which is the least explored among all the categories in existing literature. This inadequacy can encompass a wide spectrum, ranging from a lack of proficiency in using BIM authoring tools or coordination platforms to a lack of awareness about the coordination challenges encountered by team members.

Researchers tried to develop a taxonomy of design coordination issues with the aim of aiding team members in enhancing their comprehension of these issues, as confirmed by validation from industry professionals (Mehrbod, Staub-French, Mahyar, et al., 2019). Another significant impediment to addressing the deficiency in collaboration knowledge, skills, and abilities is the inadequate documentation of lessons learned from each BIM-based collaboration project. Researchers have found that keeping a precise rework log and maintaining a record of the Virtual Design and Construction (VDC) team's lessons learned can minimize the likelihood of overlooking issues detected in the field. Such records offer project participants the necessary insights to identify and prevent similar issues in subsequent projects (Alsuhaibani, 2021). Furthermore, the literature underscores the importance of skill development programs, which may include intensive training sessions or workshops where seasoned professionals can impart their expertise to enhance the comprehension and knowledge regarding BIM (Evans & Farrell, 2020a).

1.3.3 Potential solution frameworks for Task-related obstacles

As per researchers, task-related barriers exert the least influence on collaboration networks within a BIM-based context. The subfactor 'demand,' found within the task category, highlights the issue of inadequate access to the right information when it is needed (Oraee et al., 2019). This represents a substantial impediment to collaboration and arises from subpar communication quality (Hosseini et al., 2016). The principal reason team members struggle to obtain timely and pertinent information is the inadequate quality of communication. Consequently, implementing strategies to enhance situational awareness and foster improved communication within the team could aid in alleviating this obstacle. In a study conducted by Adamu et al., a quasi-experiment involved multidisciplinary professionals, leading to the redefinition of Social BIM (SBIM) and the enhancement of shared situational awareness among project participants working remotely. This experiment demonstrated that real-time audio-visual collaboration contributes to improved communication in BIM-based collaborative efforts (Adamu et al., 2015).

1.3.4 Potential solution frameworks for Context-related obstacles

Researchers noted that factors linked to organizational culture and the working environment are categorized under the context category (Oraee et al., 2019). In particular, the absence of a team-oriented mindset and substantial communication taking place outside of the BIM framework significantly influenced collaboration.

Informal communication outside of the BIM framework poses a challenge to the adequate documentation of lessons learned from each project. To move team members away from resorting to informal communication channels, it is essential to employ frameworks that facilitate members to communicate with one another through the BIM collaboration platform. In this context, the Social BIM framework introduced in the study by Adamu et al., could offer valuable assistance. The study examined four distinct collaboration protocols: (i) one-to-one, (ii) one-to-many, (iii) many-to-one, and (iv) many-to-many (Adamu et al., 2015). Among the various protocols, the many-to-many protocol provided the highest degree of shared situational awareness within the team, facilitating communication among members through text, audio, and video via the BIM platform. This protocol holds promise for helping members refrain from informal communication, as reported by the participants.

In addition to the utilization of such frameworks to enhance formal communication within the team, researchers suggested the application of Lean Construction strategies to BIM coordination. They also identified specific steps where Lean problem-solving techniques could prove beneficial for BIM (Pedo et al., 2021). The key recommendations emerging from this study encompassed various aspects, including optimizing flow management and conducting systematic waste analysis during the clash detection phase, as well as promoting the exchange of lessons learned between projects.

1.3.5 Potential solution frameworks for Team-related obstacles

The team category, along with process and context, has received more comprehensive research attention. This category encompasses challenges associated with the roles of participants in BIM collaboration and the dynamics of relationships among team members (Oraee et al., 2017, 2019). One of the most substantial obstacles within this category is the individualistic approach adopted by team members in BIM-based collaboration, coupled with their resistance to sharing information (Oraee et al., 2019).

1.3.5.1 Potential frameworks for defining BIM specific roles

In a typical non-BIM project, coordination responsibilities are typically divided among the project manager, design manager, and site manager. However, in BIM-enabled projects, the role of the BIM coordinator takes on a more strategic dimension, deviating from the conventional multidisciplinary collaboration dynamics. In the work of (Badi & Diamantidou, 2017), the authors supported this notion and observed that the centrality of new roles in BIM-enabled projects, such as the BIM coordinator or BIM manager, exhibits a moderate level of prominence. They also noted that the competition between BIM roles and project managers for leadership positions can lead to collaboration inefficiencies. Moreover, non-BIM stakeholders tend to see BIM-actor roles as primarily emphasizing technical skills over interpersonal abilities, whereas those engaged in BIM believe that their roles contribute to driving change through effective coordination (P. M. Bosch-Sijtsema et al., 2019). This suggests that while BIM roles have gained acceptance in the industry, there is still a notable absence of a comprehensive understanding of these roles.

Researchers also delved into the influence of BIM-specific roles and how their evolving definitions adapt to meet the requirements of advancing technologies and the changing landscape of the industry. An in-depth quantitative analysis of the influence and feasibility of BIM-related positions and their scope of responsibilities revealed that BIM-specific roles serve as a valuable complement to bridge the gap in BIM proficiency within the conventional project management roles. With modern project managers and MEP coordinators increasingly incorporating BIM-specific skills, there is a higher probability that independent BIM-specific roles may diminish or become integrated into the responsibilities of the project manager (Hosseini et al., 2018). Furthermore, in the work by P. Bosch-Sijtsema and Gluch , they examined the roles and activities of BIM participants, as well as the alterations and disruptions these introduce to conventional construction methods (P. Bosch-Sijtsema & Gluch, 2021). The inquiry asserted that BIM-specific professionals are consistently challenging and reshaping construction norms. These two studies distinctly demonstrated that BIM roles and their definitions will evolve swiftly over time, leading to corresponding changes in the construction industry's structure.

1.3.5.2 Potential framework for improving the relationship between team members

Obstacles linked to interpersonal relationships among team members, including issues such as a deficit of trust, stand out as one of the prominent hurdles within the team category. (Oraee et al., 2019). The practice of working in isolation, often referred to as 'silos' within a team, remains quite pervasive within the construction industry. It commonly originates from project participants hesitating to share their work with other disciplines during the initial stages, resulting in notably inefficient collaboration within the BIM-enabled projects (Akponeware & Adamu, 2017). As a potential remedy for this challenge, researchers suggested introducing open work in progress (OWIP) within the common data environment, as an alternative to the traditional work in progress (Akponeware & Adamu, 2017). Within the OWIP phase, all participating disciplines in the collaboration can securely access the design and offer feedback. Consequently, the enhanced security measures in this suggested framework mitigate designers' reservations about sharing their work with team members. This, in turn, contributes to the clash avoidance and fosters efficiency during the coordination phase of BIM collaboration.

1.4 Relationship between the obstacles and the prospective efficiency frameworks

This section provides a concise overview of contemporary literature, examines the primary obstacles in BIM-based coordination and proposes potential BIM efficiency frameworks to address these challenges. Additionally, it delineates the specific phase of BIM-based design coordination that is most influenced by each category of obstacles. Here a comprehensive synthesis of the findings is offered, establishing links between the prominent obstacles unveiled in the existing literature and potential efficiency-enhancing frameworks. The primary stages and workflow within the BIM-based design coordination process are also discussed, as described by the literature. Ultimately, the relationship between the identified challenges and suitable solution frameworks is explored in addition to their applicability in the various phases of BIM-based design coordination.

Figure 1.2 visually depicts the five distinct obstacle categories: process, actor, task, context, and team, along with the linkages connecting each obstacle category to its corresponding contemporary BIM efficiency frameworks.

Figure 1.3 provides an illustration of the fundamental key steps and workflow integral to BIM-based design coordination. This diagram has been formulated drawing insights from the research of (Pedo et al., 2021). The literature has pinpointed the following essential stages in the design coordination process: (i) define coordination strategy, (ii) generate specialty models, (iii) prepare federated model, (iv) perform interference check, (v) analyze detected issues, (vi) share federated model, (vii) organize coordination meetings, (viii) resolve detected issues, (ix) update and publish 3D model. Typically, following the design coordination meetings, team members representing various disciplines reach a consensus on the approach to rectify the identified clashes. Subsequently, the models undergo adjustments in accordance with the team's resolutions, and this cycle iterates until the defined criteria are met. The primary activities within the design coordination phase may vary depending on the initial coordination strategy and the BIM execution plan.

Figure 1.4 employs a color-coding scheme to designate obstacle categories and the corresponding suggested solution frameworks, indicating the specific stages within the timeline of the BIM design coordination phase where they exert the most significant influence. This visual representation underscores how the initial five phases of BIM-based design coordination are particularly impacted by the identified obstacles. Of these five stages, the first two phases are the ones most significantly and adversely influenced by the obstacles.

Process-related challenges primarily exercise their impact on the coordination strategy, model generation, and the clash detection phase. Actor-related obstacles influence both the initial and final stages of the design coordination process. Task-related obstacles primarily come into play during the individual model generation phase. Context-related challenges become more prominent in the later stages of coordination, where effective communication among team members is critical. Finally, Team-related impediments are most evident in the coordination strategy and the individual model generation phase, which also happen to be the initial steps of the coordination phase. Table 1.2 offers a comprehensive perspective on the intricate interplay between obstacle categories, proposed solution frameworks, and the corresponding stages of the design coordination process. This tabular presentation provides a detailed overview of the relationships among various elements, emphasizing the dynamic nature of the challenges encountered in each stage and the corresponding strategies proposed for resolution. Table 1.3 illustrates the relationship between obstacle categories and the proposed solution frameworks, which are categorized based on the stages of design coordination they are applicable to.

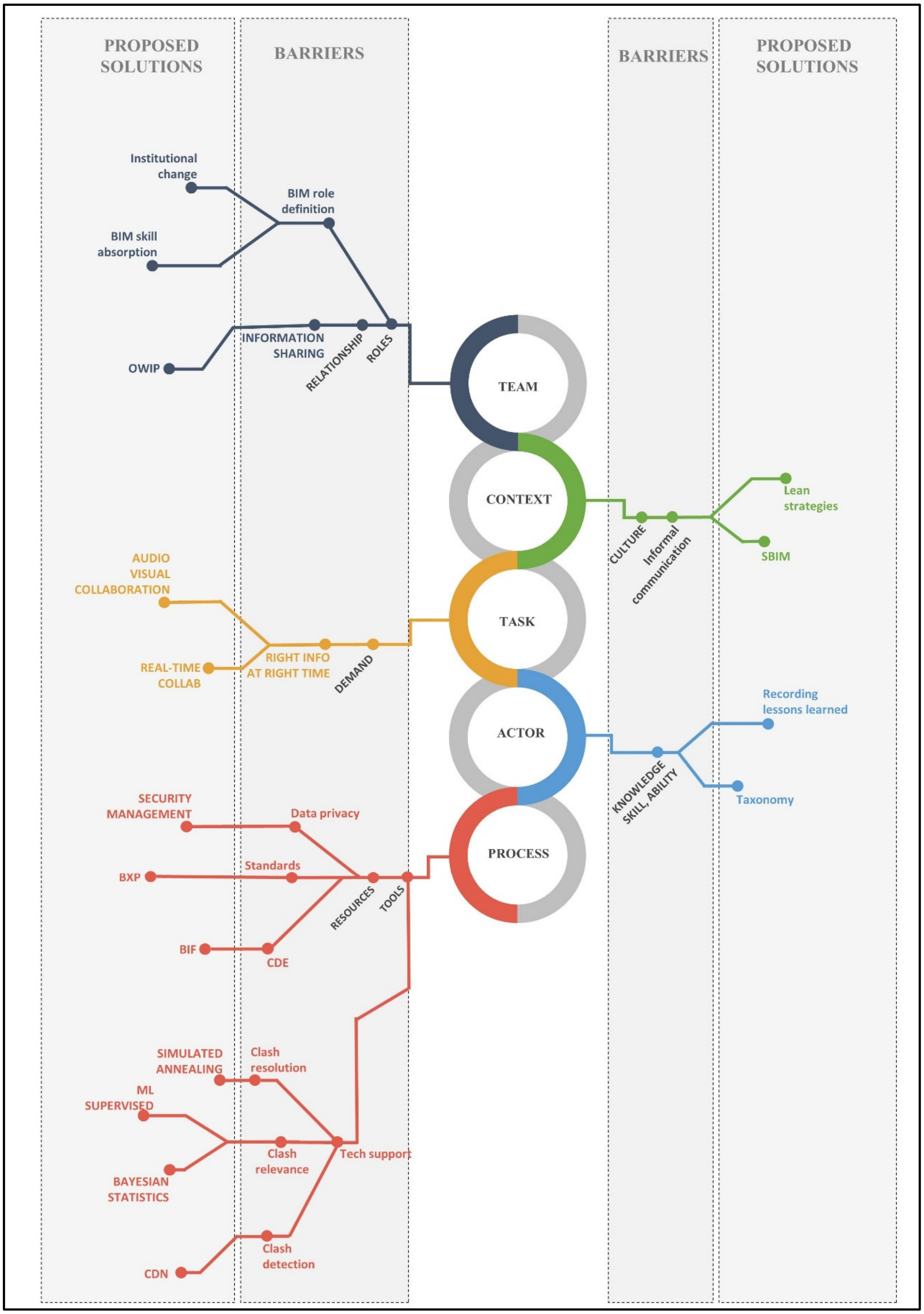

Figure 1.2 Obstacle categories and their connection to potential solution frameworks

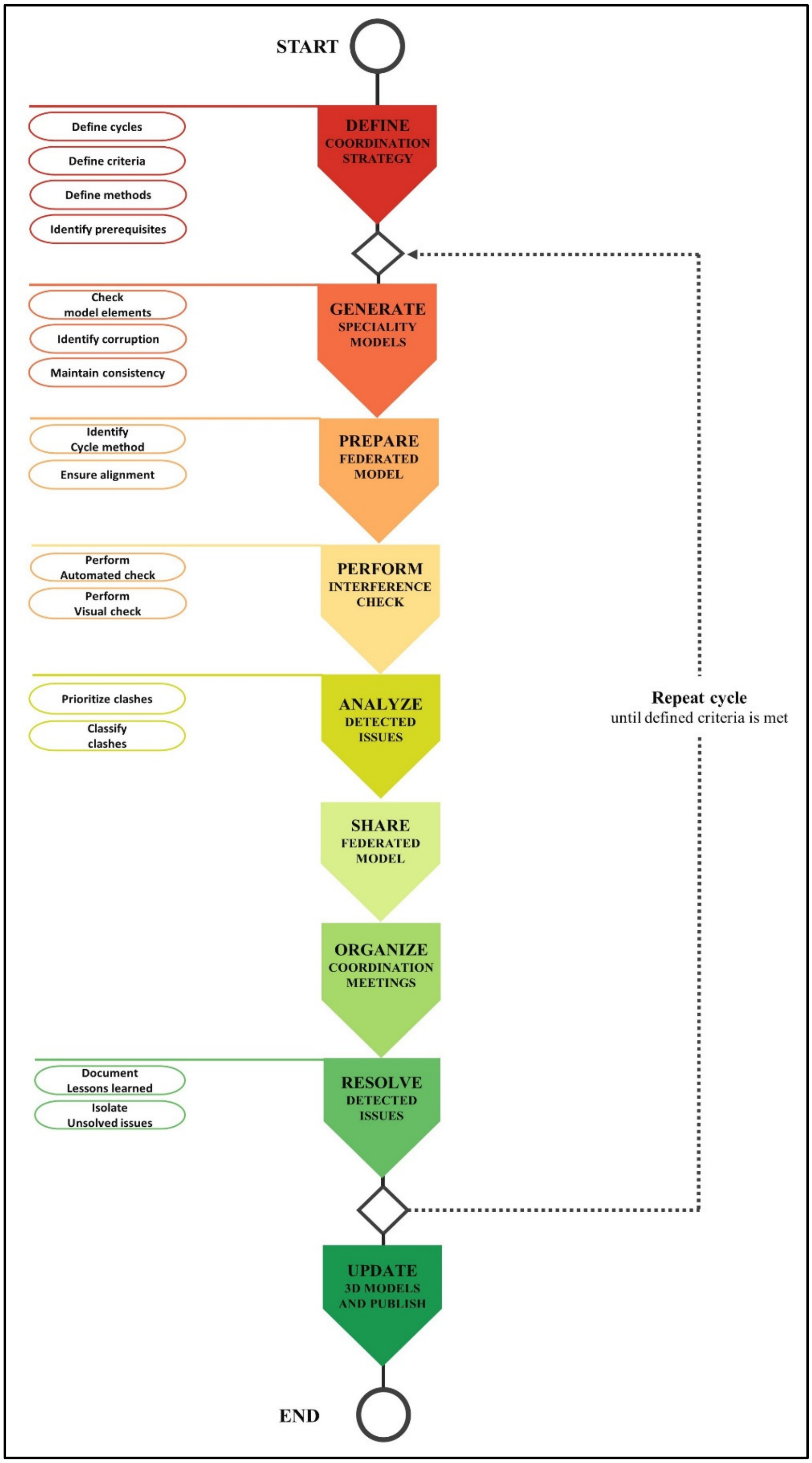

Figure 1.3 Key steps of BIM-based coordination
Taken from Pedo et al. (2021)

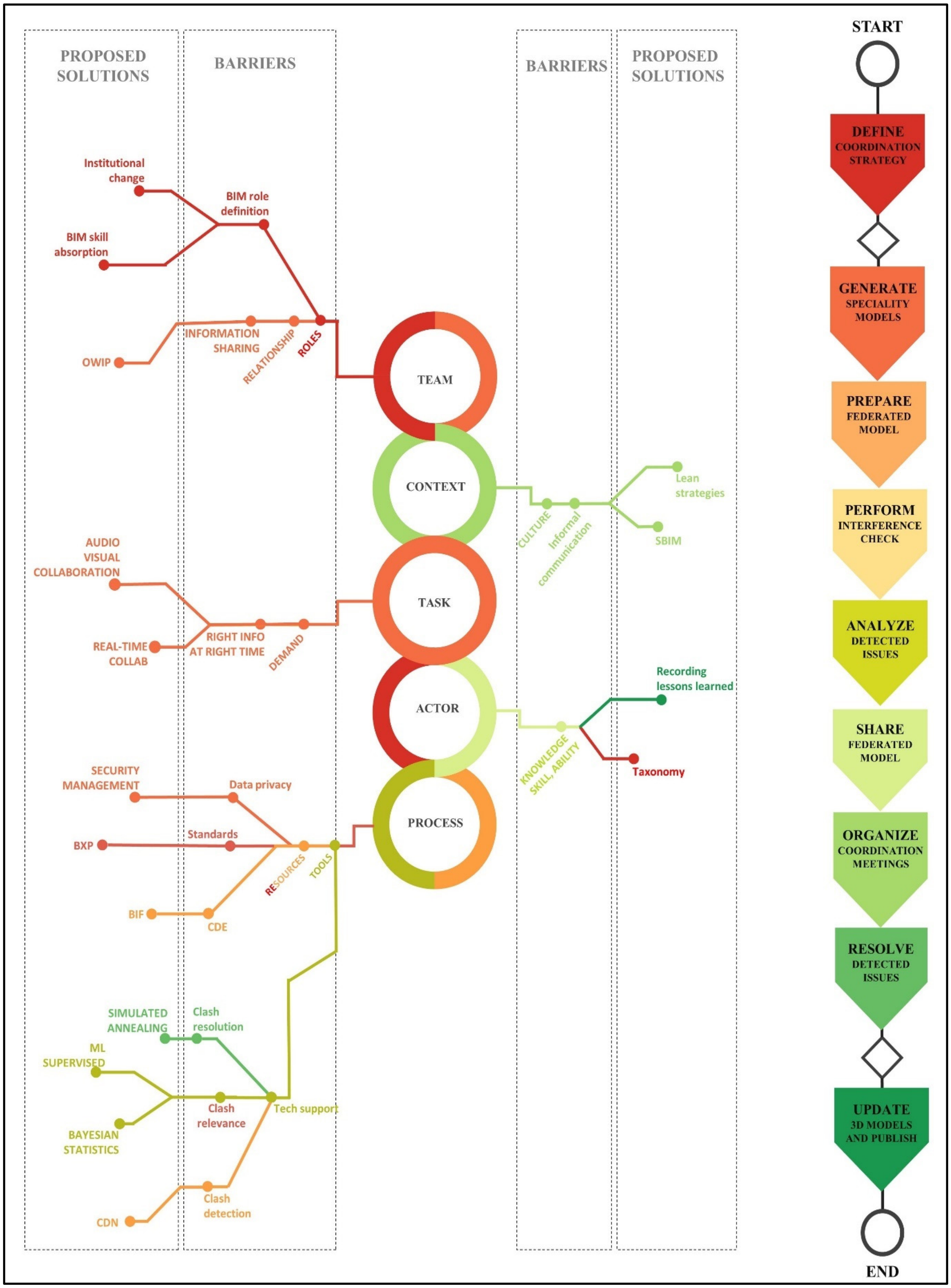

Figure 1.4 Connections between obstacles and steps of BIM coordination

Table 1.2 Interrelation between obstacles and BIM coordination steps

Obstacle category	Obstacle subcategory	Potential solution frameworks	Stage of design coordination
Process	Resources	BIM integration framework (BIF) for improved CDE	Prepare federated model
		BIM execution plan for standard maintenance	Define coordination strategy
		Security management And role-based access for data privacy	Generate speciality models
	Tools	Component dependent network (CDN) for clash detection	Perform interference check
		Supervised machine learning for clash relevance prediction	Analyze detected issues
		Bayesian statistics for clash relevance prediction	
		Simulated annealing algorithm for resolving clashes	Resolve detected issues
Actor	Knowledge, skills, ability	Taxonomy for a better understanding of coordination issues	Define coordination strategy
		Recording lessons learned	Update and publish 3D models
			Share federated model
Task	Demand of the right information at the right time	Real time collaboration	Generate speciality models
		Audio-visual collaboration	
Context	Informal communication outside BIM	Social BIM	Organize coordination meetings
		Applying Lean strategies To BIM process	
Team	Roles	BIM skill absorption by project manager	Define coordination strategy
		Institutional change to support new technology	
	Relationship	Open work in progress (OWIP) to encourage information sharing	Generate speciality models

Table 1.3 Impact of obstacles on BIM coordination steps

Timeline stage of design coordination	Potential solution strategies	Obstacle subcategory	Obstacle category
Define coordination strategy	BIM execution plan for standard maintenance.	Resources	Process
	Taxonomy for a better understanding of coordination issues.	Knowledge, skills, ability	Actor
	BIM skill acquisition by project manager.	Roles	Team
	Institutional change to support innovative technology.	Roles	Team
Generate specialty models	Security management and role-based access for data privacy.	Resources	Process
	Real-time collaboration.	Demanding the right information at the right time	Task
	Audio-visual collaboration.	Demanding the right information at the right time	Task
	Open work in progress (OWIP) to encourage information sharing.	Relationship	Team
Prepare federated model	BIM integration framework (BIF) for improved CDE.	Resources	Process
Perform interference check	Component-dependent network (CDN) for clash detection.	Tools	Process

Table 1.3 Impact of obstacles on BIM coordination steps (cont'd)

Timeline stage of design coordination	Potential solution strategies	Obstacle subcategory	Obstacle category
Analyze detected issues Publish federated model	Supervised machine learning for clash relevance prediction.	Tools	Process
	Bayesian statistics for clash relevance prediction.	Tools	Process
Share federated model	Recording lessons learned.	Knowledge, skills, ability	Actor
Organize coordination meetings	Social BIM framework.	Informal communication outside the BIM platform	Context
	Applying Lean strategies to BIM process.	Informal communication outside the BIM platform	Context
Resolve detected issues	Simulated annealing algorithm to resolve clashes.	Tools	Process
Update and publish 3D models	Recording lessons learned.	Knowledge, skills, ability	Actor

In summary, the work shown in this chapter affirms that the obstacles to BIM collaboration, as identified in numerous studies, primarily impact the early stages of BIM-based design coordination. When obstacles, particularly in the initial phases, manifest during specialty model generation and federated model creation, they can impede the overall efficiency of coordination and, by extension, influence the subsequent phases of the construction project. From the comprehensive analysis of the literature, it is evident that the primary impact of the identified obstacles is observed in the initial two phases of design coordination, namely the formulation of coordination strategy and the generation of specialty models. Among the five categories being considered, it's evident that team-related, task-related, and process-related hurdles have the most significant impact on these stages. They increase clashes between disciplines and lead to more design errors. Consequently, a comprehensive inquiry is imperative to address the obstacles that affect these critical stages of design coordination. Such an investigation will serve as a valuable resource for multidisciplinary BIM collaboration team members, aiding them in preventing clashes in BIM project coordination in the future.

This chapter undertook an extensive review of the existing literature to evaluate the current state of research, pinpoint prominent challenges, and delve into potential future directions within the pertinent subject area.

CHAPTER 2

CLASHES IN BIM PROJECTS

The second chapter revealed that the obstacles affecting the first two phases of design coordination predominantly stem from conflicts between the models of various trades or disciplines. The initial research objectives aim to pinpoint gaps in existing research related to clash management and proactive clash avoidance and to identify the most prominent causes of clashes in BIM-based multidisciplinary coordination. As a logical progression in any research aimed at proactively minimizing the occurrence of clashes it is important to understand what the causes of clash are. Thus, to satisfy the research objective, the next step is to gain a comprehensive understanding of the root causes of clashes within BIM models. Subsequently, it is essential to explore the clash avoidance strategies that researchers have already experimented with, holding promise for this purpose. This chapter explores the primary factors leading to clashes in BIM models, alongside a thorough examination of proactive clash avoidance strategies that researchers have thus far investigated.

2.1 Identifying causes of clashes

This section delves into a comprehensive discussion of the leading causes of clashes or conflicts in multidisciplinary coordination based on BIM, as substantiated by numerous scientific publications. In their 2012 study, Tommelein and Gholami introduced a classification for clashes, dividing them into three distinct types: i) Hard clashes: Involves physical conflicts demanding immediate resolution; ii) Soft clashes: Refers to less critical conflicts where components are closer than a certain distance to each other; iii) Time clashes: Which may be modeled as a clearance requirement (Tommelein & Gholami, 2012). This classification offers a concise framework for understanding and addressing clashes in construction and design coordination. Subsequently, in 2017, Akponeware and Adamu conducted a review to examine the factors that impact both hard and soft geometric clashes (Akponeware & Adamu, 2017). This research identified 12 clash drivers and emphasized the utmost importance of three factors: a shortage of BIM experts, designers working in isolation, and design errors

(Akponeware & Adamu, 2017). This study also highlighted additional significant causes, such as violations of design rules, diverse file format usage, and disparities in 3D modeling. Mehrbod et al. went on to identify design discrepancy, design errors, and missing items as the underlying factors responsible for issues in design coordination, design errors being the most prominent and most frequently appearing cause (Mehrbod, Staub-French, Mahyar, et al., 2019). In 2021, Elyano and Yuliastuti corroborated this finding with their own research which showed that design error were responsible for 52.36% of the detected clashes (Elyano & Yuliastuti, 2021). In the investigation performed by Elyano and Yuliastuti the detected clashes were mostly between structural and MEP discipline. In the same study, it was uncovered that design inconsistency and design discrepancy were responsible for 39.13% and 8.51% of detected clashes respectively, and these clashes were mostly between structural, MEP, and precast components (Elyano & Yuliastuti, 2021).

This thesis addresses the most prominent causes of clashes identified from contemporary literature via a coding classification while discussing potential clash avoidance strategies. The most frequent causes of clashes identified from the literature are: (i) lack of experts, (iii) designers working in isolation, (iii) design errors, (iv) failing of design rules, and (v) disparities in design and 3D models. Figure 2.1 highlights the causes of clashes in BIM-based multidisciplinary coordination.

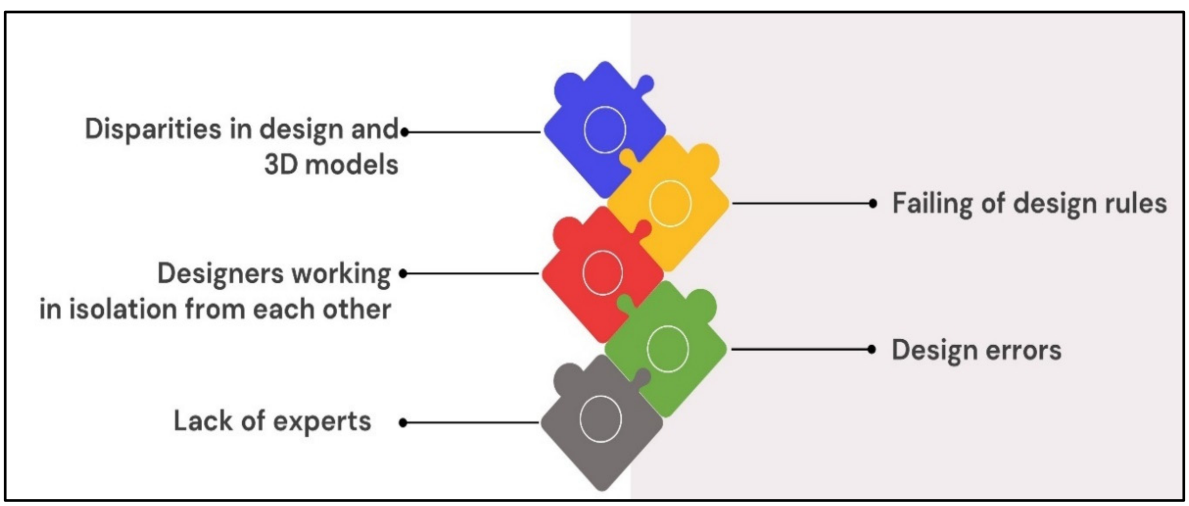

Figure 2.1 Causes of clashes in BIM-based multidisciplinary coordination

2.2 Potential clash avoidance strategies

Before venturing into the potential clash avoidance strategies, it is important to establish a definition for the term "clash avoidance".

In this research clash avoidance is identified as a proactive process where steps are taken to avoid spatial overlaps and semantic conflicts in BIM models. Clash Avoidance is exercised throughout the model construction process. Right from the first stage of designing to the last moment, techniques and strategies for clash avoidance can be implemented.

The Strategies that can help reduce the number of clashes in BIM-based coordination in light of the studied literature are discussed in this section.

2.2.1 Addressing the lack of experts

According to the research conducted by Akponeware and Adamu, a significant factor contributing to clashes in the BIM-based coordination process is the insufficient involvement of experts (Akponeware & Adamu, 2017). To enhance the BIM proficiency of individuals in the construction sector, numerous studies suggest incorporating education on BIM-based collaboration platforms and coordination processes into the training of students. Tayeh, Bademosi, and Issa further explained that the incorporation of BIM-based collaboration within the construction industry underscores the importance of integrating BIM-focused education into the curriculum of construction management and engineering training (Tayeh et al., 2019). This measure will not only elevate the skill levels of future professionals but also guarantee the establishment of effective communication and information exchange across construction projects, thus contributing to their success. The authors conducted research on the implementation of collaborative learning platforms in BIM education. They recorded student feedback, which highlighted remote real-time collaboration, the ease of resolving communication errors, and the availability of information in a single repository as among the foremost advantages of these platforms (Tayeh et al., 2019). Students also pointed out that these platforms have the capacity to notably expedite model coordination. As a result, the authors concluded that incorporating such exercises into the training period holds the potential to enhance the learning experience of future experts.

Furthermore, researchers underscored the importance of skill development programs, such as intensive training sessions or workplace workshops where seasoned professionals can impart their expertise (Evans & Farrell, 2020). These programs aim to elevate comprehension and knowledge levels concerning BIM. In conjunction with BIM training, another promising approach involves addressing team members' knowledge gaps related to coordination issues. Mehrbod et al. made an effort to establish a taxonomy of design coordination problems aimed at providing team members with an improved comprehension of these issues which was validated via industry professionals (Mehrbod, Staub-French, Mahyar, et al., 2019).

2.2.2 Solutions for designers working in isolation

Akponeware and Adamu identified that one of the fundamental reasons for clashes is the presence of workplace silos or designers operating in isolation (Akponeware & Adamu, 2017). Challenges in team dynamics, including issues such as a lack of trust and communication gaps among team members, may lead them to operate independently during the critical initial phases of the design process. To address this issue, the researchers suggested the introduction of an open-work-in-progress (OWIP) within the shared data environment, as an alternative to the conventional work-in-progress phase (Akponeware & Adamu, 2017). This would allow all collaborating disciplines secure access to the design and the opportunity to offer feedback. In order to enhance team communication, Adamu, Emmitt, and Soetanto introduced a social BIM framework and conducted testing involving four distinct collaboration protocols. These protocols varied in their levels of shared situational awareness within the team, ranging from low to high (Adamu, Emmitt & Soetanto, 2015). The protocol that facilitated the highest degree of shared situational awareness allowed team members to communicate with one another through the BIM platform, leading to improved efficiency (Adamu, Emmitt & Soetanto, 2015).

2.2.3 Addressing the occurrence of design errors

Design errors are widely acknowledged as one of the most common triggers for clashes. As elucidated by Lopez and Love, when an error occurs, an unexpected or random intervention occurs (Lopez & Love, 2012). They had earlier determined that the average direct and indirect costs associated with design errors were found to be 6.85% and 7.36% of the contract value, with errors causing schedule delays being the most detrimental (Lopez & Love, 2012). This discovery underscores that design errors significantly impede the efficiency of the construction process. Johansson et al. examined the influence of BIM in error prevention and concluded that despite the presence of knowledge about potential issues and their solutions within the organization, there is a lack of effective "matchmaking" between the two (Johansson et al., 2014). Wong et al. following their investigation into the correlation between BIM adoption and error reduction, identified design coordination as one of the most pivotal factors in reducing design errors (Wong et al., 2018). Previously, Al Hattab and Hamzeh evaluated the application of social network theory and simulation to compare traditional and BIM/Lean-based environments in the context of design error management (Al Hattab & Hamzeh, 2015). The researchers postulated that errors get resolved more rapidly within a BIM/Lean network due to individuals detecting and rectifying errors through frequent checks and effective communication. Additionally, Al Hattab and Hamzeh emphasized that, despite the advancements in BIM-based automated checking procedures, it remains crucial to address the fundamental causes of human-based errors for the reduction of design errors. They recommended that the team should thoroughly analyze the root causes, identify solutions, and document lessons learned when defects are detected, fostering a continuous learning mindset and instilling a quality-oriented approach (Al Hattab & Hamzeh, 2015).

2.2.4 Solutions to failing of design rules

Tommelein and Gholami delineated the absence of clear guidelines regarding the development of specialty systems in relation to others, with the aim of preventing overlapping spaces, as a failure in design rules. They pinpointed this as one of the primary underlying factors contributing to hard clashes (Tommelein & Gholami, 2012). In recent years, several researchers have been investigating various applications of artificial intelligence to address and mitigate such failures, which, in turn, have the potential to markedly reduce instances of hard clashes in the design process. For example, Song et al. delved into the realm of deep learning-based natural language processing (NLP) methods to convert design rule sentences into a computationally understandable data structure (Song et al., 2020). In this study, a deep learning model underwent training to extract the predicate-argument structure (PAS) from the sentences comprising building design rules. Subsequently, the trained models were employed in the process of interpreting these rules. As stated by Song et al. this approach possesses the capacity to broaden the applicability of BIM-enabled rule checking, particularly in cases where design requirements are articulated in natural language (Song et al., 2020).

2.2.5 Addressing disparities in design and 3D models

Akponeware and Adamu had pinpointed various factors contributing to clashes particularly related to discrepancies in the 3D modeling phase of BIM-based collaboration. These factors include the utilization of incorrect or insufficient levels of detail (LOD), design uncertainties, 3D model elements surpassing allowable clearance limits, and the reliance on 2D drawings instead of 3D models (Akponeware & Adamu, 2017). To address the challenge of low or incorrect Levels of Detail (LOD), the construction industry has adopted the use of LOD standards. Leading LOD matrices have been introduced by organizations such as the United States Army Corps of Engineers (USACE), the American Institute of Architects (AIA), and BIMForum. These matrices offer established standards that can be incorporated into the contract and the BIM execution plan as points of reference.

Regarding design uncertainties, Tommelein and Gholami further noted that designers' use of placeholders could potentially result in hard clashes with other systems or components when the precise component meant for that space remains uncertain (Tommelein & Gholami, 2012). Although contemporary literature doesn't explicitly tackle this matter, the continuous and open availability of communication channels among team members could potentially aid in mitigating such clashes. The cultivation of shared situational awareness within the team can provide visual access to early-stage models and enhance the quality of information exchange (Adamu, Emmitt & Soetanto, 2015). Furthermore, researchers also expressed concerns regarding soft clashes stemming from 3D objects surpassing acceptable clearance limits and components failing to maintain the required minimum clearance between one another (Tommelein & Gholami, 2012). Despite the ongoing challenges faced by certain BIM-based coordination tools in detecting soft clashes, researchers have explored various encouraging approaches in recent years. In their 2021 study, Mangal and colleagues examined the application of BIM in conjunction with a two-stage genetic algorithm (GA) to automate the optimization of steel reinforcements in reinforced concrete (RC) structures, ensuring that the clashes are reduced (Mangal et al., 2021). In this study, the initial stage of the genetic algorithm (GA) was dedicated to producing steel reinforcement layout designs that were devoid of clashes. Subsequently, the second stage of the GA was employed to optimize the dimensions of the steel reinforcement by exploring various diameter combinations and minimizing the overall consumption of steel. The researchers proposed that this same method could be tailored and applied to address similar design optimization challenges, such as optimizing the sizing of structural members (Mangal et al., 2021). Furthermore, researchers introduced an alternative approach to optimize rebar design using a hybrid metaheuristic algorithm in conjunction with BIM (Li et al., 2021). This approach involves the identification of tasks associated with rebar manufacturing and assembly, followed by the development of a multi-objective cost design formulation that takes into account design code requirements. Additionally, researchers suggested the utilization of a hybrid genetic algorithm combined with the Hooke and Jeeves method for both avoiding clashes and optimizing rebar placement (Li et al., 2021).

The last factor contributing to clashes that will be addressed in this study is the reliance on 2D drawings instead of 3D models. Akponeware and Adamu pointed out that requiring designers to conform to a 3D standard can indeed mitigate this problem. Nevertheless, this approach does not fully tackle the recurring design errors (Akponeware & Adamu, 2017). Modern researchers advocate the utilization of cloud-based BIM for facilitating real-time collaboration and seamless data exchange within project teams (Onungwa et al., 2021). This not only enhances efficiency but also diminishes the likelihood of design errors. Onungwa and colleagues carried out a case study on digital modeling, revealing seamless communication, real-time progress monitoring, and file visualization as a few of the advantages stemming from the use of cloud-based BIM technology (Onungwa et al., 2021). The researchers also delved into the most impactful BIM prospects and pinpointed the seamless and timely exchange of information among key project stakeholders through a BIM system as the most crucial factor for success (Mostafa et al., 2020). Bhonde et al. further suggested that integrating virtual reality with conventional drawings can be a viable strategy for enhancing the design's quality (Bhonde, 2019).

2.3 Future research direction

In this chapter it was possible to demonstrate that the primary sources of clashes predominantly arise during the initial stages of multidisciplinary coordination, specifically in the creation of specialty models and federated models. Researchers emphasize the importance of documenting lessons learned within the organization, so that team members can access the information in need and clashes can be avoided.

In conjunction with this discovery, substantial effort has been devoted to enhancing clash detection tools and investigating various methods to automate the clash resolution process. However, there is still no guideline or streamlined process for the documentation of lessons learned or its implementation which is the most integral part of clash avoidance. Thus, design teams still struggle with unwanted design errors and discrepancies which increase the number of clashes.

The discoveries made in this art of the thesis satisfies the first research objectives. It also suggests potential research pathways for establishing an efficient, standardized process for the proper documentation of lessons learned, and the subsequent utilization of these lessons and best practices during multidisciplinary coordination. This, in turn, aims to prevent undesired design errors and avoid clashes.

CHAPTER 3

RESEARCH METHODOLOGY

In the first and second chapters the research gaps in terms of insufficient clash management were identified and the significance of adequately documenting and applying the lessons learned, best practices or design rules acquired throughout each project had been recognized.

The present chapter is dedicated to the meticulous development of a methodology aimed at crafting a highly efficient proactive strategy for avoiding clashes, specifically tailored, and optimized for implementation within the contemporary landscape of the BIM-based construction process. This chapter seeks to satisfy the third research objective of this work which is to developing an effective methodology for crafting a proactive clash avoidance strategy.

Prior to looking into the depths of the research methodology, it is imperative to undertake a comprehensive examination of the research objectives and its goals. This preliminary step serves the purpose of not only refining the research methodology but also pinpointing potential directions for further exploration. Subsequently, a detailed exposition of the selected methodology and the solutions it yields will be presented. In the concluding section of this chapter, the data collection approach and the iterative validation methods employed in this research will be elucidated.

3.1 Research questions and objectives

After providing a concise overview of the problem statement and research objectives in the thesis introduction, the research endeavors to address the following fundamental research inquiry:

Research Question (RQ): How can an integrated system for BIM authoring tools be developed to enable the proactive application of proven knowledge, lessons learned, best practices, and design rules to promote clash avoidance in a BIM-enabled project?

To address this research question, this work investigated the existing body of knowledge to understand the importance of lessons learned for increasing the efficiency of BIM coordination process. A framework was created to understand the impact of known obstacles on different stages of the BIM coordination process which is shown in chapter 1. The causes of hard, soft and time clashes were also explored in chapter 2 to understand the approaches contemporary investigators has studied which has the potential to reduce the number of clashes in federated BIM models.

Drawing from the insights gleaned through the extensive background studies conducted in this research, the study's objectives can be summarized as follows:

Research Objective 01 (RO 01): Identification of research gaps in clash management and proactive clash avoidance within the context of BIM-based multidisciplinary coordination.
Research Objective 02 (RO 02): Identification and assessment of key obstacles and causes of clashes impacting BIM-based multidisciplinary coordination:
Research Objective 03 (RO 03): Development of an effective methodology for crafting a proactive clash avoidance strategy.
Research Objective 04 (RO 04): Identification and codification of design rules and best practices acquired from BIM experts for clash prevention.
Research Objective 05 (RO 05): Proposal of an integrated system for BIM authoring tools, aiding adherence to design rules and best practices.

3.2 The Design Science Research methodology

This research adopted Design Science Research (DSR) as the research methodology for this thesis due to its inherent suitability for addressing complex, practical challenges in the field.

The decision to adopt DSR stems from its distinct focus on generating innovative and tangible artifacts that can provide realistic and efficient solutions to real-world problems. In the context of this thesis, which endeavors to enhance the application of clash avoidance rules and strategies within the construction industry, the adoption of Design Science Research (DSR) provides a systematic and iterative framework. This approach facilitates the design, development, and evaluation of artifacts precisely tailored to the industry's unique requirements. Importantly, Design Science Research not only ensures the creation of practical solutions but also plays a vital role in disseminating these innovations to industry practitioners, fostering widespread adoption and contributing to the overall advancement of industry practices. By embracing this methodology, the thesis aspires to effectively bridge the divide between academic research and practical industry application, presenting a comprehensive strategy for tackling critical challenges, notably proactive clash management in the construction sector.

Peffers et al. concluded that the design of the conceptual process of DSR meets the following objectives: i) provide a nominal process for the conduct of Design Science Research, (ii) build upon prior literature about Design Science in Information System (IS) and reference disciplines, and (iii) provide researchers with a mental model or template for a structure for research outputs (Peffers et al., 2007). This group of researchers synthesised a process model consisting of six activities in a nominal sequence via which the DSR methodology can be efficiently practiced (Peffers et al., 2007). These activities are briefly described in Table 3.1.

Design Science Research (DSR) can be succinctly summarized as a problem-driven research methodology, systematically navigating through the phases of problem identification, artifact creation, and rigorous evaluation. This approach is marked by its pragmatic orientation, emphasizing the development of innovative and effective solutions tailored to address tangible challenges in the real world. Notably, DSR doesn't solely focus on practical outcomes; it also serves the dual purpose of contributing valuable insights to the academic understanding of the specific domain under investigation. This synthesis of practicality and academic rigor positions DSR as a versatile and impactful methodology within the broader research spectrum.

Table 3.1 Activities within the DSR methodology
Adapted from Peffers et al. (2007)

Activity	Brief description
Problem identification and motivation.	Define the research issue and provide a rationale for the significance of finding a solution.
Define the objectives of a solution	Deduce the objectives of a solution based on the problem description and what can be realistically achieved.
Design and development	Create the artifact. A design science research artifact can be any designed item that incorporates a research contribution within the design.
Demonstration	Show how the artifact is employed to address one or more examples of the problem.
Evaluation	Observe and assess how effectively the artifact aids in resolving the problem.
Communication	Share the problem's significance, the artifact, its usefulness and innovation, the thoroughness of its design, and its efficiency with researchers and other relevant audiences, as applicable, such as professionals in the field.

3.3 Implementation of the DSR methodology

Based on the analysis of Peffers et al. (2007), the activities of DSR can be distilled in three main stages to implement it in the context of proposing an effective solution to avoid clashes in BIM coordination process. These stages and their implementation parallels in this work are summarized below. Furthermore, following the exposition of parallel activities, this section outlines the methodological steps adopted for the development of a pragmatic solution geared towards the prevention of clashes.

3.3.1 Problem identification and formulation:

Activities:

i) The first step in DSR is to identify and define a specific problem or challenge that needs to be addressed in a practical domain. This problem should be well-understood and relevant to the field of study.

ii) Researchers work closely with domain experts, practitioners, or stakeholders to gain a deep understanding of the problem, its context, and the requirements for a potential solution.

Implementation:

An extensive examination of the existing literature underscores a crucial point – the significance of documenting lessons learned in the context of BIM-based multidisciplinary coordination is well-established. However, a noticeable gap becomes apparent when considering the practical application within the construction industry. Despite the acknowledged importance of this practice, a conspicuous deficiency exists: a lack of a streamlined and effective framework that would enable the seamless integration of these insights into actual design development and construction processes. This void in the current state of affairs accentuates the need for the development of an efficient framework that can translate the recognized value of lessons learned into tangible improvements in the field.

A substantial research void that emerges prominently from the comprehensive background analysis pertains to the absence of a proactive approach when it comes to clash avoidance. Historically, research efforts have predominantly concentrated on the creation of tools and methodologies for the identification and subsequent resolution of clashes in BIM-enabled construction projects. Notably, various ongoing investigations aim to automate the processes of clash detection and resolution. However, it is evident that this emphasis has not been mirrored in the context of clash avoidance. The academic and practical focus on the proactive prevention of clashes, prior to their occurrence, is notably underrepresented. This research gap underscores the critical need for a more robust and balanced approach, one that places equal weight on preventive clash avoidance as it does on post-detection resolution.

This underscores a significant revelation: the utilization of lessons learned, best practices or design rules during the early phases of BIM coordination, notably in shaping the coordination strategy and generating the specialized models (including architectural, structural, and MEP models), holds a well-defined challenge. This challenge pertains to the proactive avoidance of clashes, a problem that necessitates a solution rooted in practical artifacts originating from the DSR methodology. In essence, there exists a compelling need to harness the knowledge gained from prior industry experiences and apply it purposefully to enhance the efficiency and effectiveness of clash prevention strategies during the foundational phases of BIM coordination.

In the Design Science Research framework, the phase involving collaboration with domain experts, practitioners, and stakeholders is pivotal, particularly after defining the research problem and recognizing gaps in existing knowledge. This collaborative step is instrumental in gaining an in-depth understanding of the problem's context, complexities, and practical nuances. It aligns the research with the real-world intricacies of the domain, refines the problem definition, identifies specific solution requirements, and leverages the valuable insights and experience of experts and stakeholders. In essence, this collaboration enhances the research's practical relevance, bridging the gap between theory and application.

As a parallel activity in this research, a concurrent effort was made to engage with a diverse panel of experienced industry professionals, encompassing engineers, architects, and BIM specialists. This engagement aimed to validate the insights derived from the literature review and background study while delving deeper into the research gap and the prevailing problem. This assembly of industry experts played a pivotal role in offering an encompassing perspective on the most effective best practices and valuable lessons learned. These insights are poised to be of paramount significance, particularly when it comes to the proactive avoidance of clashes in the early phases of BIM coordination. Their combined expertise gave us a thorough grasp of the strategies and methods with the most promise for practical success in the early phases of BIM coordination.

3.3.2 Artifact design, development, and evaluation:

Activities:

i) In this step, researchers create an artifact or solution that aims to solve the identified problem. This artifact can take various forms, such as software applications, algorithms, conceptual frameworks, or even physical devices.

ii) The development process is often iterative, involving multiple cycles of design and refinement. Researchers apply their expertise and relevant theories to design the artifact.

iii) Rigorous evaluation methods are employed to assess the effectiveness of the artifact. The evaluation provides evidence of how well the artifact addresses the problem and whether it meets the specified requirements.

Implementation:

The initial phase of this stage entails designing an artifact specifically tailored to address the identified problem. This artifact draws upon the knowledge and insights gathered from the experts during the preceding stage. In alignment with this context, this research embarks on the development of a comprehensive ontology. This ontology serves as the foundation for an automated system aimed at proactively avoiding clashes. It operates on the principles and rules derived from the wealth of insights provided by industry experts specializing in BIM-enabled construction. This system is designed to offer an advanced solution for clash avoidance, effectively applying the wisdom and practical knowledge garnered from these BIM professionals.

Subsequently, the research proceeded to formulate the overarching conceptual model for the system's user interface. This framework serves as the blueprint for how the finalized system will engage with the team members, including the BIM manager, BIM coordinator, and designers. The intent is to delve into the intricacies of how this communication and interaction will be meticulously orchestrated and delineated within the system, aligning it closely with the roles and responsibilities of each team member. Next, the research advanced to the implementation phase, encompassing the development of the artifact. This phase involved the creation of pseudocode to underpin the system's logic and to construct the tutorial section dedicated to clash avoidance. It is worth noting that the system has been designed as a plugin meticulously integrated with the BIM authoring platform, aligning it seamlessly with the existing workflows and operations within this platform. This procedure unfolds as an iterative journey, requiring multiple rounds of refinement and calibration. This iterative process necessitated thorough adjustment, fine-tuning, and calibration with a specific set of rules, systematically evolving the initial artifact. The primary objective of these iterations was to establish an initial artifact with basic functionalities which can assist the designer to implement the best practices or design rules during their work session. This basic artifact was specifically designed to assess the effectiveness of the devised strategy in practice.

In the culminating phase of this comprehensive design, development, and evaluation process, the effectiveness of the created artifact was subjected to a rigorous assessment. This evaluation was carried out through a multifaceted approach, which included soliciting feedback from industry experts via focused group sessions and, crucially, by putting the artifact into practical use within a real-world project context. This thorough evaluation process served the purpose of not only validating the artifact's capabilities but also ascertaining its proficiency in addressing the very problem that motivated this endeavor in the first place.

3.3.3 Communication and knowledge transfer:

Activities:

i) The final stage involves communicating the results and outcomes of the DSR process. Researchers document their work, detailing the design and development of the artifact, as well as the results of the evaluation.

ii) Findings are typically published in academic journals, conference papers, or reports to share knowledge with the research community.

iii) The artifact and its associated knowledge may be disseminated to practitioners and industry stakeholders to facilitate its adoption in real-world settings.

Implementation:

As the first step of the communication and knowledge transfer stage of DSR, this work thoroughly documents the research findings, including the design artifact, its functionality, and any critical insights or lessons learned during the development process. The findings from the first stages of the DSR (background studies, problem identification, and formulation) were published on CSCE 2022, and CCC 2022 conferences. The developed conceptual framework on the artifact and the development of the research methodology was published on CSCE 2023 conference. The artifact design, and development stages and the complete conceptual framework were presented in Symposium *Innover Ensemble* 2022 and 2023. Future endeavors will involve efforts to disseminate the comprehensive research findings, encompassing all aspects of artifact development, evaluation stages, and the achieved results of this work. This dissemination will extend to prominent academic journals and international conferences, thereby contributing to the broader scholarly and professional discourse in the field.

3.3.4 Developed methodology for clash avoidance

A comprehensive schematic representation of the clash avoidance methodology, as aligned with the principles of the Design Science Research methodology, is illustrated in Figure 3.1.

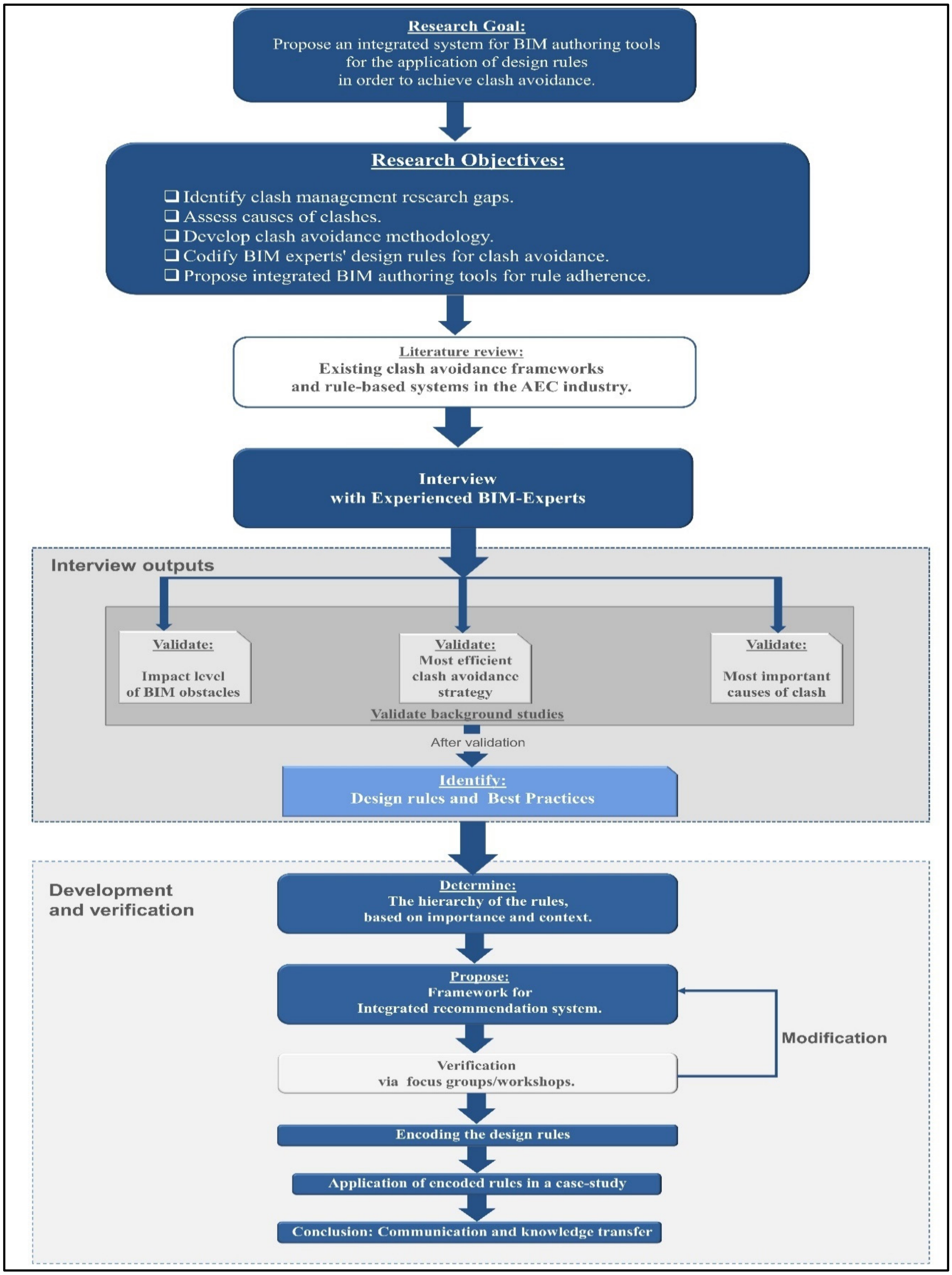

Figure 3.1 Comprehensive schematic representation of the research methodology

3.3.4.1 Goal and objectives:

Clash avoidance is fundamentally a proactive strategy that can be effectively employed at various stages throughout the modeling process using Building Information Modeling (BIM) authoring tools. The primary goal of establishing a clash avoidance approach is to develop a cohesive system that seamlessly integrates industry best practices, design rules, and the knowledge gained from previous experiences to proactively minimize clashes. This system aims at actively supporting and guiding designers in the implementation of these rules and best practices as they progress through the modeling process. In essence, it is intended to serve as a valuable tool for designers, helping them navigate the modeling process with a focus on reducing clashes and enhancing overall design quality.

3.3.4.2 Literature review:

Previously extensive studies regarding the causes of clashes, clash avoidance strategies and rule-based design optimization approaches have been studied for this work. The findings from this review were explained in chapter 1 and 2 respectively. In the realm of studies investigating the utilization of rule-based systems for design and code compliance optimization, Vaidyanathan et al. present an innovative approach. Their method enables the generation of building system designs and engineering solutions guided by functional rules, ultimately resulting in designs characterized by minimal clashes and coordination issues (Vaidyanathan et al., 2015). In a separate study, Sydora and Stroulia introduce a straightforward domain-specific language designed to computationally represent interior design rules. They also outline a method for assessing the compliance of these rules with BIM models (Sydora & Stroulia, 2020). Ismail et al. in their research, assert that the key challenge in automatic compliance systems lies not in the development of new approaches but rather in the art of selecting and seamlessly integrating existing techniques (Ismail et al., 2017). The literature review conducted in this research indicates that the most fitting methodology for proactive clash avoidance is Design Science Research (DSR). This choice stems from the necessity for the active implementation of functional rules and best practices that are validated by industry experts during the creation of the BIM management plan and BIM model.

3.3.4.3 Interview with experienced BIM experts:

The upcoming phase of this project places a significant emphasis on gathering validation for the findings accumulated in this work thus far, drawing upon the insights and expertise of seasoned industry professionals. It is worth noting that the construction industry has witnessed a rapid evolution in BIM adoption and its associated practices over recent years. Many theories and strategies that once held promise may no longer be as relevant in the current state of the industry. Therefore, this phase becomes of high importance as it seeks to assess the real-world applicability of the conclusions derived from our earlier research endeavors.

Furthermore, this stage serves as a safeguard to ensure that any clash avoidance approach rooted in the foundations of the prior work is not only effective but optimally impactful. It is, in essence, a crucial checkpoint to align this research outcomes with the dynamic landscape of the construction industry and to guarantee that this endeavor continues to address contemporary challenges and needs. This phase will de discussed in detail in the following chapter.

3.3.4.4 Interview outputs:

The data collected from the interviews validated the findings of the background study. The outputs of the interview also determined the actual impact level of the identified BIM obstacles shown in chapter 1. Moreover, the results also identified the primary causes of clashes and the most effective clash avoidance strategy, considering the causes and strategies outlined in chapter 2 within the current state of the construction industry. During the interview individual participants provided their subjective ratings of the impact of BIM obstacles and causes of clash in addition to the efficacy of existing clash avoidance strategies. Once the background studies are validated the design rules and best practices to be followed during the modeling phase were also collected from the same BIM experts.

3.3.4.5 Development and verification:

Once the design rules and best practices are collected from the BIM experts, the hierarchy of the rules were determined based on the design context and importance. During the interview, the experts provided a preliminary idea about the importance of each rule they mentioned. This score will be used to filter the rules and to determine their hierarchy based on the type of building and the building system they apply to. Based on the selected rules the framework for the integrated recommendation system was designed. Following this framework, the development of the clash avoidance ontology ensued to enhance comprehension of the knowledge transmission process. Conclusively, a set of sample rules was chosen to construct a prototype incorporating various functionalities derived from the proposed framework. This prototype is poised for real-life case study testing to assess the efficacy of the proposed solution in facilitating clash avoidance.

CHAPTER 4

INTERVIEW WITH BIM EXPERTS

Within this chapter, the multifaceted activities entailing collaboration with industry experts in the context of the research's problem statement is comprehensively explored. This collaborative effort seeks to satisfy the fourth research objective of identifying and codifying design rules and best practices from industry experts for clash avoidance. This process engages closely with domain experts, experienced practitioners, and vested stakeholders, and holds paramount significance. Its primary aim is to foster a profound and holistic comprehension of the problem at hand, its intricate context, and the nuanced requirements that underpin the development of a prospective solution or artifact for proactive clash avoidance.

This collaborative engagement stands as an indispensable cornerstone of the research methodology for this endeavor. By actively involving industry experts, their wealth of knowledge and real-world insights is tapped, which, in turn, will greatly inform and enrich the understanding of the problem domain in question. It not only ensures that this research remains deeply rooted in practical relevance but also enhances the potential for crafting a highly effective and context-aware solution to the challenge of proactive clash avoidance.

4.1 Interview method

Previously, researchers have conducted thorough explorations of different categories of qualitative interview designs for rich data collection. These categories are: i) informal conversational interview, ii) general interview guide approach, and iii) standardized open ended interviews (Turner III, Hagstrom-Schmidt, 2022). A brief introduction for these three categories of interview design in light of the authors investigation is provided in Table 4.1.

Table 4.1 Categories of qualitative interview design
Taken from Turner III, Hagstrom-Schmidt (2022)

Category of qualitative interview design	Description
Informal Conversational Interview	• Characterized by spontaneous generation of questions in a natural interaction. • Questions come from 'in moment experiences' as a mean to further understand the context. • Questions are not designed beforehand and are constructed as the conversation moves forward. • Viewed as unreliable for its flexible nature and difficulty of data coding.
General Interview Guide Approach	• Characterized by a more structured approach than the informal interview. • Inconsistency in posing research questions may lead to researchers interchanging their approach. • Researcher may ask follow-up or probing questions based on the participant's responses to pre-constructed questions.
Standardized Open-Ended Interviews	• Characterized by extremely structured wording of the questions. • Participants are asked identical questions, but the wording is such that the responses are open ended. • Allows the participants to contribute as much detailed information as they desire.

The engagement and collaboration with the industry experts is done in the form of standardized open-ended interviews from which qualitative data is extracted to fulfill the goals of this collaboration.

A standardized open-ended interview design is well-suited for achieving these collaboration goals due to several advantages such as the in-depth insights as open-ended questions enable experts to provide detailed and comprehensive responses. This depth is crucial for identifying obstacles, promising strategies, and recommended rules in BIM coordination. Experts can share their experiences and perspectives more freely, leading to richer insights. Additionally, the structured flexibility ensures that the researcher can probe further based on the expert's response without deviating from the structured framework. This method enables a contextual and holistic understanding of industry-specific challenges and generates qualitative data that is rich in insights, making it well-suited for exploring nuances and subjective views.

4.2 Steps of the standardized open-ended interview process

This section described the steps of the standardized open-ended interview process which in essence is a semi-structured process in the light of the works of Kallio et al. (Kallio et al., 2016). Figure 4.1 shows the steps of the interview design and data collection process. In this thesis the following steps to design this interview and data collection process were applied: i) Identifying the goals of the interview process, ii) Formulating the preliminary semi-structured interview questionnaire, iii) Pilot testing of the interview questionnaire, iv) Selecting the participants, v) Conducting the interviews and data transcription, vi) Coding the responses, and vii) Validating the collected design rules and best practices.

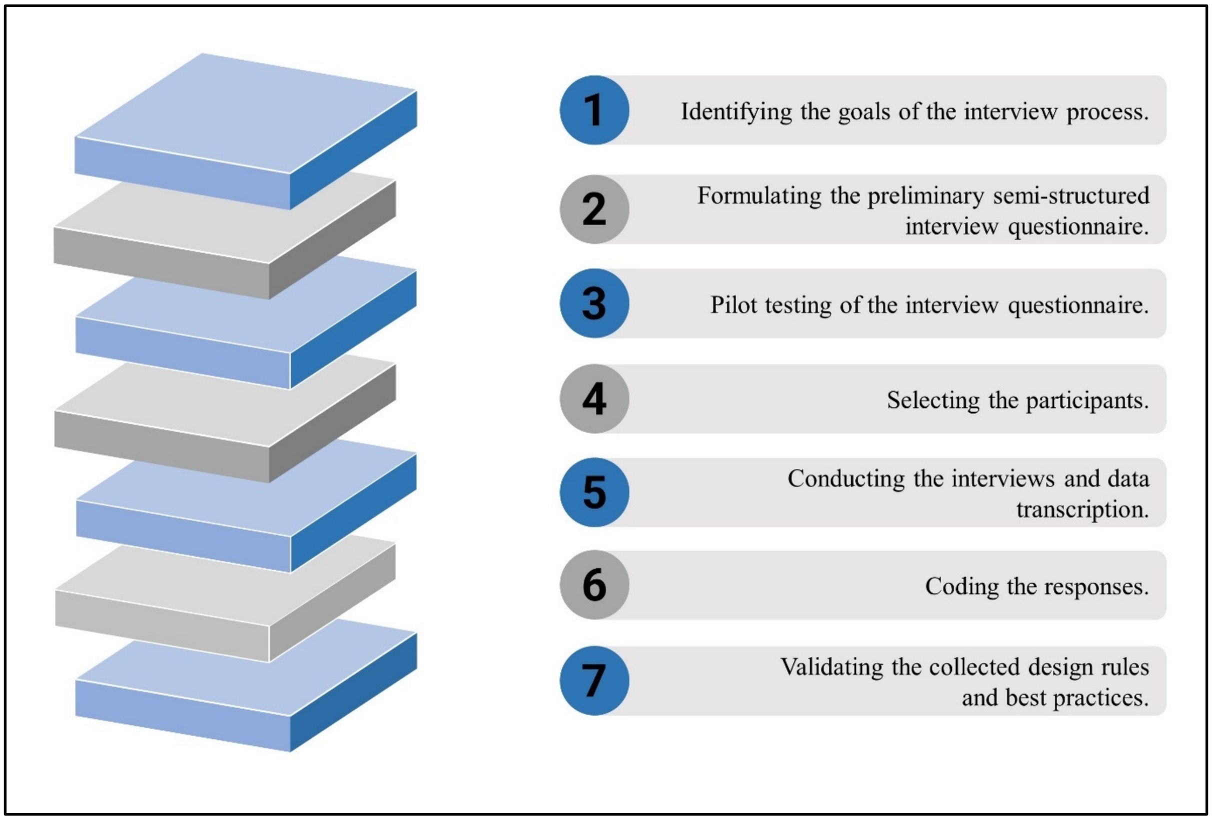

Figure 4.1 Steps of the interview design and data collection process

4.2.1 Identifying the goals of the interview process

Identifying the goals of this interview process is the first step of the interview design as shown in figure 4.1. Clearly outlining the specific goals and the main topics or themes one intends to explore in the interviews will guide the development of the questionnaire. The goals of this collaboration via interviewing industry experts are as follows: i) identify the most important obstacles in BIM coordination with the help of the expert's opinion, ii) identify which clash avoidance strategies the experts deem more promising or necessary for contemporary industry state, and iii) identify which rules and best practices the professionals recommend for model creation to avoid clashes. The following sub-sections will delve deeper into the next stages of the process. The goals of this interview process are derived from the frouth research objective of this thesis which seeks to identify and codify design rules for clash avoidance with the help of industry professionals.

4.2.2 Formulating the preliminary semi-structured interview questionnaire

The objective of this phase was to create an interview guide, comprising a well-structured set of questions designed to facilitate the collection of interview data (Kallio et al., 2016). This guide was formulated based on prior expertise in constructing questions that are both methodically sound and logically cohesive. To maximize the richness of the data collected, it is imperative that the questions in the interview guide are meticulously crafted. These questions should be participant-centric, devoid of any leading or biased elements, possess crystal-clear wording, and focus on single facets of inquiry (Kallio et al., 2016). According to Kallio et al., this kind of questionnaire incorporates a two-tiered approach to questioning, comprising main themes and follow-up questions (Kallio et al., 2016). The main themes serve as the foundational pillars, encapsulating the essence of the research's core subject matter. This structuring not only guides the inquiry process but also cultivates an inclusive environment, encouraging participants to freely express their unique perspectives and share valuable experiences. This deliberate approach ensures that the research not only captures diverse insights but also fosters open and meaningful dialogue between the researcher and the participants.

The questionnaire for this interview was formulated according to the guidelines provided by prior works (Kallio et al., 2016 ; Turner III, Hagstrom-Schmidt, 2022). Within the semi-structured questionnaire, four primary sections of questions were meticulously crafted, with the purpose of effectively fulfilling the objectives outlined in subsection 4.2.1.

Table 4.2 provides a comprehensive overview of the various questionnaire sections, offering insights into the specific objectives associated with each section. Furthermore, it details the precise allocation of the number of questions for each section, providing a structured and informative framework for the research study. In conjunction with Table 4.2, Table 4.3 enriches the understanding by presenting a selection of sample questions derived from each section of the questionnaire. This additional table not only offers a glimpse into the types of inquiries posed but also outlines the response options available.

Table 4.2 The questionnaire sections and corresponding goals

Questionnaire section	Corresponding goal	Number of questions
Introduction	Ice-breaking ; establishing expertise and experience ; establishing a level of BIM-awareness	**11**
Validate the BIM-coordination obstacles	Identify the most important obstacles in BIM coordination with the help of the expert's opinion	**24**
Validate the clash avoidance strategies	Identify which clash avoidance strategies the experts deem more promising or necessary	**2**
Insights on design rules or best practices for clash avoidance	Identify which rules and best practices the professionals recommend for model creation to avoid hard clashes	**3**

Table 4.3 Sample questions and response options

Questionnaire section	Sample questions	Response choices
Introduction	1. Did you receive any BIM-related training during your formal education before being involved in BIM projects? 2. If you have received BIM-related training during your service, please explain the focus of your training briefly. 3. How do you define your job responsibilities in the BIM coordination process?	Short open ended answer ; Multiple response
Validate the BIM-coordination obstacles	Please rate the following obstacles in BIM coordination based on importance. (Very Important – Important – Moderately Important – Slightly Important – Not Important) 1. Difficulties in sharing information, models, and folders across multiple platforms. 2. Not having a proper standard for BIM collaboration or coordination (National and organizational). 3. Concerns with data security and privacy among the team members. 4. Team members not having visual access to Work-in-Progress files (Verbal explanation and examples will be provided).	Rating the options according to the scale; Follow-up question with open ended answer to explain their choices.
Validate the clash avoidance strategies	Researchers have identified that the following strategies might be helpful in significantly reducing the number of multidisciplinary clashes. (Rate on the scale specified below.) Strongly disagree — Disagree – Slightly disagree – Slightly agree – Agree - Strongly agree ** The strategies devised via previous investigations are specified with this question.	Rating the options according to the scale; Follow-up question with open ended answer to explain their choices.
Insights on design rules or best practices for clash avoidance	Based on your experience, recommend three technical design rules or steps or best practices to follow while creating MEP specialty models so clashes can be avoided as much as possible. Please rank the three rules from ‘Most Important’ to ‘Least Important'.	Short open ended answer ; Ranking the rules based on importance.

This study adopts two different methods for qualitative data collection and the initial phase consisted of an interview which utilized the first phase questionnaire comprising 40 questions. The scheduled interview duration for the initial phase was a minimum of 45 minutes.
The second phase of the qualitative data collection was focused entirely on validating the collected design rules or best practices from the industry professionals during the first phase. This phase will be described in the last step of the designed interview process.

4.2.3 Pilot testing of the interview questionnaire

Conducting a pilot test with a small group to refine the designed questions and make sure they are effectively eliciting the information needed is the next step of this process. Recognizing the potential need for question reformulation and assessing its practical application, testing the interview guide allowed for informed modifications and refinements to the interview queries. The pilot testing stage for the designed interviews was conducted with three students from *École de technologie supérieure*, each with varying experience levels in working on BIM-enabled projects. The students have 3, 5, and 6 years of experience respectively in working on BIM-enabled projects. The informed consent from each participant was collected, explaining the purpose of the pilot test, and ensuring their voluntary participation. The interview sessions with each of the three participants were arranged separately. The sessions were virtual and conducted via Microsoft Teams. During these interviews, the initial set of questions were used to gather their responses. Afterwards, the participants were encouraged to provide feedback on the clarity and effectiveness of the questions. Feedback was requested about their experience with the questions. They were asked about any difficulties they encountered, whether the questions prompted detailed responses, and if they felt comfortable sharing their experiences. Based on the feedback and analysis of the responses, the interview questions were revised to enhance clarity, depth, and effectiveness. For this questionnaire, the word and tone of the questions were reviewed. Once the interview questions have been refined, they were finalized for the main data collection stage.

4.2.4 Selecting the participants

In the initial phase of the interview process, a targeted approach was employed to select participants who possessed relevant knowledge and experience aligned with the research objectives outlined in chapter 3. This method of participant selection was known as purposive sampling, allowing for the intentional inclusion of individuals who could offer diverse perspectives within the architecture, engineering, and construction (AEC) industry.

The study aimed to engage AEC professionals from a variety of architectural firms, engineering consulting firms, and construction companies across North America and Europe. The criteria for participant eligibility were carefully defined, requiring a minimum of five years of experience in the AEC industry, with a focus on the execution of BIM-enabled projects of varying scales. Potential participants were chosen according to their professional background and level of expertise. The recruitment process involved reaching out to potential participants through email and recommendations. The initial communication not only provided a clear overview of the study's objectives but also sought their consent for participation. Emphasis was placed on maintaining transparency regarding the research goals and the potential benefits of their involvement. During the initial outreach, the study's objectives were clarified, and their involvement was sought, along with their consent. To ensure a well-rounded representation, the selection process encompassed professionals from different roles within the AEC domain, such as BIM managers, BIM coordinators, architects, structural engineers, and MEP (Mechanical, Electrical, and Plumbing) engineers. This diverse range of participants was crucial in capturing insights from various perspectives within the industry.

Ten AEC professionals from various sectors willingly volunteered to take part in the initial phase of the study. A detailed breakdown of the participant demographics can be found in Table 4.4.

Table 4.4 Participant demographics for the initial phase of interview

Participants	Organization	Country	Experience in AEC and BIM (in years)	Position
1	Engineering design company	Canada	10+	National Practice Director
2	Engineering design company	Canada	7	BIM Coordinator (MEP)
3	Engineering design company	Canada	8	BIM Manager (MEP)
4	Architectural design company	Canada	6	BIM Coordination Specialist (Arch)
5	Engineering design company	Canada	7	BIM Coordinator (MEP)
6	Engineering design company	Canada	6	BIM Team Leader (MEP)
7	Engineering design company	Canada	5	Assistance Project Manager
8	Engineering design company	USA	10+	VDC Manager
9	Architectural design company	Canada	5	Designer (Building envelop)
10	Architectural design company	Canada	6	Associate Architect (Buildings)

4.2.5 Conducting the interviews and data transcription

The interviews were carried out virtually, with predetermined dates and times. All participants agreed to allocate a minimum of 45 minutes for each interview session. Microsoft Teams served as the chosen online platform for conducting video interviews. Following the participants' responses to each open-ended question, additional probing inquiries were posed to delve deeper into their preferences and viewpoints. This approach aimed to gain a more profound understanding of the context underlying their responses.

The participants had willingly given their consent to record the entirety of the interview audio, a critical step that allowed for subsequent transcription of the interviews and facilitated the extraction of valuable data. This recording process ensured that the interview data could be accurately preserved and analyzed.

To transcribe interviews from audio recordings, the necessary tools were gathered, including the audio recording of each interview and the transcription provided by Microsoft Teams software. The automatic transcription was manually corrected and the answers to the short open-ended questions were transcribed verbatim in the first step of the process. A uniform format was preserved during transcription. In the second round of corrections and edits, the open-ended question responses were transcribed into Microsoft Excel, presenting a more concise and lucid version that retained the participants' tone and focus of their responses.

4.3 Results from the interviews

The interview responses were coded in Microsoft Excel which involved systematically categorizing and organizing qualitative data to identify patterns, themes, or concepts. The responses for each section of the questionnaire were analyzed separately according to the interview goal they correspond to as shown in subsection 5.2.2. Here the results identified from each section of the questionnaire are elaborated further.

4.3.1 Findings from the responses: Introduction section of the questionnaire

Within the introduction section, industry experts not only demonstrated their in-depth understanding of BIM but also provided insights into their formal and informal education concerning BIM collaboration, as well as the utilization of various tools and techniques in this field. The responses collected in this section reveal a significant trend. It shows that a substantial 80% of the participants had received formal education in BIM-based collaboration prior to commencing their professional careers related to BIM. Interestingly, the data also demonstrates that every single expert participant, constituting 100% of the group, has undergone additional training through workshops or courses during the course of their professional journey. This finding is shown in figure 4.2. These training initiatives were either self-directed or organized by their respective organizations, highlighting a strong commitment to continuous professional development. This section of the questionnaire also delved into the preferred tools selected by the experts for their BIM collaboration and clash management processes. Figures 4.3, 4.4, and 4.5 displays the tools favored by this group of participants.

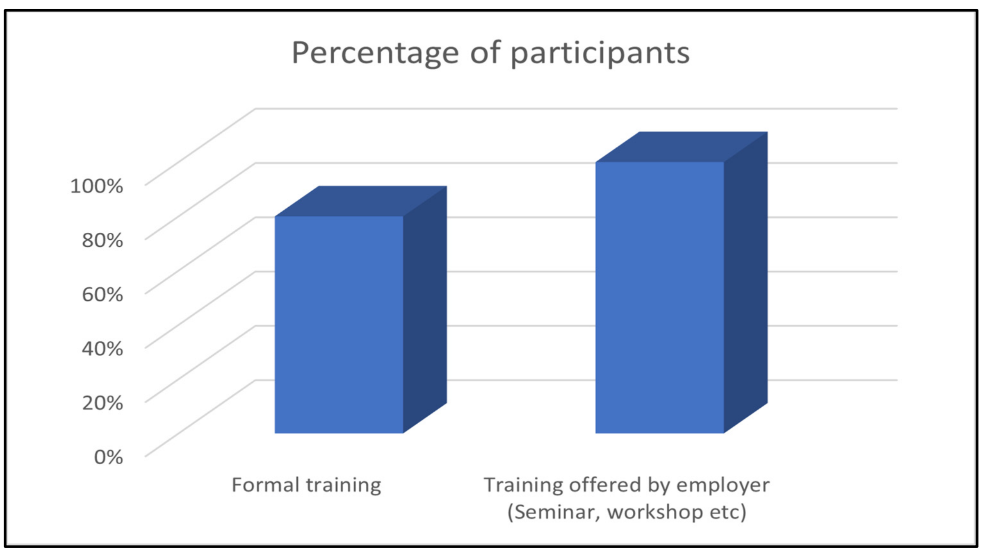

Figure 4.2 Education received by participants on BIM-based collaboration

Within figure 4.3, the initial observation highlights the diverse BIM authoring tools favored by the participants. Notably, all participants exhibit familiarity with the model generation capabilities of Revit, while Tekla Structures and Archicad follow as the next preferred choices.

It's worth noting that some professionals also have experience in creating models through alternative software, such as Rhinoceros 3D. Figure 4.4 visualizes the preferred clash management tools for the industry experts.

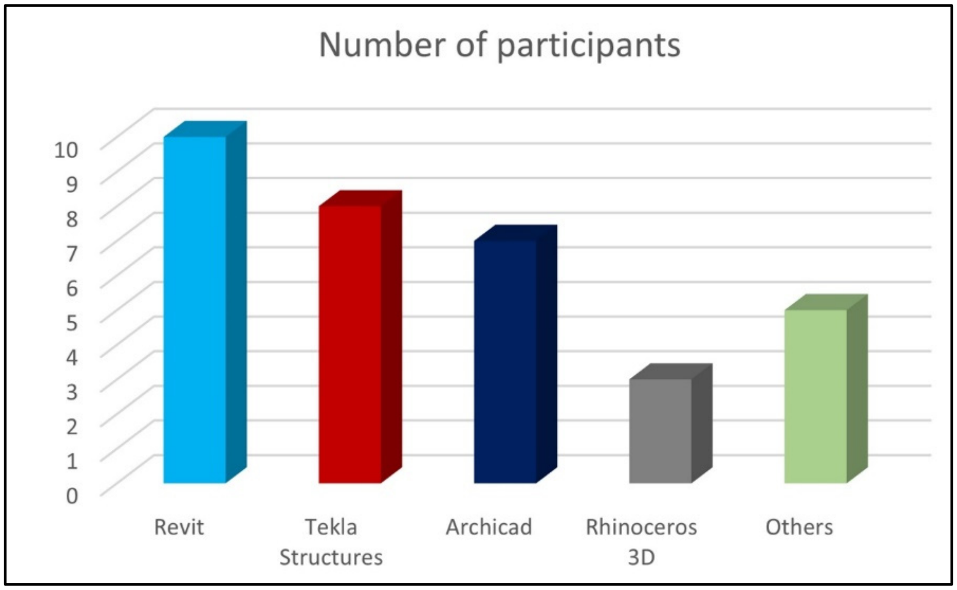

Figure 4.3 Preferred BIM authoring tools among the participants

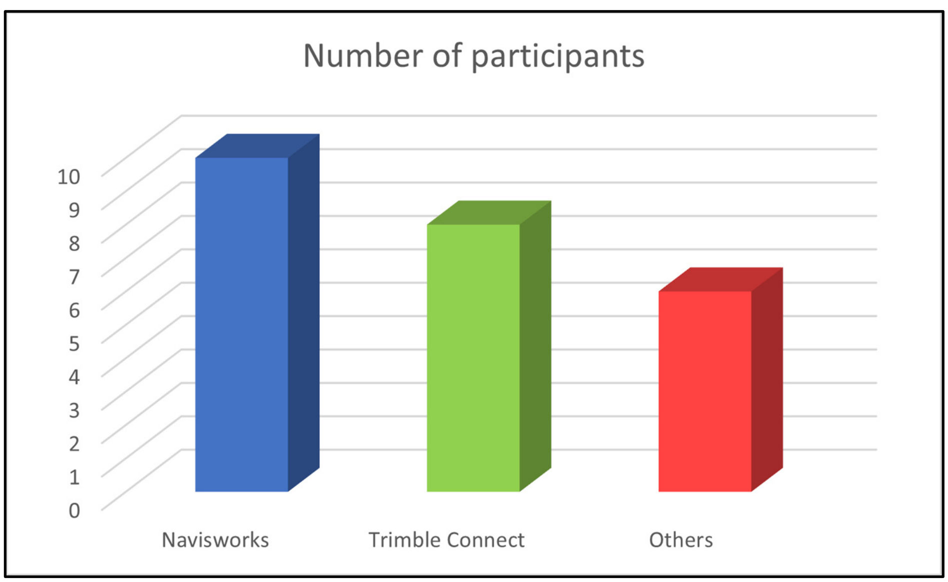

Figure 4.4 Preferred clash management tools among the participants

Figure 4.4 shows that Navisworks is the unanimous top choice for clash management, with Trimble Connect being a close second among the participants. Half of the participating professionals also previously used other clash management tools for a brief period but expressed their preference for Autodesk clash management tools. Conclusively, figure 4.5 highlights the predominant BIM collaboration platform chosen by the selected group of professionals. The data depicted in the figure underscores a unanimous preference for Autodesk Construction Cloud among all participants. Additionally, a noteworthy number of individuals in this cohort exhibit familiarity with Revizto and BIM Track. Remarkably, Microsoft Teams emerges as the universal choice for communication and document sharing, emphasizing its widespread adoption within this professional community.

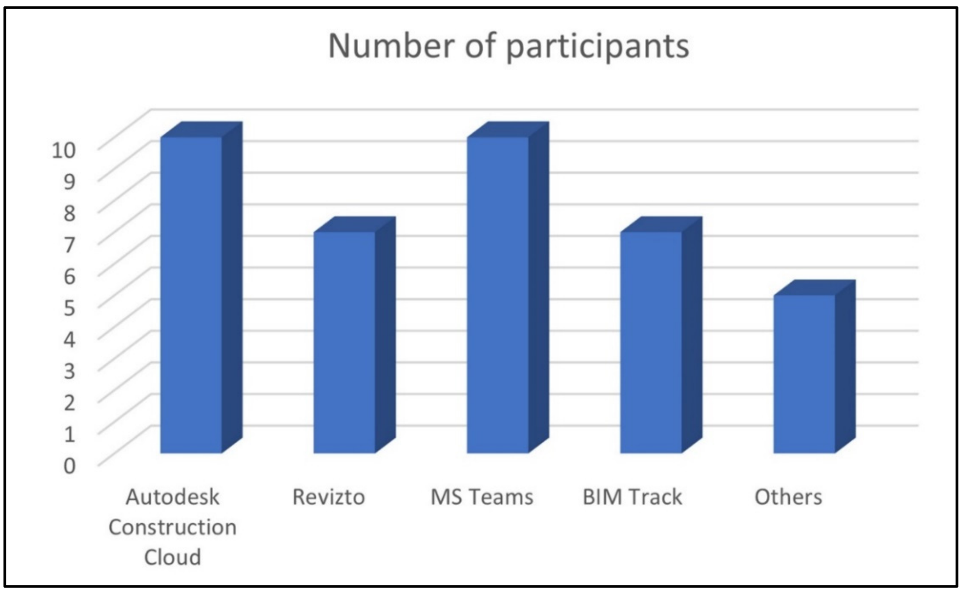

Figure 4.5 Preferred BIM collaboration platform among the participants

Findings from the introduction section of the questionnaire shows that, all participants show familiarity with the model generation capabilities of Revit, while Tekla Structures and Archicad follow as the next preferred choices. For clash management tool preference, a clear trend emerges where Navisworks is the unanimous top choice for clash management, with Trimble Connect being a close second among the participants. The data also reveals that all participants opt for Autodesk Construction Cloud as their preferred BIM authoring tool. Many of them also possess prior experience with Revizto and BIM Track.

4.3.2 Findings from the responses: Validating the BIM coordination obstacles

The second section of the questionnaire aims to confirm the significance of BIM coordination obstacles in today's context, as perceived by experienced AEC professionals. Within this section, each question was carefully designed to present the participant with a comprehensive list of obstacle categories that had been thoroughly examined in section 1.3 of chapter 1. The participants were then requested to assess and rank these individual obstacles according to their perceived importance in the BIM coordination process. To facilitate this ranking, a carefully structured scale was implemented, offering participants a range of options to express the importance they attributed to each obstacle category. This scale consisted of five levels, allowing participants to assign a value that best represented their judgment: very important; important; moderately important; slightly important; not important. By employing this structured ranking scale, participants were able to provide a nuanced and detailed evaluation of the obstacles' importance, contributing to a comprehensive understanding of their role within the BIM coordination process. The Borda Count method was employed to establish a ranked order of importance for the obstacles or options based on the responses obtained from the participants in this section. According to Lansdowne and Woodward (1996) the Borda method is a straightforward positional voting approach used to establish candidate rankings by assessing the cumulative points allotted to each candidate (Lansdowne & Woodward, 1996). This method is easy to execute and offers the flexibility of incorporating weights for alternative criteria where each criteria needs to be carefully selected (Lansdowne & Woodward, 1996). In the application of this method, each option was initially assigned a numerical value between 1 and 5, in accordance with the ranking scale. Specifically, a rating of 1 was aligned with 'not important,' while a rating of 5 corresponded to 'very important.' The next step was, determining the cumulative score for each topic by adding together the individual points assigned by each participant based on their respective rankings. This process involved aggregating the scores from all participants to gauge the overall significance of each topic. In the last step, the individual obstacles within each category were systematically arranged in a descending order, primarily contingent on their collective total scores. Here, the obstacle boasting the highest score was awarded the foremost ranking, making it the most important, while the one with the lowest score was positioned at the end of the ranking list, making it the least important. This arrangement allowed for a clear representation of the relative importance of each obstacle within its respective category. Based on the ultimate rankings established through this analysis and verified by the participants, table 4.5 reveals the foremost obstacles for BIM coordination within each respective category. While table 4.6 shows the most promising and useful clash avoidance strategies and tool functionalities.

Table 4.5 Importance of identified BIM coordination obstacles according to experts

Category of obstacles	Sub-category of obstacles	Individual obstacles ranked from most important to least important	Cumulative total score received from the collected data
Process	Resources	1. Not having a proper standard for BIM collaboration or coordination (National and organizational).	44
		2. Difficulties in sharing information, models, and folders across multiple platforms.	42
		3. Concerns with data security and privacy among the team members.	18
		4. Team members not having visual access to Work-in-Progress files	11
	Tools	1. Too many clashes detected in clash detection software.	47
		2. Absence of automatic clash management tools.	44
		3. BIM tools not supporting multiple file formats.	12

Table 4.5 Importance of identified BIM coordination obstacles according to experts (cont'd)

Category of obstacles	Sub-category of obstacles	Individual obstacles ranked from most important to least important	Cumulative total score received from the collected data
Actor		1. Not having access to a reference library of project history and documents to use when problems arise.	26
		2. Not having enough members experienced in BIM tools and collaboration process in the organization.	22
Task		1. Not being able to instantly request information from team members when in need.	36
		2. Not having a single, central channel for all team communication.	11
Context		1. Lack of teamwork mentality within the project team.	38
		2. Team members communicate with each other outside of organizational or BIM platforms.	14
Team	Roles	1. Not having a clear scope of work or outlined responsibility for BIM professionals.	16
		2. Not having a clear chain of command between project managers, project coordinators, BIM managers, and BIM coordinators.	11
	Relationship	1. Not enough trust among design team members which results in work silos and a lack of collaboration.	22

Table 4.6 Ranking of clash avoidance strategies and tool functionalities

Category	Individual strategy or functionalities	Cumulative total score received from the collected data
Strategies for reducing clashes	1. Introduction of BIM tools or automation **during the specialty model creation phase.**	46
	2. Use of BIM tools that perform Artificial Intelligence enabled optimization of 3D models **after the specialty model creation phase.**	44
	3. Availability of a rule-based approach to optimize design **during the generation of federated models**.	42
	4. Standardized documentation of lessons learned within the team and organization.	36
	5. Better implementation of standardization of LOD practices within the construction industry.	26
	6. Open Work in Progress (OWIP) where team members can get a visual preview of the designer's model.	12
Clash avoidance tool functionalities	1. An always-available knowledge base that the designer can access at will.	42
	2. A warning pops up whenever the designer makes a decision that goes against recommended design rules and can cause a clash.	42
	3. A tutorial about the design rules at the beginning of every work session.	36
	4. Trust calibration functionalities.	22

The ordered list of individual obstacles presented in Table 4.5 highlights those considered most significant by industry experts within the context of contemporary times. According to these experts, "too many clashes detected in clash detection software" occupies the highest position in the rankings, primarily due to the substantial effort and resources necessary for the investigation and resolution of these clashes. Absence of automatic clash management tools and not having a proper standard for BIM collaboration or coordination ranks as close seconds. Given the emergence of contemporary cloud-based BIM collaboration platforms such as Autodesk Construction Cloud; obstacles such as not having visual access to work-in-progress documents and not having a single, central channel for all team communication have diminished in significance, as evidenced by their lower priority in the list of obstacles.

The same method was applied to identify which clash avoidance strategies the experts deem more promising or necessary from the collected data. Table 4.6 shows the most promising and useful clash avoidance strategies and tool functionalities according to industry expert's opinion. Table 4.6 provides a clear depiction of the consensus among experienced professionals, who strongly believe that the introduction of automated support, both during and after the specialty BIM model creation phase, holds immense potential to significantly diminish the occurrence of clashes. Moreover, they express a favorable inclination towards the importance of thorough documentation and the incorporation of lessons learned within their respective organizations.

Furthermore, in the context of the proposed clash avoidance tool's functionalities, designers have notably endorsed two crucial elements. First and foremost, they emphasize the value of having a readily accessible clash avoidance knowledge base that can serve as a constant point of reference for every designer. This feature is regarded as one of the most pivotal aspects of the tool's functionality. Designers from all disciplines who are involved in the process of BIM model creation must have access to this knowledge base. Additionally, designers emphasize the significance of warnings that promptly alert users when a design rule has been deviated from, potentially leading to a clash. These insights underscore the preferences and priorities of these seasoned professionals in optimizing the BIM coordination processes.

4.3.3 Findings from the responses: rules and best practices for clash avoidance

Within the questionnaire's third section, the experts were tasked with a specific directive: to offer a set of design rules and best practices deemed highly valuable for the purpose of clash avoidance during the BIM coordination process and the model creation phase. The distinctiveness of this request lay in the expectation that these design rules and best practices would be tailored to three distinct disciplines: Architecture, Structural, and MEP. In essence, the experts were called upon to provide discipline-specific guidance to enhance the coordination process and minimize clashes within their respective areas of expertise.

The questions presented to the experts were deliberately left open-ended, allowing them the flexibility to contribute a diverse range of technical rules or best practices. In figure 4.6, the phases involved in the process of extracting individual rules from the qualitative data collected through the interviews is depicted. In the initial phase of extraction, a detailed and systematic approach was employed to manually extract and isolate distinct rules from the interview transcripts. After this initial categorization, rules that shared a fundamental similarity in essence were carefully amalgamated, leading to the creation of more concise and comprehensive individual rules. This meticulous process ensured a thorough refinement of the collected insights, enhancing the clarity and applicability of the derived technical guidelines.

In the subsequent step, an effort was made to standardize the wording of these rules, ensuring uniformity throughout the compilation. This standardization was crucial for facilitating the extraction of logical insights from the collection of rules, promoting a systematic and coherent understanding of the provided guidance. Subsequently, an endeavor was undertaken to discern the precise sequence in which the collected rules and best practices are to be applied. In this phase, a clear observation emerged, indicating that specific rules come into play right from the inception of the BIM Management Plan (BMP). However, a significant portion of these rules is most effectively applied during the model creation work sessions conducted by individual designers. This distinction highlights the temporal sequence of rule implementation, with some being integral to the planning phase in the BMP and others taking center stage during the practical modeling efforts of individual designers.

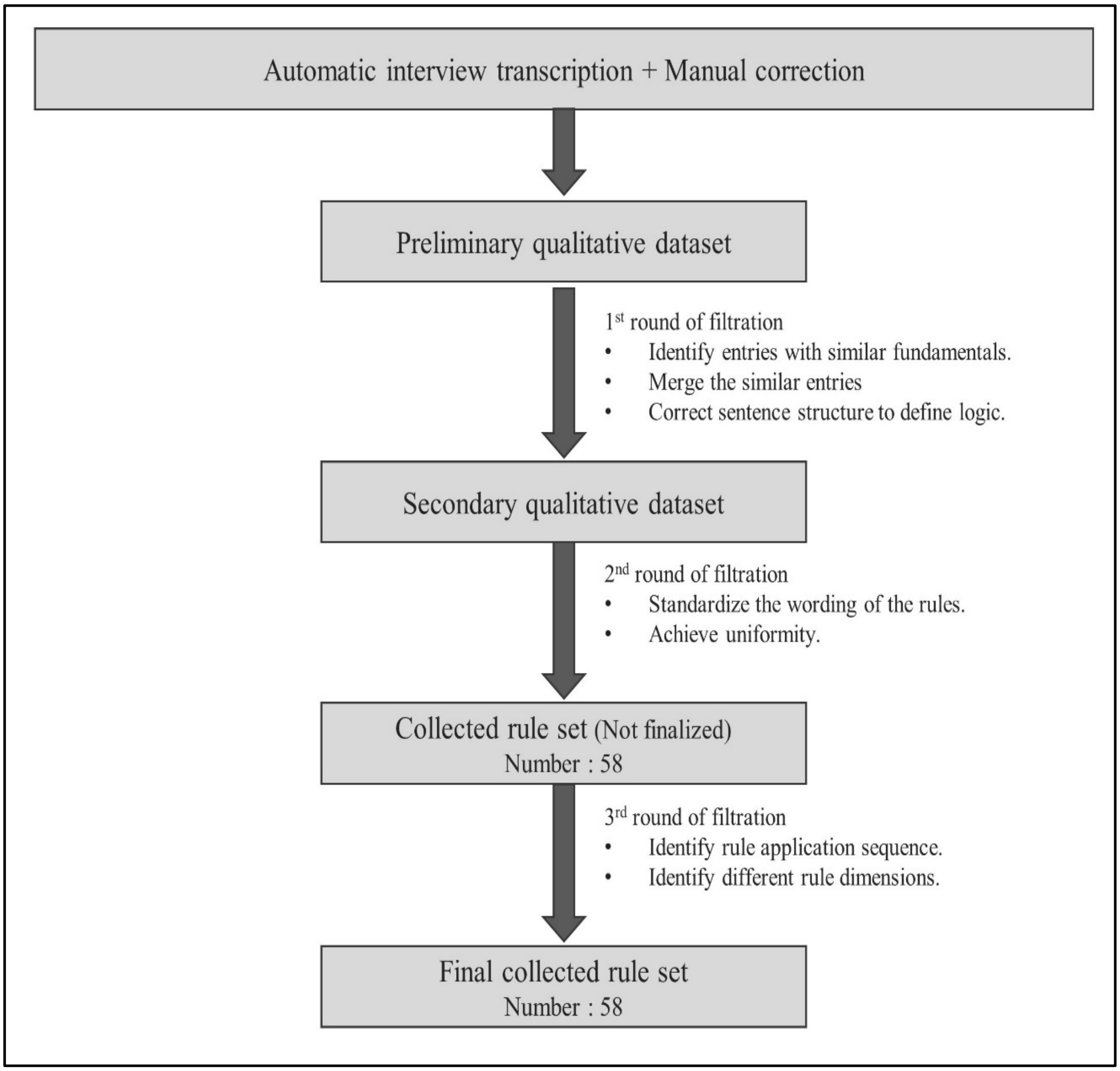

Figure 4.6 Phases involved in the process of extracting rules from the data

This sequencing analysis holds significance in comprehending the functionalities and overall impact of these rules, shedding light on the context in which they play a pivotal role. In addition to establishing the order in which rules should be applied, a systematic exploration was conducted to discern various dimensions that could be extracted from the rules. These dimensions encompassed crucial facets, including the format in which rules were represented, their interconnection with the overall coordination process, the specific workflows they catered to, the nature of clashes they were intended to mitigate, and the level of adherence expected for each rule. This comprehensive analysis enabled a more profound understanding of the rules' intricacies and their multifaceted role within the BIM coordination framework. Table 4.7 shows the different categories of dimensions extracted from the 58 rules collected from the interviews.

Table 4.7 Categories of dimensions extracted from clash avoidance rules

Clash avoidance rule's dimension categories	Dimension's sub-category
Relationship of the Rules to the coordination process	Directive
	Strategy
	Recommendation
	Collaboration and spatial
Type of Workflow	Cad-to-BIM
	BIM-based
Type of Clash	Hard clash
	Soft clash
Requirement	Mandatory
	Best practice
Stage of application	Pre-modeling
	Modeling
	Post-Modeling

The dimension labeled "Relationship of the Rules to the coordination process" elucidates how each gathered rule corresponds to various stages within the entire coordination process. Rules categorized under the 'Directive' dimension are to be deliberated in the kick-off meeting and integrated into the BIM management plan. Those falling under the 'Strategy' dimension necessitate explicit delineation in the BIM management plan, while rules identified within the 'Recommendation' dimension should be incorporated into the clash avoidance tutorial and knowledge base. Lastly, the 'Collaboration and spatial' dimension designates rules that merit active application during the creation of the BIM model by individual designers.

The category under the "Types of workflow" dimension indicates whether a rule is relevant exclusively to BIM-based projects or if it extends to CAD-to-BIM projects as well. The category under the "Types of clash" dimension distinguishes the rule's suitability for either hard or soft clash avoidance. The category labeled "Requirement" indicates whether the rule is deemed mandatory by experienced professionals for the purpose of achieving clash avoidance or if it is considered a best practice. Lastly, the category "Stages of application" illustrates the temporal placement of the rule concerning the BIM modeling process, encompassing three dimensions: pre-modeling, modeling, and post-modeling.

The initial sets of rules collected for the three distinct disciplines, namely Architectural, Structural, and MEP, have been systematically coded with all the associated dimensions. These comprehensive rule sets are documented in Annex I, Annex II, and Annex III respectively.

4.3.4 Rating the collected design rules and best practices

Following the meticulous coding of interview responses and the subsequent extraction of clash avoidance rule sets from the amassed qualitative data, the next crucial phase of this collaborative process involved the validation of these findings through a collective assessment with industry experts.

At this particular stage of the research, a deliberate effort was made to engage with current BIM professionals and engineers. These individuals were solicited to assess a comprehensive set of rules using a structured scale measuring their efficacy. This scale was designed with five distinct gradations: "most effective," "effective," "moderately effective," "slightly effective," and "not effective." The evaluation process involved the participation of five professionals who were invited to provide their insights via a web-based form shared with them. Within this web form, a total of 58 finalized rules were presented, each accompanied by the various dimensions associated with these rules, as previously identified in 4.3.3. This evaluation phase was instrumental in gauging the practical effectiveness of the clash avoidance rules from the perspective of industry experts. In order to mitigate potential biases, it was ensured that none of the participants who had previously been involved in the interview phase of this research were included in the subsequent validation stage. All the participants selected for this validation stage were exclusively drawn from Canada, thus reflecting a specific regional perspective. This diverse group comprised a total of five individuals, with a balanced representation of expertise. Among them, three participants brought their valuable insights as BIM professionals, while the remaining two participants specialized in the field of MEP engineering.

Following the collection of rankings for the 58 design rules, a rigorous selection process was initiated. Only those rules that received a rating of 'moderately effective' or higher, as determined by the consensus of the majority of the participants, specifically three out of the five participants, were deemed eligible for progression to the subsequent stage. These selected rules served as the foundation for the design, development, and eventual evaluation of the proposed artifact, ensuring that only the most promising and impactful rules were considered for further development. This stringent criterion upheld the robustness of the artifact and its alignment with the collective expert judgment. The carefully curated and validated rules correspond to Architectural, Structural, and MEP specialty models respectively. These selected rules, totaling 35 in number, constitute a curated set that emerged as the most effective and promising in the context of the BIM coordination process. Tables 4.8 and 4.9 collectively display the carefully chosen rules applicable to the architectural specialty model stemming from the validation stage. Furthermore, these tables offer a comprehensive view of the dimensions that were meticulously identified for each individual rule, providing valuable insights into the multifaceted aspects and characteristics of these rules. This compilation serves as a pivotal resource in advancing the understanding and development of clash avoidance strategies within the field of Architecture, Structural engineering, and MEP specialization.

Table 4.8 Validated clash avoidance rules for architectural specialty model

Discipline	Clash Avoidance Rules	RULE PRESENTATION FORMAT DURING COORDINATION (MEETINGS + WORK SESSION)
Architectural	Priority list among the disciplines (STRC, MEP, ARCH) for each projects must be decided during the kickoff meeting.	BIM Management Plan ; Must be present in kickoff meeting agenda.
	The Level Of Detail (LOD) matrix must be defined clearly for the discipline.	BIM Management Plan
	Always lock/pin the site model in place.	Tutorial Module of Clash Avoidance Assistant ; Reminder
	Axes and levels must be pinned and locked as soon as they are created.	Tutorial Module of Clash Avoidance Assistant ; Reminder
	MEP consultants should provide information about how much volume or space is needed between the ceiling and slab.	BIM Management Plan ; BIM Coordination Meetings
	MEP consultants should provide exact dimension regarding the thickness of the ceiling needs for maintenance accessibility.	BIM Management Plan ; BIM Coordination Meetings
	The dimensions provided by MEP consultants must be available to every modeler/designer/technichian when they are working on BIM model.	Tutorial Module of Clash Avoidance Assistant
	The dimensions of the space between ceiling and slab should precisely match the dimensions provided by the MEP consultants.	Error prompt if the dimension is less than recommended
	The ceiling thickness in the BIM model should precisely match the dimensions provided by the MEP consultants.	Error prompt if the dimension is less than recommended
	The interior walls must not travel over the ceiling.	Tutorial Module of Clash Avoidance Assistant ; Error prompt if the dimension is less than recommended
	Use of basic walls without material and layer thickness details should be avoided in the BIM model.	Reminder ; Error prompt if basic wall is detected
	For work shared models, the model must be synchronized with the 'Central' model frequently (min. 1 time/hour)	Tutorial Module of Clash Avoidance Assistant ; Reminder
	For every work session during modeling, errors must be resolved as quickly as possible (Most important: Duplicate elements must be deleted)	Tutorial Module of Clash Avoidance Assistant ; Reminder

Table 4.9 Dimensions of the clash avoidance rules for architectural discipline

Discipline	**Clash Avoidance Rules**	**Dimension categories**												
		Relationship of the Rules to the coordination process				Type of Workflow		Type of Clash		Requirement		Stage of application		
		Directive	Strategy	Recommendation	Collaboration and spatial	CAD to BIM	BIM-Based	Hard Clash	Soft Clash	Mandatory	Best Practice	Pre-modeling	Modeling	Post-Modeling
Architectural	Priority list among the disciplines (STRC, MEP, ARCH) for each projects must be decided during the kickoff meeting.		X			X	X	X	X	X		X		
	The Level Of Detail (LOD) matrix must be defined clearly for the discipline.	X				X	X	X	X	X		X		
	Always lock/pin the site model in place.	X			X	X	X	X	X	X		X		
	Axes and levels must be pinned and locked as soon as they are created.	X				X	X	X	X	X			X	
	MEP consultants should provide information about how much volume or space is needed between the ceiling and slab.				X	X	X	X	X	X			X	
	MEP consultants should provide exact dimension regarding the thickness of the ceiling needs for maintenance accessibility.				X	X	X		X	X			X	
	The dimensions provided by MEP consultants must be available to every modeler/designer/technichian when they are working on BIM model.			X		X	X	X	X	X			X	

Table 4.9 Dimensions of the clash avoidance rules for architectural discipline (cont'd)

Discipline	Clash Avoidance Rules	Dimension categories												
		Relationship of the Rules to the coordination process				Type of Workflow		Type of Clash		Requirement		Stage of application		
		Directive	Strategy	Recommendation	Collaboration and spatial	CAD to BIM	BIM-Based	Hard Clash	Soft Clash	Mandatory	Best Practice	Pre-modeling	Modeling	Post-Modeling
Architectural	The dimensions of the space between ceiling and slab should precisely match the dimensions provided by the MEP consultants.				X	X	X	X	X	X			X	
	The ceiling thickness in the BIM model should precisely match the dimensions provided by the MEP consultants.				X	X	X		X	X			X	
	The interior walls must not travel over the ceiling.				X	X	X	X		X			X	
	Use of basic walls without material and layer thickness details should be avoided in the BIM model.			X		X	X	X		X			X	
	For work shared models, the model must be synchronized with the 'Central' model frequently (min. 1 time/hour)	X			X	X	X	X	X	X			X	
	For every work session during modeling, errors must be resolved as quickly as possible (Most important: Duplicate elements must be deleted)	X			X	X	X	X	X	X			X	

Similarly, in tables 4.10 and 4.11, the comprehensive compilation of clash avoidance rules for the structural discipline is presented, accompanied by their identified dimensions. Concluding the set, tables 4.12 and 4.13 provide a detailed overview of the collected and validated clash avoidance rules specifically for the MEP discipline, including their associated dimensions.

Table 4.10 Validated clash avoidance rules for structural specialty model

Discipline	Clash Avoidance Rules	RULE PRESENTATION FORMAT DURING COORDINATION (MEETINGS + WORK SESSION)
Structural	Always lock/pin the site model in place.	Tutorial Module of Clash Avoidance Assistant ; Reminder
	Axes and levels must be pinned and locked as soon as they are created.	Tutorial Module of Clash Avoidance Assistant ; Reminder
	The structural discipline should receive the first iteration LOD 200 model from the architectural discipline before starting their modeling.	BIM Management Plan ; BIM Coordination Meetings
	Once the structural discipline has received the LOD 200 architectural model then the MEP discipline should be consulted.	BIM Management Plan ; BIM Coordination Meetings
	Structural and MEP consultants should clearly identify the spaces for mechanical elements within the sheer walls, and beams.	BIM Management Plan ; BIM Coordination Meetings
	MEP consultant should provide the exact measurements for required duct and shaft openings.	BIM Management Plan ; BIM Coordination Meetings
	The duct and shaft openings in the BIM model should precisely match the dimensions provided by the MEP consultants.	Error prompt if the dimension is less than recommended
	For work shared models, the model must be synchronized with the 'Central' model frequently (min. 1 time/hour)	Tutorial Module of Clash Avoidance Assistant ; Reminder
	For every work session during modeling, errors must be resolved as quickly as possible (Most important: Duplicate elements must be deleted)	Tutorial Module of Clash Avoidance Assistant ; Reminder

Table 4.11 Dimensions of the clash avoidance rules for structural discipline

Discipline	Clash Avoidance Rules	Dimension categories												
		Relationship of the Rules to the coordination process				Type of Workflow		Type of Clash		Requirement		Stage of application		
		Directive	Strategy	Recommendation	Collaboration and spatial	CAD to BIM	BIM-Based	Hard Clash	Soft Clash	Mandatory	Best Practice	Pre-modeling	Modeling	Post-Modeling
Structural	Always lock/pin the site model in place.	X			X	X	X	X	X	X		X		
	Axes and levels must be pinned and locked as soon as they are created.	X				X	X	X	X	X				

Table 4.11 Dimensions of the clash avoidance rules for structural discipline (cont'd)

Discipline	Clash Avoidance Rules	Dimension categories												
		Relationship of the Rules to the coordination process				Type of Workflow		Type of Clash		Requirement		Stage of application		
		Directive	Strategy	Recommendation	Collaboration and spatial	CAD to BIM	BIM-Based	Hard Clash	Soft Clash	Mandatory	Best Practice	Pre-modeling	Modeling	Post-Modeling
Structural	The structural discipline should receive the first iteration LOD 200 model from the architectural discipline before starting their modeling.		X			X	X	X	X	X		X		
	Once the structural discipline has received the LOD 200 architectural model then the MEP discipline should be consulted.		X			X	X	X	X		X	X		
	Structural and MEP consultants should clearly identify the spaces for mechanical elements within the sheer walls, and beams.		X			X	X	X	X	X		X		
	MEP consultant should provide the exact measurements for required duct and shaft openings.				X	X	X	X		X		X		
	The duct and shaft openings in the BIM model should precisely match the dimensions provided by the MEP consultants.				X	X	X	X	X	X		X		
	For work shared models, the model must be synchronized with the 'Central' model frequently (min. 1 time/hour)				X	X	X	X	X	X			X	
	For every work session during modeling, errors must be resolved as quickly as possible (Most important: Duplicate elements must be deleted)	X			X	X	X	X	X	X			X	

Table 4.12 Validated clash avoidance rules for MEP specialty model

Discipline	Clash Avoidance Rules	RULE PRESENTATION FORMAT DURING COORDINATION (MEETINGS + WORK SESSION)
MEP	The work hierarchy of the MEP BIM model for each project should be decided in the kick-off meeting.	BIM Management Plan ; BIM Coordination Meetings
	Always lock/pin the site model in place.	Tutorial Module of Clash Avoidance Assistant ; Reminder
	Axes and levels must be pinned and locked as soon as they are created.	Tutorial Module of Clash Avoidance Assistant ; Reminder
	The insulation dimensions between pipes and ducts should be clearly defined and modeled.	Tutorial Module of Clash Avoidance Assistant ; Reminder
	The modeled insulation should match the required dimensions precisely.	Error prompt if the dimension is less than recommended
	HVAC , all slopes and fire protection system should be modeled simultaniously with maximum team coordination.	Tutorial Module of Clash Avoidance Assistant ; Reminder
	All clearance spaces required for maintenance should be communicated to all team members.	BIM Management Plan ; BIM Coordination Meetings ; Tutorial Module of Clash Avoidance Assistant
	The first model iteration should be shared with the architecture and structural disciplines.	BIM Management Plan ; BIM Coordination Meetings
	The MEP discipline must request and receive the the latest ceiling plans from the architectural discipline (Via weekly package publication).	BIM Management Plan ; BIM Coordination Meetings
	The MEP discipline must do a manual check to ensure that they have the latest positions of all ceiling fixtures.	BIM Management Plan ; BIM Coordination Meetings
	For work shared models, the model must be synchronized with the 'Central' model frequently (min. 1 time/hour)	Tutorial Module of Clash Avoidance Assistant ; Reminder
	For every work session during modeling, errors must be resolved as quickly as possible (Most important: Duplicate elements must be deleted)	Tutorial Module of Clash Avoidance Assistant ; Reminder
	The MEP discipline must do quality checks to ensure all necessary electrical and fire protection components shown in the 2D plan are present within the model.	BIM Management Plan ; BIM Coordination Meetings ; Tutorial Module of Clash Avoidance Assistant

Table 4.13 Dimensions of the clash avoidance rules for MEP discipline

Discipline	Clash Avoidance Rules	Dimension categories												
		Relationship of the Rules to the coordination process				Type of Workflow		Type of Clash		Requirement		Stage of application		
		Directive	Strategy	Recommendation	Collaboration and spatial	CAD to BIM	BIM-Based	Hard Clash	Soft Clash	Mandatory	Best Practice	Pre-modeling	Modeling	Post-Modeling
MEP	The work hierarchy of the MEP BIM model for each project should be decided in the kick-off meeting.	X				X	X	X	X	X		X		
	Always lock/pin the site model in place.	X			X	X	X	X	X	X		X		
	Axes and levels must be pinned and locked as soon as they are created.	X			X	X	X	X	X	X		X		
	The insulation dimensions between pipes and ducts should be clearly defined and modeled.			X	X	X	X	X	X	X			X	
	The modeled insulation should match the required dimensions precisely.				X	X	X	X	X	X			X	
	HVAC , all slopes and fire protection system should be modeled simultaniously with maximum team coordination.		X			X	X	X	X	X	X		X	
	All clearance spaces required for maintenance should be communicated to all team members.		X	X		X	X	X	X	X			X	

Table 4.13 Dimensions of the clash avoidance rules for MEP discipline (cont'd)

Discipline	Clash Avoidance Rules	Dimension categories: Relationship of the Rules to the coordination process				Type of Workflow		Type of Clash		Requirement		Stage of application		
		Directive	Strategy	Recommendation	Collaboration and spatial	CAD to BIM	BIM-Based	Hard Clash	Soft Clash	Mandatory	Best Practice	Pre-modeling	Modeling	Post-Modeling
MEP	The first model iteration should be shared with the architecture and structural disciplines.		X			X	X	X	X	X	X			X
	The MEP discipline must request and receive the the latest ceiling plans from the architectural discipline (Via weekly package publication).		X			X	X	X	X	X				X
	The MEP discipline must do a manual check to ensure that they have the latest positions of all ceiling fixtures.		X			X	X	X	X	X				X
	For work shared models, the model must be synchronized with the 'Central' model frequently (min. 1 time/hour)	X			X	X	X	X	X	X			X	
	For every work session during modeling, errors must be resolved as quickly as possible (Most important: Duplicate elements must be deleted)	X			X	X	X	X	X	X			X	
	The MEP discipline must do quality checks to ensure all necessary electrical and fire protection components shown in the 2D plan are present within the model.		X			X		X	X	X				X

This chapter successfully fulfills the fourth research objective by compiling design rules and best practices for clash avoidance. The complete interview questionnaire showing the question sections and the questions are added in Annex IV. The next chapter will focus on developing a clash avoidance system for BIM authoring tools, drawing insights from the presented data.

CHAPTER 5

SYSTEM DESIGN, DEVELOPMENT, AND EVALUATION

Within this chapter, the design of the proposed rule-based system for comprehensive clash avoidance, coupled with the development of the prototype are explored in detail. This chapter satisfies the fifth research objective which seeks to design the integrated system for BIM authoring tools aiding adherence to design rules. The chapter encompasses fundamental components, offering an understanding of the structure of a rule-based system. It further elaborates on the conceptual model that underpins the proposed system's design. The chapter also delves into the visual representation of the conceptual model of the proposed system's functionalities which are deemed important by the industry experts, and UML (Unified Modeling Language) sequence diagram, which illustrate the individual rule execution function. Additionally, it shows the development of an ontology specially tailored to facilitate comprehensive clash avoidance. Together, these elements form the backbone of the proactive approach to clash avoidance, promoting a holistic understanding of the system's design and operation.

5.1 The necessity of a Rule-based system

According to researchers a conventional rule-based system or rule-based expert system harnesses human expert knowledge to address real-world problems that typically necessitate human intelligence for resolution. This expertise is typically conveyed within the computer system either in the form of rules or as structured data (Abraham, 2005). Expert systems offer several notable advantages, including the capacity to capture and retain invaluable human experience, resulting in a repository of knowledge that can be accessed and utilized. These systems excel in providing a high degree of consistency, outperforming human experts in maintaining uniformity in decision-making and problem-solving. They also prove invaluable in scenarios where human expertise is required across multiple locations simultaneously, particularly in hostile or hazardous environments that pose risks to human well-being. Moreover, expert systems are known for their swiftness in devising solutions, often surpassing the speed at which human experts can arrive at conclusions, thus accelerating the decision-making process (Abraham, 2005). Based on the work of Abraham (2005), the basic components of an expert system are illustrated in figure 5.1.

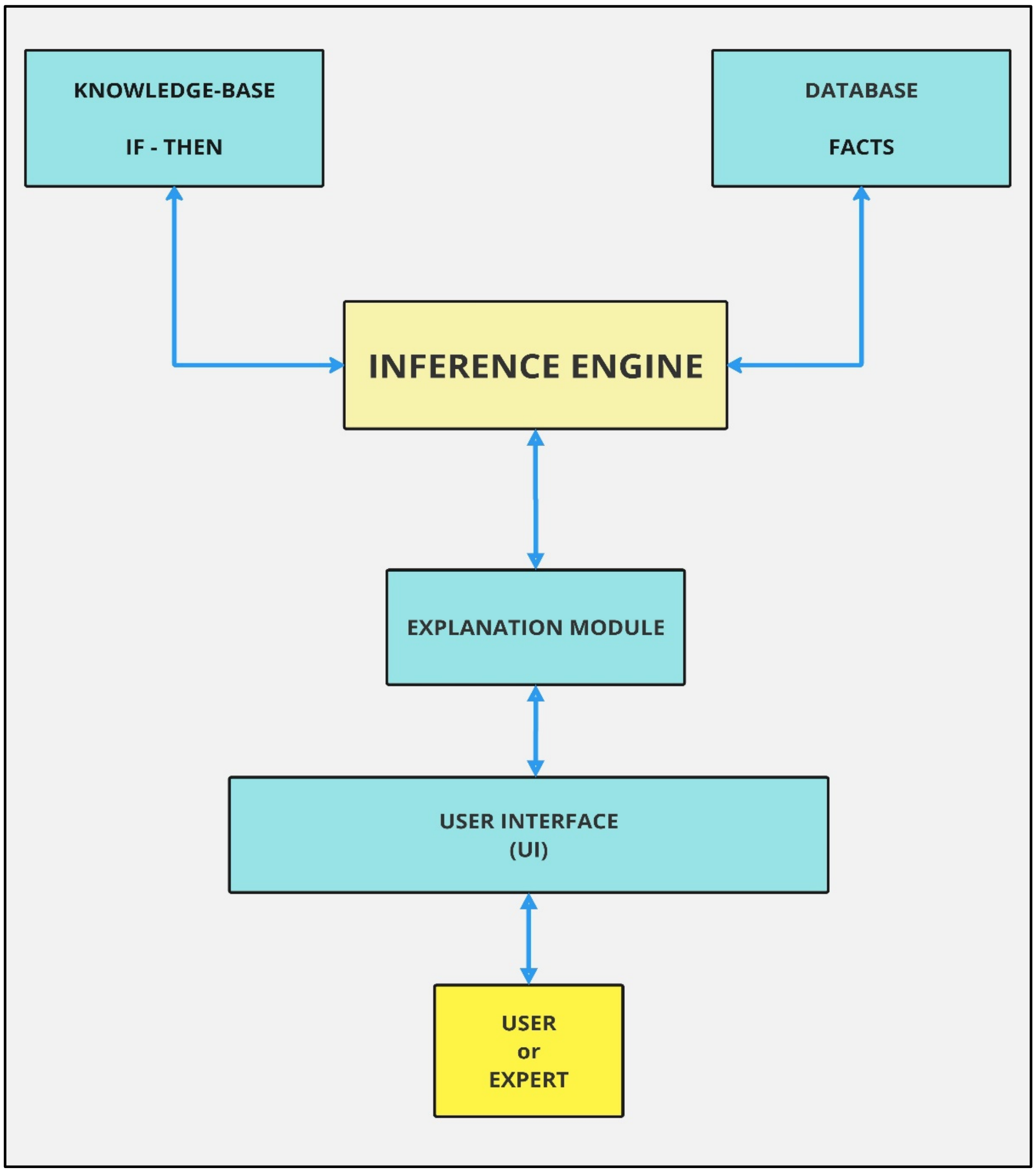

Figure 5.1 Basic components of a rule-based expert system

According to Grosan et al. (2011), a rule-based system involves the translation of a human expert's knowledge within a specific domain into an automated system (Grosan et al., 2011).

This is achieved by formulating a set of assertions and a corresponding set of rules that dictate actions based on the assertion set (Grosan et al., 2011).
These rules are typically presented in the form of if-then statements, commonly referred to as IF-THEN rules which is also known as production rules.

As per Grosan et al., the IF-THEN rules act as follows : 'IF P, THEN Q' , which is also equivalent to $P \Rightarrow Q$ (Grosan et al., 2011).

A rule-based system is comprised of IF-THEN rules, a set of facts, and an interpreter that governs the application of rules based on the provided facts. As per researchers, the concept behind expert systems involves extracting knowledge from an expert and encoding it into a rule set and when confronted with identical data, the expert system is anticipated to exhibit performance akin to that of the expert (Grosan et al., 2011). Rule-based systems, being straightforward models, can be easily customized and deployed across a wide array of problems. According to Abraham (2005), expert systems offer notable advantages, including, (i) encapsulating and safeguard invaluable human experience, (ii) excelling in creating systems that exhibit greater consistency than human experts, (iii) significantly reducing the requirement for human expertise across multiple locations simultaneously, (iv) enabling the swift development of solutions, outpacing the time typically required by human experts.

The aforementioned advantages show the superiority of a rule-based system in capturing and implementing design rules and clash avoidance best practices derived from experienced professionals. This system excels in replicating the decision-making abilities of human experts, swiftly pinpointing deviations from design rules for designers' attention. By facilitating adherence to clash avoidance guidelines, it effectively reduces the incidence of clashes, offering a dual benefit of minimizing the number of clashes and elevating the overall quality of the BIM model. In essence, the rule-based system emerges as a potent and efficient tool, streamlining clash avoidance processes and fostering the creation of specialty BIM models of superior quality. The fundamental components of a rule-based system are shown in table 5.1.

Table 5.1 Fundamental components of a rule-based system

Components of rule-based expert system	Functionalities	Reference
The knowledge base	This repository houses essential information, data, rules, cases, and relationships used by the expert system. It can consolidate knowledge from human experts, with rules defining conditional connections between specified conditions and subsequent actions or outcomes.	(Abraham, 2005)
	The rules establish a connection between the facts articulated in the IF segment and a corresponding action outlined in the THEN segment. It is essential for the system to incorporate only pertinent rules while steering clear of irrelevant ones.	(Grosan et al., 2011)
The database	The database includes a set of facts used to match against the IF (condition) parts of rules stored in the knowledge base. These facts essentially represent the assertions and should encompass any information pertinent to the initial state of the system.	(Grosan et al., 2011)
The inference engine	Extracts information and relationships from the knowledge base, delivering responses, predictions, and recommendations akin to a human expert. It is imperative for the inference engine to adeptly locate the relevant facts, interpretations, and rules, assembling them accurately for effective decision-making.	(Abraham, 2005)
The explanation module	Enables a user to comprehend the process by which the expert system reached specific outcomes. The overarching goal of the knowledge acquisition facility is to furnish a user-friendly and effective mechanism for capturing and storing all elements comprising the knowledge base.	(Abraham, 2005)

A rule-based system consists of several fundamental components, including: the knowledge base, the data and facts base, the inference engine, the explanation module , and the user interface.

The functionalities inherent in the components of a rule-based system further substantiate the justification for proposing an artifact based on industry expertise collected from professionals within the framework of the DSR methodology.

5.2 Conceptual model for the proposed system's functionalities

The next step of this work focuses on proposing a conceptual model for the clash avoidance system based on the principles of rule-based system as discussed in section 5.1. Figure 5.2 illustrates a simplified diagram representing the conceptual model which shows the workflow of the recommendation system proposed. This section will briefly describe some basic functionalities of the proposed system and how it is intended to interact with the user.

As delineated in sub-section 4.3, industry experts have identified the paramount functionality of the clash avoidance system to be the availability of a perpetually accessible knowledge base and tutorial for designers. The proposed clash avoidance system's User Interface (UI) is designed to initiate a prompt, offering the designer the option to peruse the clash avoidance tutorial and knowledge base at the commencement of each work session. The designer retains the autonomy to either engage with the tutorial or dismiss the prompt. Throughout the course of the work session, the designer has the flexibility to consult the tutorial at their discretion, thereby ensuring continuous reference for adherence to design rules and enhancing the overall quality of the BIM model. This proactive approach contributes to a more informed and effective design process.

The next important functionality of the clash avoidance system according to the experts' opinion in sub-section 4.3 is, an error prompt or warning when the clash avoidance system detect deviation from the encoded design rules. The collected design rules and best practices will be encoded into the proposed system as the knowledge base and the facts from the database will be compared against it. The facts in the database will be collected using the BIM authoring tool's Application Programming Interface (API) as the BIM modeler works on the model. The encoded design rules will have a condition or an antecedent and an action or a consequent part. The condition part, being a logical test will need to be satisfied for the action part to be executed. For spatial relationship rules, such as the required clearance in the ceiling space for ducts, for example, the dimension in the BIM model must satisfy the minimum required dimension saved in the condition section of the rule. If the model dimension is less than the requirement, the action (i.e.: Error prompt) will be executed. After launching the BIM authoring tool, the designer will have the option to review the best practice and design rules in the form of a tutorial.

Within the design process, every decision made by the designer pertaining to clash avoidance rules is designated as an operator decision, subject to a comprehensive assessment against the knowledge base. In the event of an error prompt, the system provides a succinct, yet informative explanation related to the specific rule in question. This empowers the designer with the flexibility to either accept the system's explanation, aligning it with their decision, or opt to dismiss it based on their expertise and judgment. This iterative process ensures a dynamic and collaborative interaction between the designer and the system, fostering a nuanced understanding of clash avoidance rules and allowing for informed decision-making throughout the design workflow.

In instances where the prompt is overridden, the proposed system adopts a proactive approach, presenting the designer with a more comprehensive explanation. This strategy aims to not only address the specific decision but also to refine and bolster the designer's confidence in the system's recommendations.

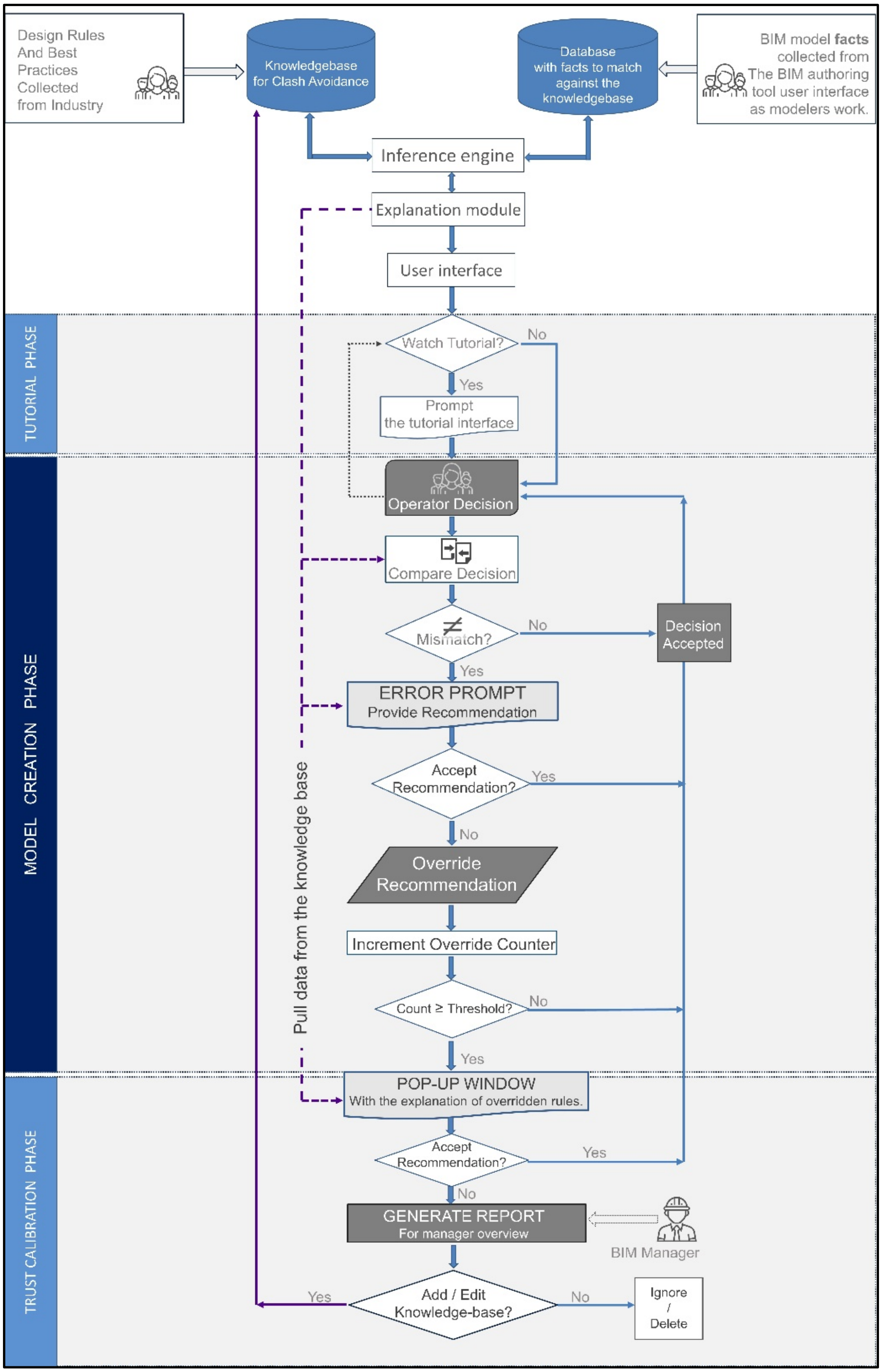

Figure 5.2 Conceptual model of the proposed system

The explanation module assumes a pivotal role in facilitating both the initial error prompt and the subsequent detailed explanations of overridden rules, fostering a deeper understanding of the decision-making process.

To uphold transparency and accountability, all overridden rules are systematically documented in a report, which undergoes review by key stakeholders such as the BIM team leader, BIM coordinator, or BIM manager. This review process ensures that any deviations or overrides are comprehensively examined within the context of project objectives and standards. Furthermore, the system affords the team leader or manager the opportunity to contribute to or modify the knowledge base. This feature not only promotes ongoing refinement but also ensures adaptability in decision-making processes, aligning the system with evolving project requirements and industry best practices.

For the creation of a robust clash avoidance system, it is crucial to comprehend the interrelationships among key actors in BIM coordination (such as designers and BIM coordinators), BIM authoring tools, various clash types, and the design rules governing clash avoidance. A Web Ontology Language (OWL) was formulated whose purpose is to visually represent these relationships, enhancing the comprehension of how these components interconnect in both the occurrence and prevention of clashes which is shown in figure 5.3.

Formulating the ontology with OWL language involved defining classes, individuals, properties, and relationships to represent knowledge in the domain. Once the domain is established, classes were created to represent fundamental concepts such as "Clash" and "ClashAvoidanceRules." Then these classes were populated with instances or individuals, such as "HardClash" or "SequentialRules".

To establish relationships between these entities, properties were used. For example, a property such as "is a" is defined to connect instances of clashes with their specific types. To enhance the ontology, specific values can be incorporated to attribute properties, adding precision to this ontology. A hierarchy is constructed by defining subclasses and superclasses, organizing entities in a structured manner. Additionally, restrictions can be used on the properties to introduce more nuanced relationships, ensuring a more accurate representation of the domain. Furthermore, annotations can be added to provide supplementary information or comments, enhancing the clarity of the developed ontology. The ontology needs to be regularly reviewed and refined considering the evolving requirements of this domain. This iterative approach will ensure that the developed ontology remains a robust and accurate representation of knowledge within the chosen domain. Ultimately, OWL provides a powerful framework for creating semantic structures that enable effective data sharing and reasoning in complex domains such as the BIM clash prevention.

The UML sequence diagram for the individual functionality of the clash avoidance system shows how the system identifies a particular rule deviation comparing the designer's decision to the knowledge base via the inference engine and communicates with the designer about the deviated rule via the explanation module. Figure 5.4 illustrates the communicative relationship among the designer, the BIM authoring tool User Interface, the BIM authoring tool API, and the foundational components of the clash avoidance system which are the knowledge base, the database, the inference engine and the explanation facilities. Each element is represented using UML symbols, and the arrows delineate the communication pathways, providing a visual guide for developers and stakeholders. This involved breaking down the system's actions into a logical sequence, considering the roles of each component. The diagram underwent iterative refinement to ensure precision and clarity. The final UML sequence diagram serves as a valuable tool offering a comprehensive depiction of the clash avoidance system's behavior and enhancing the understanding of its intricate processes.

For this work, Revit was selected as the BIM authoring tool to host the system developed since all industry experts who participated in the interview stage of the research were familiar with this software. The UML sequence diagram shows the functionalities of the rule-based system for clash avoidance in the context of Revit software.

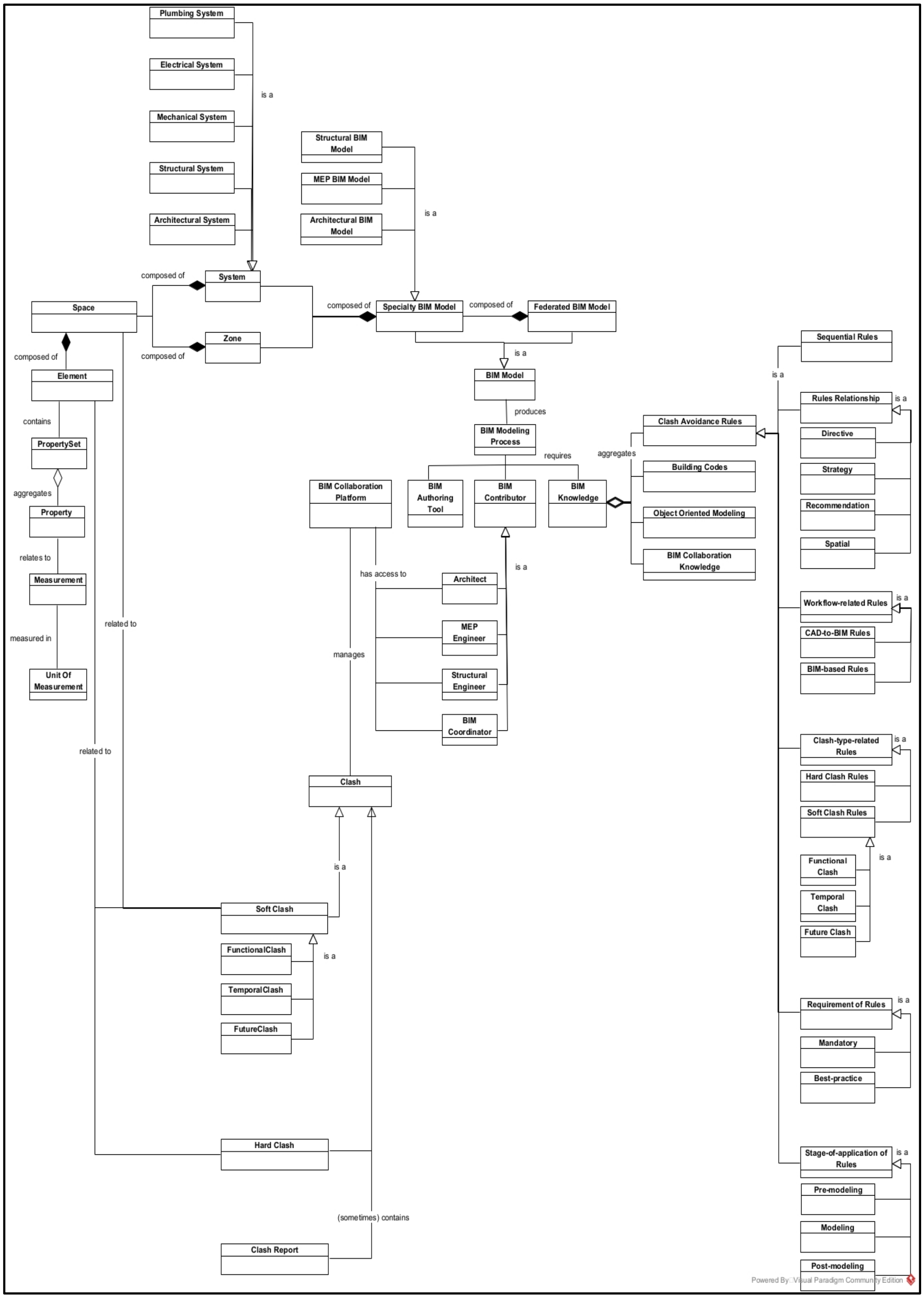

Figure 5.3 Ontology depicting interrelationship between the actors and components of BIM coordination

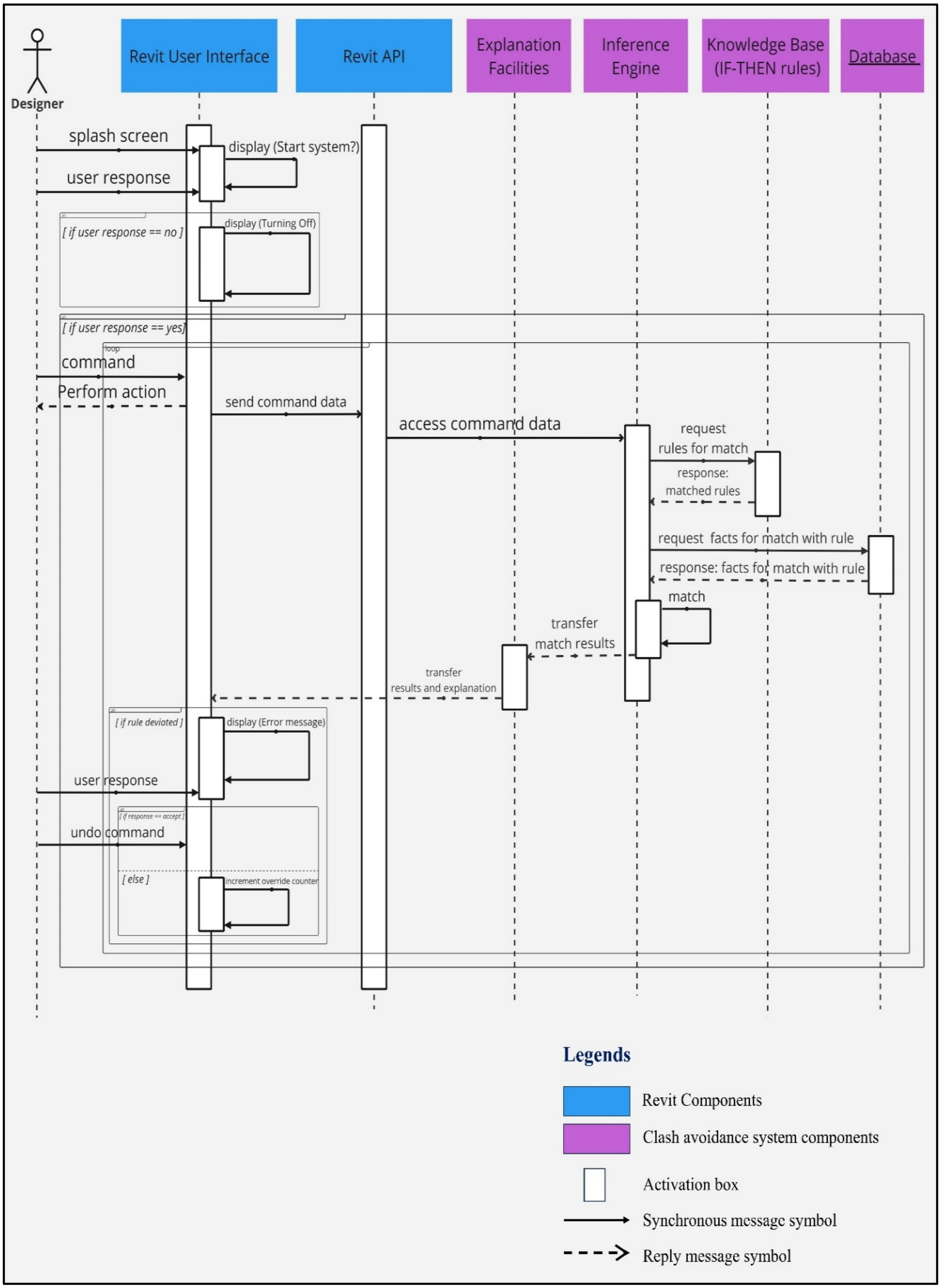

Figure 5.4 UML sequence diagram for clash avoidance system

5.3 Revit API based plugin development

The initial step of prototyping the proposed clash avoidance system involves the careful selection of sample rules from the pool of validated 35 design rules. This selection process takes into account the significance of the validated rules, along with considerations for the dimensions of these rules. Since the clash avoidance system functions as a plugin within the Revit environment, emphasis is placed on choosing rules that can be effectively implemented and verified using the capabilities of the Revit API. Notably, rules falling only under the dimensions of 'directive' or 'strategy' are excluded from consideration. This decision is informed by the recognition that these particular rules are necessary only during the creation of the BIM management plan and initiation of BIM coordination meetings. By focusing on rules that align with the capabilities of the Revit API and excluding those requiring pre-emptive implementation, the prototype aims to streamline its functionality within the Revit environment and ensure practicality and efficiency in clash avoidance.

The design rules and best practices selected for developing the prototype are as follows; (i)when the plugin starts, the designer must have the option to review the clash avoidance tutorial ; (ii) always have the clash avoidance tutorial accessible to the designer do they can refer back to it at will ; (iii) always lock or pin the linked models in place ; (iv) the interior walls should not travel over the ceiling.

All chosen rules need to be standardized within a single plugin. This plugin should have the capability to present the clash avoidance tutorial whenever designers wish to review it. Furthermore, it should be enabled to simultaneously examine the BIM specialty model from any discipline, for deviations from clash avoidance rules.

At this juncture, the Clash Avoidance Assistant system was chosen to be hosted on Revit version 2024. This selection was based on the consideration that most engineering and architectural consultancy firms typically opt for the latest software version, making Revit 2024 the preferred choice. As per the Revit API documentation, the programming language of choice for developing plugins that seamlessly integrate with the platform and effectively communicate with the API is C#.

Figure 5.5 shows the simplified construction of the C# based code for the clash avoidance plugin which outlines the logics for the execution of the selected clash avoidance rules. The first function provides the user with initial choice of whether to review the clash avoidance tutorials or perform clash avoidance rule deviation check. The *ShowInitialDialogue* function initiates user interaction, presenting two options: to explore Clash Avoidance Tutorials or perform a clash avoidance rule deviation check. If the user selects the tutorial option, the *ShowClashAvoidanceTutorial* function opens a web link directing to the clash avoidance tutorial. The documents saved in the shared link can be edited by the authorised personnel in need. So the clash avoidance tutorial and rule base can be changed depending on the type of building, building system, and the type of project.

On the other hand, if the user opts for the clash avoidance rule deviation check, the *LaunchRuleDeviationCheck* function is invoked. This function first retrieves all linked model instances in the model, prompting the user to pin any unpinned models byshowing them the name of the linked model whose pinned status in ‘unpinned’. Subsequently, the code checks for walls in the model. If any wall's height surpasses a predefined threshold, a dialogue is displayed, indicating that the interior wall height cannot exceed the ceiling height. The predefined height threshold is taken from a shared parameter file which is also editable based on the need of the particular project or building system. The error message shown when this rule is deviated provides guidance on adjusting the wall height. The function concludes by returning a list of wall_ids for reference. Figure 5.6 and 5.7 shows how the plugin communicates with the designer to provide constant access to the clash avoidance tutorial and to show error prompts which results in better rule adherence.

```
# The function provides the user with initial choice of whether to look into the clash avoidance
tutorials or perform clash avoidance rule deviation check

Function ShowInitialDialogue():


        Option1= "Show Clash Avoidance Tutorials"

        Option2 = "Launch Clash Avoidance Check


        If Option1 is clicked:

                ShowClashAvoidanceTutorial()

        Else
                LaunchRuleDeviationCheck()

Return


# Function to open the clash avoidance tutorial
Function ShowClashAvoidanceTutorial():

        OpenWeblink('Link to tutorial')

Return


# Function that performs clash avoidance rule deviation check
Function LaunchRuleDeviationCheck():

        Get linked model instances

        For each linked model instances:

                If model is not Pinned:

                        ShowDialogue('Please pin the linked model(s)' + linked_model_ids)


        Check if there are any walls in the model
        For each walls:
                If wall height > defined threshold from shared parameter ceiling height:
                        ShowDialogue("Interior wall height cannot exceed ceiling height \n",
                                    "Please change the height of " + wall_ids)

                        Return list of wall_ids
```

Figure 5.5 Simplified construction of the C# based code for the clash avoidance plugin

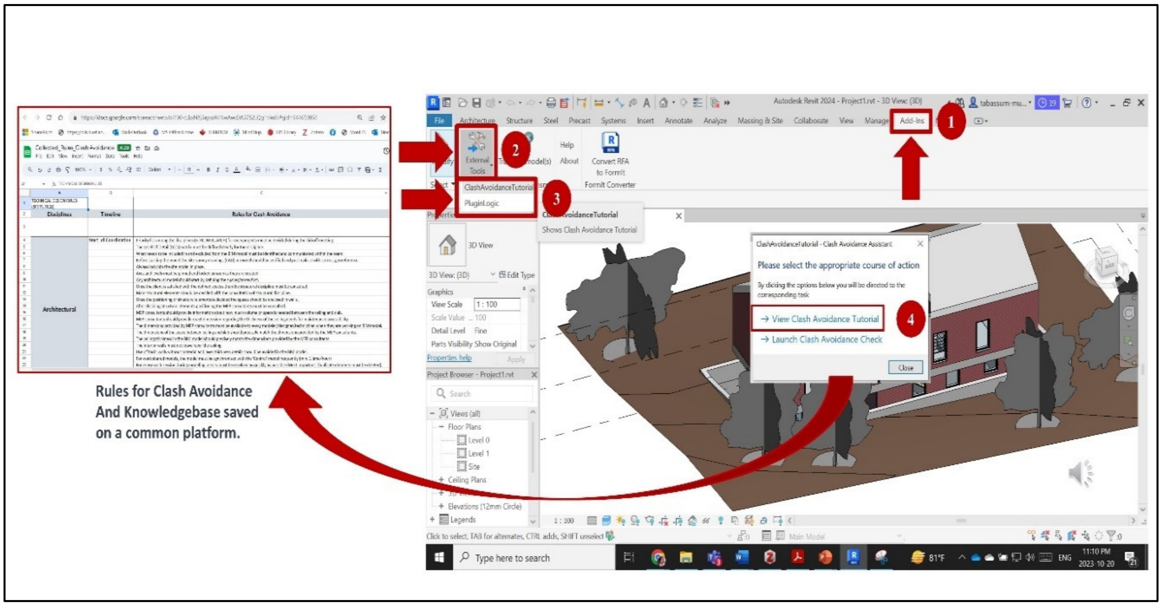

Figure 5.6 Always accessible clash avoidance tutorial in the plugin

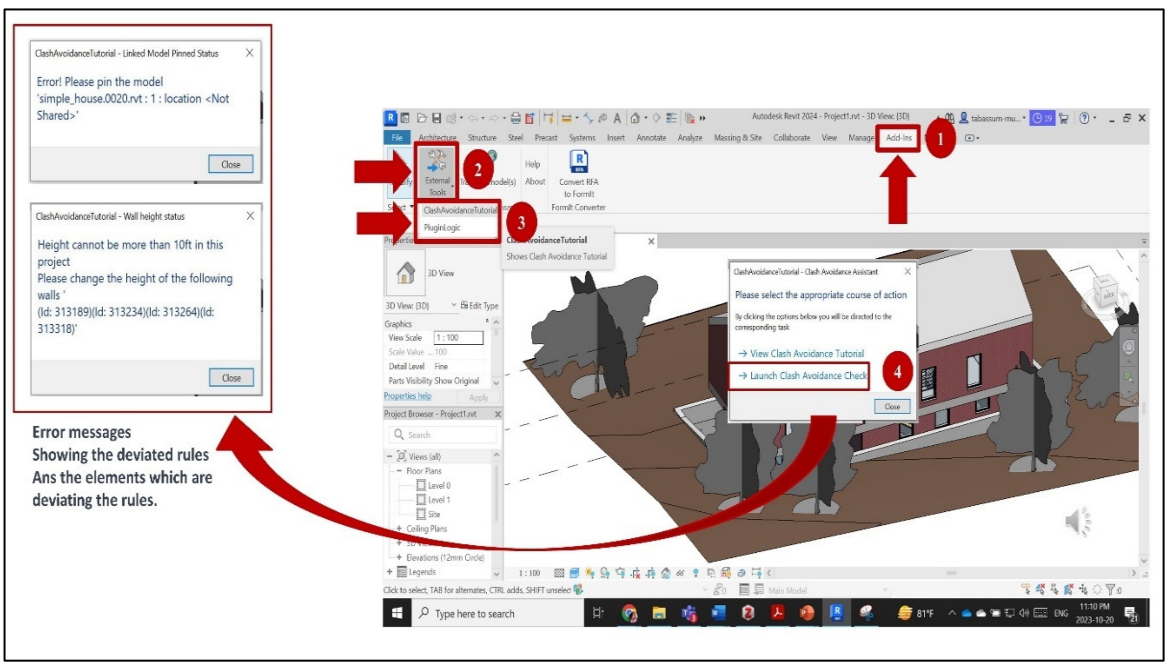

Figure 5.7 Error prompt shown to the designer when rules are deviated

This simplified code encapsulates the primary decision flow and actions associated with the clash avoidance system plugin, offering users the flexibility to either delve into educational resources or actively assess clash avoidance rule deviations within the BIM model. The modular design promotes clarity and ease of maintenance, aligning with best practices in plugin development for Revit.

5.4 Evaluation of the clash avoidance system

The developed prototype of the clash avoidance system plugin was evaluated using two real-life case studies. The first case study took place in the architectural specialty model creation phase of a mixed-use building project. The partner organization is based in USA and is the architectural design consultant for this project and was responsible for providing the design documents and architectural specialty BIM model to the structural and MEP engineering design consultants. The second case study took place during the MEP specialty model creation phase of a warehouse building ptoject. The partner organization which provides engineering design consultation is based in Canada.

5.4.1 Findings from the first case study : Architecural specialty model creation

5.4.1.1 Project description

The multipurpose building comprising both commercial and residential facilities is slated for construction in Illinois, USA. The project adopts the traditional design-bid-build delivery method. The owner has engaged architectural consultants to deliver the building's design, accompanied by a fully realized architectural BIM model using the Revit 2024 software. The project owner has additionally chosen structural and MEP engineering design consultants. These consultants stipulate a minimum Level of Detail (LOD) of 300 for the architectural BIM model to commence their respective system designs. This specific LOD necessitates the architectural model to possess accurate and detailed geometry.

The proposed mixed-use development boasts a net floor area of approximately 17,927 square feet, excluding the basement and garage areas. The basement, comprising 2,157 gross square feet, serves as a foundational space. The commercial space, foyer, and hall collectively occupy a net area of 2,588 square feet, providing a dedicated area for commercial activities.

Accommodating a net space of 2,950 square feet, the garage is designed to meet parking requirements. The residential component, featuring 22 dwelling units, encompasses a gross space of 15,339 square feet. This holistic configuration ensures a versatile and well-organized utilization of space in the envisioned development.

5.4.1.2 Application of the clash avoidance system plugin

The clash avoidance system plugin designed for Revit's 2024 version was distributed to two voluntary participants, both of whom serve as architectural designers and hold responsibilities for developing the architectural model for both the residential and commercial segments of the mixed-use building. The participants will be addressed as ‘designer 1’ and ‘designer 2’ in the rest of this sub-section. Clash avoidance system plugin was subjected to evaluation by designer 1 and 2. The assessment focused on key aspects including ease of use, efficacy in avoiding clashes, model quality improvement, and ease of deployment.

In a structured evaluation process, both designers actively utilized the clash avoidance system plugin over the course of one week during their work sessions dedicated to the multipurpose building model creation. Following this practical application, a comprehensive interview was conducted by the researcher, wherein the designers shared their insights on key aspects of the evaluation. The interview framework required the designers to assign ratings to the prototype on a scale from 0 to 5, with 0 indicating the lowest efficacy and 5 signifying the highest.

During the interview, the designers were further prompted to elucidate the reasoning behind their individual ratings, providing a qualitative dimension to the numerical scores. Table 5.2 shows the responses and ratings from designer 1 and 2 for each aspect of the clash avoidance system plugin evaluation stage. This approach aimed to capture nuanced feedback and valuable insights into the practical usability and effectiveness of the clash avoidance system plugin in their real-life work scenarios and areas for potential improvement.

Table 5.2 Evaluation results from the first case study

Key aspects	Participants	Rating	Summarized opinion	Possible improvement
Ease of use	Designer 1	4	Relatively intuitive and user-friendly. The interface design facilitated a smooth navigation experience. However, a minor learning curve was identified, leading to a reduced rating.	Tutorial of the plugin usage can be provided for designers.
	Designer 2	5	The plugin exceptionally easy to use, with an interface that facilitated quick adoption. The logical flow of choices provided an intuitive experience.	
Efficacy in avoiding clashes	Designer 1	5	Appreciated the proactive features, resulting in a flawless clash avoidance mechanism.	Advised on adding more rules to the rule deviation check function.
	Designer 2	5	Believes that the proactive features were instrumental in preventing clashes early in the design phase	

Table 5.2 Evaluation results from the first case study (cont'd)

Key aspects	Participants	Rating	Summarized opinion	Possible improvement
Model quality improvement	Designer 1	4	Acknowledged the positive impact. Plugin will save significant work hours while checking model deliverables from other professionals.	Advised on further threshold for checking model element status for more precision.
	Designer 2	5	Believes the early identification of rule deviation saved work hour in addition to improving model quality. Find the accessibility to clash avoidance tutorial particularly useful.	
Ease of deployment	Designer 1	5	Deployment was seamless, with the plugin effortlessly integrating into the existing workflow.	
	Designer 2	4	Deployment was generally smooth	

This approach aimed to capture nuanced feedback and valuable insights into the practical usability and effectiveness of the clash avoidance system plugin in their real-life work scenarios and areas for potential improvement. In summary, both designers provided positive feedback, emphasizing the plugin's efficacy in avoiding clashes, ease of use, and contributions to improving the model quality. While designer 1 suggested further enhancements, both

designers agreed on the plugin's seamless deployment and positive impact on clash prevention, showcasing a robust performance in real-life industrial use.
The consensus between both designers is that the Clash Avoidance System can be implemented organization-wide due to its straightforward deployment and user-friendly interface.

5.4.2 Findings from the second case study : MEP specialty model creation

5.4.2.1 Project description

The second case study takes place during the MEP specialty model creation phase of a compact warehouse facility. This facility is to be constructed in Ontario, Canada, employing the traditional design-bid-build delivery method. The owner of the project has enlisted the engineering consultants to formulate the warehouse's MEP design, incorporating a comprehensive specialty BIM model using Revit 2024 software. The MEP consulting team received the site models and the interior and exterior architectural specialty models from the architectural design team. The BIM management plan for the project required the MEP specialty model to have accurate and detailed geometry for their subsequent system designs. The MEP design team decided to build separate mechanical, electric, plumbing, and fire safety BIM models, which were combined to create the deliverables for this project. The modeling for the sub-disciplines was done simultaneously and was started as soon as the architectural specialty models and site models were received.

This compact warehouse project boasts a net floor area of approximately 8,500 square feet. The layout includes a functional ground floor area of 7,000 square feet dedicated to storage and operational activities. The remaining 1,500 square feet comprise a mezzanine level intended for additional storage or office space. The architectural configuration is tailored to meet the specific needs of a warehouse facility while providing a seamless and well-organized space for storage and operational requirements.

5.4.2.2 Application of the clash avoidance system plugin

The clash avoidance system plugin designed for Revit's 2024 version was distributed to two voluntary participants that will be addressed as 'designer 3' and 'designer 4' in this sub-section. Both designers provided the evaluation for the system which is summarized in table 5.3.

Table 5.3 Evaluation results from the second case study

Key aspects	Participants	Rating	Summarized opinion	Possible improvement
Ease of use	Designer 3	5	The interface was intuitive and user-friendly, ensuring a seamless navigation experience. Users encountered no learning curve and particularly valued the constant accessibility of the knowledge base.	
	Designer 4	5	The plugin proved exceptionally user-friendly, featuring an interface that enabled quick adoption.	
Efficacy in avoiding clashes	Designer 3	4	The plugin is extremely helpful for reducing design errors and instill best practices. Acknowledges that the clash prevention functionalities saved time and can save significant man hours if applied throughout the project.	Suggested enhancing the rule deviation check function by incorporating additional rules and allowing customization based on the project type.

Table 5.3 Evaluation results from the second case study (cont'd)

	Designer 4	5	Believes that the proactive features were instrumental in preventing clashes in the design phase.	
Model quality improv-ement	Designer 3	4	Plugin was particularly helpful in checking model quality for participant's discipline and for checking models received from other disciplines.	Recommended that more dimension threshold for checking the status of model elements for quality enhancement.
	Designer 4	5	The participant found the plugin highly beneficial in maintaining standard quality and expressed the belief that its adoption across the entire organization could lead to quality standardization.	
Ease of deploy-ment	Designer 3	5	Deployment was seamless, with the plugin effortlessly integrating into the existing workflow.	
	Designer 4	5	Deployment was seamless and took very little time.	

Designer 3 holds the responsibilities for developing the electrical specialty model, and designer 4 is responsible to developing the fire safety specialty model for the compact warehouse building. Similar to the first case study, this assessment also focused on key aspects including ease of use, efficacy in avoiding clashes, model quality improvement, and ease of deployment. Both designers actively engaged with the Clash Avoidance System plugin throughout dedicated work sessions focused on creating their respective sub-discipline’s specialty model, spanning two weeks. Subsequent to this hands-on application, the researcher conducted an extensive interview, prompting designers to provide ratings for various aspects of the prototype. Designers utilized a rating scale from 0 to 5 during the interview, with 0 representing the lowest efficacy and 5 denoting the highest. Throughout the interview, designers were encouraged to elaborate on the rationale behind their assigned ratings, adding a qualitative perspective to the numerical scores. The responses and ratings from designer 3 and 4 for each aspect of the Clash Avoidance System plugin evaluation stage are presented in Table 6.3.

Both designers offered positive feedback, highlighting the plugin's effectiveness in clash avoidance, user-friendly interface, and its positive influence on enhancing model quality. Although designer 3 suggested adjusting the dimension threshold for model element checking, they also confirmed that the plugin's clash avoidance capabilities result in substantial time savings. Both designers concurred on the plugin's seamless deployment and its significant impact on preventing clashes and design errors. They collectively affirmed the system's robust performance in real-life industrial applications. The designers for the second case study did not mention any discipline specific issues while using the plugin.

CHAPTER 6

DISCUSSION

This chapter provides an interpretation of the findings derived from case studies and establishes connections with the pre-existing knowledge within the context of clash avoidance strategies in BIM-based multidisciplinary coordination. Initially, this chapter consolidates the primary research discoveries and relates them to the original research question. Subsequently, it positions these findings within the scope of the current research, elucidating implications and connections with prior studies. Thirdly, limitations and prospects for future work are delineated. Finally, a comprehensive overview of the discussions is presented, accompanied by potential avenues for subsequent research studies.

6.1 Discussion on the research questions and key findings

The goal of this research is to propose a method streamlining the multidisciplinary coordination by proactively avoiding clashes in BIM-based multidisciplinary coordination. The research question posed in this work seeks to develop an integrated system for BIM authoring tools to enable the proactive application of proven knowledge, lessons learned, best practices, and design rules to promote clash avoidance in a BIM-enabled project. The research question was formulated to align with the research goal. This research question was further broken down in research objectives which guided the work towards its key findings. This thesis extensively examined previous research on clash avoidance, revealing limited existing studies. The analysis highlighted knowledge gaps, particularly in proactive clash management. The background analysis revealed that researchers have explored various obstacles impacting BIM-based coordination. Researchers have pinpointed specific categories of obstacles influencing various aspects of the process, including process, actor, task, context, and team. Notably, these obstacles predominantly impact the coordination strategy development and specialty BIM model creation stages. As these stages represent the initial steps in the coordination process, any obstacles encountered here can significantly compromise the overall efficiency of the BIM coordination for the entire project in subsequent stages. The background analysis also studied the causes of clashes identified by previous research works, with design errors and the failure of design rules being identified as the primary contributors to the highest number of clashes in BIM models. The comprehensive analysis also considered existing investigations focused on addressing these causes. A key finding from this study suggests that documenting lessons learned and best practices within the organization, coupled with disseminating this information to all members, holds the potential to significantly decrease design errors and clashes in BIM models given that the team members ensure the application of the said lessons learned.

The methodology of this research was chosen based on the findings derived from the background studies. Design Science Research methodology which was selected for this work requires working closely with domain experts, practitioners, or stakeholders to gain a deep understanding of the problem, its context, and the requirements for a potential solution. The collaboration with industry experts represents a crucial step in validating the importance of the work undertaken, focusing on clash management within the BIM collaboration process. Clash management, which involves identifying and resolving clashes in the virtual representation of a construction project, is a persistent concern in BIM coordination. Through extensive collaboration with domain experts, a total of 58 design rules or best practices were identified as essential in preventing clashes during BIM coordination. These design rules address architectural, structural, and MEP disciplines. These rules were collected from the expertise and insights of industry professionals who are well-versed in the intricacies of clash management and BIM process management within BIM workflows. To refine and prioritize these design rules, a subsequent phase of investigation took place, involving consultation with experienced professionals in the field. This thorough examination led to the identification of 35 rules that were deemed the most critical for effective clash avoidance and for enhancing the overall quality of the BIM model. The gathered design rules underwent a comprehensive analysis to elucidate various facets of their application. This examination sought to delineate the temporal aspects of rule application within the BIM collaboration process, specifying instances such as when a rule should be applied. Additionally, the analysis extended to understanding the methodological dimensions of rule application, encompassing considerations such as how a rule should be implemented. The analysis further delved into the modalities of applying these rules, encompassing diverse approaches such as reminders, error prompts, integration into the BIM management plan, and incorporation into BIM coordination meetings. This exploration aimed to provide insights into the varied mechanisms through which these rules could be effectively deployed for clash avoidance. Moreover, the study probed the applicability of these rules across different workflow paradigms, distinguishing between scenarios such as CAD-to-BIM and fully BIM-based collaboration workflows. This examination served to highlight the adaptability and relevance of the identified rules within distinct operational contexts, contributing to a more nuanced understanding of their potential impact across various BIM implementation scenarios.

The proposed clash avoidance system derived from design rules and best practices endorsed by industry experts as highly effective for clash prevention, is the main artifact of this study. The system is specifically crafted to operate within the BIM authoring tool environment, aiding designers in adhering to design rules and best practices during BIM model creation. This ensures the proactive avoidance of clashes. The practicality and effectiveness of the developed artifact prototype were assessed through two real-world case studies. These case studies aimed to understand the artifact's impact on clash avoidance and enhancement of BIM model quality. Additionally, it evaluated how the artifact aids designers in adhering to expert-recommended best practices and lessons learned.

6.2 Contextualisation of the key findings

In light of the current trends emphasizing efficiency in clash management within BIM-based coordination, the conceptual foundation of the proposed artifact is rooted in the theory that documenting and applying lessons learned can significantly enhance proactive clash avoidance. It expanded upon and applied pre-existing concepts and theories with the knowledge collected from the experienced industry experts, addressing the industry's challenge of a deficiency in practical approaches for clash avoidance.

The main goal of the proposed artifact is to work as an integrated system for BIM authoring tools which enables the proactive application of proven knowledge, lessons learned, best practices, and design rules to promote clash avoidance in a BIM-enabled project. To explore this research query, the thesis delved into the current knowledge base to discern the significance of incorporating lessons learned in enhancing the efficiency of the BIM coordination process. The effort to understand the impact of known obstacles on different stages of the BIM coordination process showed that the initial phases of BIM-based design coordination are particularly impacted by the identified obstacles categories. Specifically, obstacles categorized under the 'process' category exert a notable influence on the strategy formulation, model generation, and clash detection phases. Obstacles associated with 'actor' category impact both the initial and concluding stages of the design coordination process. 'Task' category of obstacles become prominent during the individual model generation phase. This investigation shows that the obstacles manifest during specialty model generation and federated model creation, they can impede the overall efficiency of coordination and, by extension, influence the subsequent phases of the construction project. Through a thorough literature review, it becomes apparent that the most significant impact of the identified obstacles occurs in the initial two phases of design coordination: the formulation of the coordination strategy and the generation of specialty models. Among the five categories of obstacles, the team-related, task-related, and process-related hurdles have the most significant impact on these stages.

To fulfill the thesis's goal, five research objectives were pursued. The initial objectives aim at pinpointing gaps in existing research related to clash management and proactive clash avoidance and to identify the most prominent causes of clashes in BIM-based multidisciplinary coordination. A thorough investigation on the causes of clashes and clash management strategies studied by prior research works was undertaken to identify the research gaps. The findings demonstrated that the primary sources of clashes predominantly arise during the initial stages of multidisciplinary coordination, specifically in the creation of specialty models and federated models. Researchers emphasize the importance of documenting lessons learned within the organization, so that team members can access the information in need and clashes can be avoided. Despite substantial efforts to improve clash detection tools and explore automation for clash resolution, there remains a lack of guidelines or streamlined processes for documenting and implementing lessons learned, a crucial aspect of clash avoidance. As a result, design teams continue to grapple with undesired design errors and discrepancies, leading to an increased occurrence of clashes. This discovery highlights potential research directions for establishing an efficient, standardized process for documenting lessons learned and leveraging these insights during multidisciplinary coordination, with the ultimate goal of preventing design errors and clashes.

The subsequent objective aimed at establishing an effective methodology for crafting a proactive clash avoidance strategy, a goal successfully realized through the adept application of Design Science Research (DSR) methodology. DSR, chosen for its inherent capacity to address complex practical challenges, methodically steers the research journey, ensuring a systematic and thorough exploration of problem identification, artifact creation, and rigorous evaluation. This meticulous approach guarantees a comprehensive and robust foundation for the proactive management of clashes in the construction industry. The next stage of this study is dedicated to fulfilling the research objective of identifying and codifying design rules and best practices obtained from BIM experts for the purpose of clash avoidance. This objective is addressed by collaboration with industry experts in the context of the research's problem statement. This step consisted of standard open-ended interview with industry experts which ensures that this research remains deeply rooted in practical relevance while enhancing the potential for crafting a highly effective and context-aware solution for proactive clash avoidance. During this collaboration, the experts showed most concerns about the high number of clashes in detection software, requiring substantial effort for resolution. Challenges such as the absence of automatic clash management tools and a lack of standard for BIM collaboration are also prominent. Cloud-based platforms such as Autodesk Construction Cloud have reduced issues related to visual access and centralized communication channels, lowering their priority among obstacles. Designers strongly endorse two key functionalities in the proposed clash avoidance tool: a readily accessible knowledge base for continuous reference and timely warnings for deviations from design rules. The qualitative data collected from the professionals resulted in 58 design rules and best practices which the professionals believe can reduce clashes in BIM models. Industry professionals rated the gathered rules to ultimately solidify a refined set of 35 rules recognized as the highly effective and promising for improving the BIM coordination process. The carefully curated and validated rules correspond to Architectural, Structural, and MEP specialty models respectively. The findings from the collaboration with industry experts shows that the increasing number of clashes remains a prominent issue in the BIM coordination process. The findings also identify the lack of automatic clash management tools and lack of proper documentation of lessons learned as the most prominent obstacles in BIM collaboration. Which concurs with the findings of the literature review section of this thesis presented in chapter 1.

Once the set of rules was compiled with the assistance of experienced industry professionals a conceptual model for the clash avoidance system was proposed based on the principles of rule-based system. The proposed clash avoidance system features a constantly accessible knowledge base and tutorial for designers, ensuring they can refer to it throughout their work. It prompts designers to explore the tutorial at the beginning of each session, enhancing the quality of BIM models. Additionally, the system issues error prompts for deviations from encoded design rules, fostering informed and effective design practices. These functionalities have been deemed important by the industry professionals in the interview stage of the study. Next, sample design rules were selected from the collected set of rules and a prototype clash avoidance system based on the selected sample rules was created. This clash avoidance system prototype functions as a plugin within the Revit environment, The Clash Avoidance Assistant plugin was tailored for Revit 2024, aligning with the industry trend for the latest software version. Developed using C#, it ensures seamless integration with the Revit API, optimizing communication and functionality. The evaluation of the developed system prototype was done via real world projects where designers used the system to understand it's efficacy in terms of ease of use, clash avoidance, and model quality improvement. The case studies demonstrated the plugin's smooth implementation and its effective role in preventing clashes, highlighting its robust performance in practical industrial scenarios. The development and evaluation of the clash avoidance system for BIM authoring tools satified the final objective of this study.

6.3 Research limitations

Recognizing these limitations is crucial for a nuanced understanding of the study's scope and potential implications. Most of the insights gathered in the design rules and best practices collection phase originate from industry professionals based in North America which introduces a potential limitation in terms of generalizing clash avoidance system outcomes to a more diverse international context. The inclusion of perspectives from a broader geographical spectrum would offer a more comprehensive understanding of the system's applicability on a global scale. Additionally, the development of the prototype involved a limited number of clash avoidance design rules, raising considerations about the system's adaptability to a broader range of clash scenarios. Addressing this limitation requires expanding the rule set to enhance the system's applicability across various contexts and construction projects. Furthermore, the evaluation stage was conducted via two real world case studies focusing on the specialty model creation for architectural and MEP discipline. The evaluation stage lacks control test for a quantitative assessment due to time constraint. This scope limitation calls for future studies to include diverse clash scenarios and evaluators, ensuring a more robust and comprehensive evaluation of the clash avoidance system.

In navigating these limitations, this research sets the stage for continued exploration and refinement of clash avoidance strategies in BIM-based multidisciplinary coordination. By acknowledging and addressing these constraints, future efforts can further enhance the applicability, adaptability, and overall effectiveness of the proposed clash avoidance system in construction industry practices.

CONCLUSION

The thesis conclusion will provide context to the major findings, interpret results derived from data collection, artifact design and development, and case study. Additionally, this section will also establish connections with the current body of knowledge in the realm of clash management within BIM-based multidisciplinary coordination. Initially, the research summarizes the key findings and correlates them with the initial research question. Subsequently, these findings are contextualized within the scope of this research, exploring their implications and alignments with prior studies. Following that, limitations and the future trajectory of the work are delineated. Finally, the conclusion includes a summary of discussions and proposes potential avenues for subsequent research studies.

The literature review conducted in this thesis reveals that obstacles in BIM-based multidisciplinary coordination have been extensively discussed in recent years. Researchers have placed significant importance on documenting lessons learned and implementing strategies to enhance the efficiency of construction projects. The background study further indicates that the initial two stages of the multidisciplinary coordination process, namely developing the coordination strategy and generating specialty models, are particularly susceptible to these obstacles. This underscores the critical need for targeted interventions and innovative solutions in these early phases of coordination to mitigate challenges and improve overall project outcomes.

Subsequently, this thesis delved into contemporary research on clash management, exploring the predominant causes of clashes and examining prior solutions proposed by researchers to address these issues. The investigation revealed that the primary sources of clashes often originate during the initial stages of multidisciplinary coordination, particularly in the development of specialty models and federated models, aligning with the literature review findings. Furthermore, the study highlighted significant efforts in enhancing clash detection tools and exploring automated clash resolution methods. However, a notable gap persists in the absence of guidelines or a streamlined process for documenting and implementing lessons learned—a crucial aspect of the proactive approach to clash management, specifically clash avoidance. As a consequence, design teams continue to grapple with undesired design errors and discrepancies, contributing to an increased occurrence of clashes.

This discovery underscores potential research avenues for establishing an efficient and standardized process for the systematic documentation of lessons learned, coupled with their subsequent incorporation into multidisciplinary coordination practices. The objective is to proactively prevent undesired design errors and mitigate clashes, addressing a critical aspect of effective clash management in BIM-based projects.

Following this, the thesis underscores the pivotal collaboration with industry experts to affirm and refine earlier findings, specifically focusing on delineating the most effective methods for avoiding clashes. The incorporation of lessons learned, design rules, and best practices from experienced industry professionals was a fundamental aspect of this collaborative effort. In the initial round of interviews, ten professionals possessing extensive knowledge in BIM actively participated, contributing valuable insights and experiences. The outcome of this collaboration resulted in a comprehensive set of 58 design rules, spanning architectural, structural, and MEP disciplines. This collaborative approach aimed to enrich clash avoidance strategies by leveraging the collective expertise of industry practitioners. The findings derived from the initial round of interviews underwent further validation by a distinct group of industry professionals. The conclusive set of design rules and best practices, as a result of this iterative process, culminated in a total of 35 rules. This validation process reinforced the robustness and reliability of the identified design rules and best practices for clash avoidance in BIM-based multidisciplinary coordination.

The insights gathered from the two rounds of interviews underscore the consensus among industry experts that automatic intervention within the BIM authoring tool during the specialty model creation phase holds significant potential to substantially diminish the number of clashes and enhance the overall quality of models. Additionally, the experts emphasized the critical importance of maintaining an always-available knowledge base for clash avoidance rules and error prompts. These serves as resources that consistently guides designers, notifying them when deviations from design rules occur. This emphasis on real-time guidance and continuous adherence to clash avoidance principles reflects a holistic approach to improving BIM model quality throughout the design process.

These findings served as the foundation for the design and development of the rule-based clash avoidance system prototype. Crafted as a C# based plugin compatible with the Revit 2024 environment, this system aimed to provide a seamless experience for designers. The plugin offers constant accessibility to clash avoidance tutorials, housing design rules and best practices. Simultaneously, it notifies designers of any deviations from the encoded rules, ensuring real-time guidance. In the evaluation phase, the plugin underwent practical testing in a real-world scenario, specifically during the creation of an architectural specialty model for a mixed-use building. The two participating architectural designers expressed positive feedback, emphasizing the plugin's efficacy in clash avoidance, user-friendly interface, and its notable contribution to enhancing model quality. While one designer suggested potential enhancements, both affirmed the plugin's seamless deployment and its positive impact on preventing clashes, showcasing robust performance in real-life industrial applications.

This study draws its foundational design rules and best practices from seasoned industry professionals spanning diverse sectors within the construction industry. However, a notable limitation lies in the geographical concentration of the participating professionals, as all contributors are based in North America. This geographical constraint may influence the generalizability of the clash avoidance system's outcomes to a broader international context.

Furthermore, the prototype development incorporates a limited set of clash avoidance design rules, presenting a challenge in comprehensively assessing the plugin's performance in reducing clashes. The total number of collected rules for the prototype amounted to 35, potentially limiting the system's adaptability to a broader spectrum of clash scenarios.

Lastly, the evaluation stage featured two professionals from the same organization and the same discipline collaborating on the same project to assess the plugin. While their feedback provided valuable insights, the absence of a control test to objectively measure the system's efficacy poses a limitation in quantitatively determining its impact on clash reduction. A more extensive and varied set of clash scenarios and a diverse pool of evaluators would contribute to a more robust and generalizable evaluation of the clash avoidance system.

A significant avenue for future research involves the meticulous encoding of crucial collaboration and spatial design rules extracted from the amassed clash avoidance rules and best practices. The subsequent application of the system across a spectrum of real-world projects, encompassing specialty model creation for all disciplines, would provide an invaluable opportunity to gauge the true impact of the system on enhancing the efficiency of BIM-based multidisciplinary coordination. This future work could employ comprehensive quantitative metrics to assess the system's effectiveness across diverse scenarios.

Furthermore, exploring the system's potential to predict clashes based on deviated rules using artificial intelligence (AI) represents an intriguing avenue for further investigation. By incorporating AI techniques, the system could evolve to anticipate clashes and proactively offer suggestions or interventions to prevent clashes from occurring, thereby enhancing its predictive capabilities.

Additionally, there is a prospect for future work in developing automation that assists designers not only in clash avoidance but also in correcting design errors. This dual-functionality approach aims to not only reduce the number of detected clashes but also streamline the correction of design discrepancies. Investigating the feasibility and effectiveness of such automation would contribute to the construction industry tremendously.

ANNEX I

CLASH AVOIDANCE RULES : ARCHITECTURAL

Table-A I-1 Collected clash avoidance rules for the architectural discipline and their representation format

Discipline	Clash Avoidance Rules	RULE PRESENTATION FORMAT DURING COORDINATION (MEETINGS + WORK SESSION)
Architectural	Priority list among the disciplines (STRC, MEP, ARCH) for each projects must be decided during the kickoff meeting.	BIM Management Plan ; Must be presented in kickoff meeting agenda.
	The Level Of Detail (LOD) matrix must be defined clearly for the discipline.	BIM Management Plan
	What needs to be included in and excluded from the BIM model must be identified and communicated within the team.	BIM Management Plan ; BIM Coordination Meetings
	Before starting ro model, the Site survey drawings (CAD) or model should be verified and put in place with correct georeference.	BIM Management Plan ; BIM Coordination Meetings
	Always lock/pin the site model in place.	Tutorial Module of Clash Avoidance Assistant ; Reminder
	Axes and levels must be pinned and locked as soon as they are created.	Tutorial Module of Clash Avoidance Assistant ; Reminder
	Any architectural model should start by defining the spaces/zones first.	Tutorial Module of Clash Avoidance Assistant
	Once the client is satisfied with the defined spaces then the structural discipline must be consulted.	BIM Management Plan ; BIM Coordination Meetings
	Main structural elements should be decided with the consultation of structural discipline.	BIM Management Plan ; BIM Coordination Meetings
	Once the positioning of structural elements is decided the spaces should be enclosed in walls.	BIM Management Plan; Tutorial Modele of Clash Avoidance Assistant.
	After deciding structural elements positioning the MEP consultants must be consulted.	BIM Management Plan ; BIM Coordination Meetings
	MEP consultants should provide information about how much volume or space is needed between the ceiling and slab.	BIM Management Plan ; BIM Coordination Meetings
	MEP consultants should provide exact dimension regarding the thickness of the ceiling needs for maintenance accessibility.	BIM Management Plan ; BIM Coordination Meetings
	The dimensions provided by MEP consultants must be available to every modeler/designer/technichian when they are working on BIM model.	Tutorial Module of Clash Avoidance Assistant

Table-A I-1 Collected clash avoidance rules for the architectural discipline and their representation format (cont'd)

Discipline	Clash Avoidance Rules	RULE PRESENTATION FORMAT DURING COORDINATION (MEETINGS + WORK SESSION)
Architectural	The dimensions of the space between ceiling and slab should precisely match the dimensions provided by the MEP consultants.	Error prompt if the dimension is less than recommended
	The ceiling thickness in the BIM model should precisely match the dimensions provided by the MEP consultants.	Error prompt if the dimension is less than recommended
	The interior walls must not travel over the ceiling.	Tutorial Module of Clash Avoidance Assistant ; Error prompt if the dimension is less than recommended
	Use of basic walls without material and layer thickness details should be avoided in the BIM model.	Reminder ; Error prompt if basic wall is detected
	For work shared models, the model must be synchronized with the 'Central' model frequently (min. 1 time/hour)	Tutorial Module of Clash Avoidance Assistant ; Reminder
	For every work session during modeling, errors must be resolved as quickly as possible (Most important: Duplicate elements must be deleted)	Tutorial Module of Clash Avoidance Assistant ; Reminder
	A first iteration of the model with LOD 200 should be created with the correct dimensions of walls and ceilings.	BIM Management Plan ; Quality Control
	The first LOD 200 model iteration should be shared with the structural and MEP disciplines.	BIM Management Plan ; BIM Coordination Meetings

ANNEX II

CLASH AVOIDANCE RULES : STRUCTURAL

Table-A II-1 Collected clash avoidance rules for the structural discipline and their representation format

Discipline	Clash Avoidance Rules	RULE PRESENTATION FORMAT DURING COORDINATION (MEETINGS + WORK SESSION)
Structural	Before starting the model the Site survey drawings (CAD) or model should be verified and put in place with correct georeference.	BIM Management Plan ; BIM Coordination Meetings
	Always lock/pin the site model in place.	Tutorial Module of Clash Avoidance Assistant ; Reminder
	Axes and levels must be pinned and locked as soon as they are created.	Tutorial Module of Clash Avoidance Assistant ; Reminder
	The structural discipline should receive the first iteration LOD 200 model from the architectural discipline before starting their modeling.	BIM Management Plan ; BIM Coordination Meetings
	Once the structural discipline has received the LOD 200 architectural model then the MEP discipline should be consulted.	BIM Management Plan ; BIM Coordination Meetings
	Structural and MEP consultants should clearly identify the spaces for mechanical elements within the sheer walls, and beams.	BIM Management Plan ; BIM Coordination Meetings
	MEP consultant should provide the exact measurements for the required duct and shaft openings.	BIM Management Plan ; BIM Coordination Meetings
	The duct and shaft openings in the BIM model should precisely match the dimensions provided by the MEP consultants.	Error prompt if the dimension is less than recommended
	A first iteration of the model with LOD 200 should be created with the correct dimension of duct and shaft openings, and the correct positioning of MEP components within the structural elements.	Tutorial Module of Clash Avoidance Assistant ; Error prompt if the dimension is less than recommended
	For work shared models, the model must be synchronized with the 'Central' model frequently (min. 1 time/hour)	Tutorial Module of Clash Avoidance Assistant ; Reminder
	For every work session during modeling, errors must be resolved as quickly as possible (Most important: Duplicate elements must be deleted)	Tutorial Module of Clash Avoidance Assistant ; Reminder
	The first model iteration should be shared with the architecture and MEP disciplines.	BIM Management Plan ; BIM Coordination Meetings

ANNEX III

CLASH AVOIDANCE RULES : MEP

Table-A III-1 Collected clash avoidance rules for the MEP discipline and their representation format

Discipline	Clash Avoidance Rules	RULE PRESENTATION FORMAT DURING COORDINATION (MEETINGS + WORK SESSION)
MEP	The work hierarchy of the MEP BIM model for each project should be decided in the kick-off meeting.	BIM Management Plan; BIM Coordination Meetings
	The confirmed work hierarchy must be communicated to all team members.	BIM Coordination Meetings ; Tutorial Module of Clash Avoidance Assistant
	MEP disciplines should collaboratively breakdown the space and define what height and space should be reserved for each discipline above the ceiling (identified as lanes).	BIM Management Plan; BIM Coordination Meetings; Tutorial Module of Clash Avoidance Assistant
	MEP discipline should breakdown what height and space should be reserved for each discipline in the shafts (identified as lanes).	BIM Management Plan; BIM Coordination Meetings; Tutorial Module of Clash Avoidance Assistant
	Before starting the model the Site survey drawings (CAD) or model should be verified and put in place with correct georeference.	BIM Management Plan ; BIM Coordination Meetings
	Always lock/pin the site model in place.	Tutorial Module of Clash Avoidance Assistant ; Reminder
	Axes and levels must be pinned and locked as soon as they are created.	Tutorial Module of Clash Avoidance Assistant ; Reminder
	MEP design should start from modeling the Mechanical room.	Tutorial Module of Clash Avoidance Assistant ; Reminder during the work sessions
	Once the Mechanical room is modeled then the HVAC system should be modeled.	Tutorial Module of Clash Avoidance Assistant ; Reminder during the work sessions
	The insulation dimensions between pipes and ducts should be clearly defined and modeled.	Tutorial Module of Clash Avoidance Assistant; Reminder during the work sessions
	The modeled insulation should match the required dimensions precisely.	Error prompt if the dimension is less than recommended
	Next, all components with slopes should be modeled (sanitation, rainwater management etc.)	Tutorial Module of Clash Avoidance Assistant; Reminder during the work sessions
	Finally, all components of the fire protection system should be modeled.	Tutorial Module of Clash Avoidance Assistant; Reminder during the work sessions
	HVAC , all slopes and fire protection system should be modeled simultaniously with maximum team coordination.	Tutorial Module of Clash Avoidance Assistant; Reminder during the work sessions

Table-A III-1 Collected clash avoidance rules for the MEP discipline and their representation format (cont'd)

Discipline	Clash Avoidance Rules	RULE PRESENTATION FORMAT DURING COORDINATION (MEETINGS + WORK SESSION)
MEP	All clearance spaces required for maintenance should be communicated to all team members.	BIM Management Plan; BIM Coordination Meetings; Tutorial Module of Clash Avoidance Assistant
	The clearance spaces in the BIM model should match the required dimensions acquired from guidelines or designers.	Error prompt if the dimension is less than recommended
	A first iteration of the model with LOD 200 should be created with the correct dimensions for all elements. The use of placeholders should be minimized.	Tutorial Module of Clash Avoidance Assistant; Reminder during the work sessions
	The first model iteration should be shared with the architecture and structural disciplines.	BIM Management Plan and BIM Coordination Meetings
	The MEP discipline must request and receive the the latest ceiling plans from the architectural discipline (Via weekly package publication).	BIM Management Plan and BIM Coordination Meetings
	The MEP discipline must do a manual check to ensure that they have the latest positions of all ceiling fixtures.	BIM Management Plan and BIM Coordination Meetings
	All electrical components that are in the 2D plan should be modeled in 3D.	Tutorial Module of Clash Avoidance Assistant; Reminder during the work sessions
	The final MEP BIM model should have LOD 350 (recommended but may not be possible to adhere to always).	BIM Management Plan, BIM Coordination Meetings; Tutorial Module and Reminders on the Clash Avoidance Assistant
	For work shared models, the model must be synchronized with the 'Central' model frequently (min. 1 time/hour)	Tutorial Module of Clash Avoidance Assistant ; Reminder
	For every work session during modeling, errors must be resolved as quickly as possible (Most important: Duplicate elements must be deleted)	Tutorial Module of Clash Avoidance Assistant ; Reminder
	The MEP discipline must do quality checks to ensure all necessary electrical and fire protection components shown in the 2D plan are present within the model.	BIM Management Plan; BIM Coordination Meetings; Tutorial Module; Reminders on the Clash Avoidance Assistant

ANNEX IV

EVALUATION QUESTIONNAIRE FOR CLASH AVOIDANCE STRATEGIES

Table-A IV-1 The questions provided to the BIM professionals

Questionnaire Sections	Questions
Introduction	1. Full name of the participant
	2. How do you define your job responsibilities in the BIM coordination process? Please explain briefly.
	3. How many years of experience you have been working on BIM-based projects?
	4. Generally what scale of projects do you work on?
	5. What type of projects did you work on?
	6. Do you agree with the BIM coordination workflow shown in Figure 1?
	7. Please identify the stage(s) of the BIM coordination process you are responsible for.
	8. Did you receive any BIM-related training during your formal education before being involved in BIM projects?
	9. If you had previous BIM-related training, then please briefly explain the focus of your training.
	10. Did you receive any BIM-related training during your service as an employee? (i.e., Seminars, workshops, etc.)
	11. If you have received BIM-related training during your service, please explain the focus of your training briefly.

Table-A IV-1 The questions provided to the BIM professionals (cont’d)

Questionnaire Sections	Questions
Validate the BIM-coordination obstacles	1. Which BIM software(s) do you use for model creation?
	2. Which BIM software(s) do you use for clash management?
	3. Which software(s) do you use for collaboration?
	4. Please rate the following obstacles in BIM coordination based on their importance. Very Important – Important – Moderately Important – Slightly Important – Not Important **(Same question for different categories and sub-categories of clashes Total 8 repetation.)**
	5. Do you believe the are enough professionals in your team with adequate BIM expertise?
	6. If you answered ‘No’ in the previous question, what type of expertise would you prefer?
	7. How do you document the resolutions to coordination problems and clashes after the project is over?
	8. Does your organization have any standard for such knowledge capture?
	9. If you answered 'Yes' in the previous question, please briefly describe the standard.
	10. When creating the model do you work in isolation from other disciplines (for example: in WIP) or do you work collaboratively (for example: in OWIP) and have discussions with other disciplines outside of coordination meetings? (So, the work can be properly organized)
	11. When you require information from a team member (from yours or other disciplines) for clash resolution, how do you contact them usually?
	12. When you request information for clash resolution, do you face a long response time?
	13. Do you participate in coordination meetings?
	14. If you regularly participate in coordination meetings, what are your role and your responsibilities?
	15. If you do not participate in coordination meetings, please briefly explain the reason.
	16. Do you consult the coordination reports and the meeting minutes communicated each week?
	17. Are you familiar with the scope of work of BIM coordinators, BIM consultants, and BIM managers?
	18. To whom do you reach out if you face an issue in a BIM-enabled project? (Options: Project manager, BIM manager, other)

Table-A IV-1 The questions provided to the BIM professionals (cont'd)

Questionnaire Sections	Questions
Validate the clash avoidance strategies	1. Researchers have identified the following causes of clashes in BIM coordination. To which degree do you agree or disagree with each of these causes? **Options:** 1. Lack of BIM education, awareness, or expertise in team members. 2. Designers from different disciplines working in isolation and not sharing documents or model previews with each other. 3. Design errors due to lack of BIM adoption or proper BIM use. 4. Failing to comply to design rules, building codes, or standards. 5. The discrepancy between the design and the 3D models. Such as designers using placeholders instead of the actual object model, use of low or wrong level of detail (LOD), and 3D model objects exceeding allowable clearance.
	Researchers have identified that the following strategies might be helpful in significantly reducing the number of multidisciplinary clashes. To what degree do you agree or disagree with these proposed strategies? Briefly explain your choice. (Rate on the scale specified below.) Strongly disagree — Disagree – Slightly disagree – Slightly agree – Agree - Strongly agree **Options:** 1. Interactive training on BIM collaboration platforms and coordination tools for team members. 2. Open Work in Progress (OWIP) where team members can get a visual preview of the designer's model alongside having the ability to leave feedback for them. Standardized documentation of lessons learned within the team and organization. So that knowledge is captured, stored, and shared properly as design errors occur and are resolved. 3. Introduction of BIM tools or automation during the specialty model creation phase so that the software will be able to detect deviations from design rules (The process expands the scope of BIM-enabled rule checking where natural language-based design requirements exist.) 4. Use of BIM tools that perform Artificial Intelligence enabled optimization of 3D models after the specialty model creation phase for each specialty to produce clash-free models. 5. Availability of a rule-based approach to optimize design during the generation of federal models. In this approach, the system will be able to detect deviations from established design rules and best practices. 6. Better implementation of standardization of LOD practices within the construction industry
Insights on design rules or best practices for clash avoidance	1. Based on your experience, recommend three technical design rules or steps or best practices to follow while creating Architectural specialty models so clashes can be avoided as much as possible.
	2. Based on your experience, recommend three technical design rules or steps or best practices to follow while creating MEP specialty models so clashes can be avoided as much as possible.
	3. Based on your experience, recommend three technical design rules, steps or best practices to follow while creating Structural specialty models so clashes can be avoided as much as possible.

ANNEX V

CLASH AVOIDANCE IN BIM-BASED MULTIDISCIPLINARY COORDINATION : A LITERATURE OVERVIEW

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Abstract

In recent years there has been a significant amount of research aiming to increase the efficiency of Building Information Modeling (BIM) based multidisciplinary coordination process. However, unanticipated increases in cost and delays in construction projects are still visible. According to the literature, one of the principal factors affecting the efficiency of BIM-based multidisciplinary coordination and construction process is the conflict between the systems of different design disciplines. Recent years have seen a surge of automatic clash detection tools and strategies. These have provided clear benefits to the construction process by helping to reduce the number of errors discovered on-site, but the significance of this effect is hindered by the inefficiency of the clash resolution process due to the vast number of identified clashes and the resources needed to resolve them. Researchers have started focusing on devising strategies for clash avoidance during the design process to address this phenomenon. Our work is an attempt to present a literature overview of these clash avoidance strategies that range from shared situational awareness to supervised and hybrid machine learning frameworks. This work identified that the most prominent causes of clashes directly occur during the preliminary phases of multidisciplinary coordination which are generating the specialty models and federated models. Additionally, the lack of studies on proper standardized documentation of lessons learned in BIM-based multidisciplinary coordination is also recognized in this study which points toward future research directions for developing such guidelines.

Introduction

There has been a significant amount of research aimed at making the Building Information Modeling (BIM)-based multidisciplinary coordination process more efficient. Nevertheless, unanticipated increases in costs and delays in construction projects still occur. One of the principal factors affecting the efficiency of BIM-based multidisciplinary coordination is the conflict between the systems of different design disciplines. Tommelein and Gholami (2012) identify such conflicts or clashes as waste in the production system (Tommelein & Gholami, 2012). Recent years have seen a surge of automatic clash detection tools and clash filtration strategies. These have the potential to benefit the construction process by helping to reduce the number of errors discovered on-site. However, the significance of this effect is hindered by the inefficiency of the clash resolution process due to the vast number of identified clashes and the resources needed to resolve them. Some researchers are focusing on devising strategies for clash avoidance during the design process to address this phenomenon. This work presents a consolidated literature overview of these clash avoidance strategies that range from shared situational awareness to supervised and hybrid machine learning frameworks. This overview is expected to help researchers and BIM professionals to compare the efficacy and applicability of such strategies. It will also help researchers to understand the research gaps in the field of BIM-based multidisciplinary coordination by drawing a link between the workflow of multidisciplinary BIM-based coordination, and the clash avoidance strategies.

- **Objectives and Methodology**

The objectives of this literature review are: (i) to identify the causes of clashes that affect BIM-based multidisciplinary coordination, (ii) to study the proposed clash avoidance strategies for efficient multidisciplinary coordination, and (iii) to draw connections between the causes of clashes, and the clash avoidance strategies. A 'mixed-methods systematic review' was employed for this work which applies quantitative and qualitative methods to analyze the available literature so any potential biases can be avoided. The mixed-methods systematic review was carried out in 3 stages. Stage 1 consisted of a focused keyword search in the Scopus database which produced 95 publications. These keywords were selected based on their relevance to the topic of study and include building information modeling, multidisciplinary coordination, real-time collaboration, clash avoidance, clash-free model, clash management, clash optimization, design error, and design rules. In the second stage, English-language published, open-access journal articles, conference papers, and book chapters were selected to shortlist 86 documents. Afterward, VOSviewer was used to conduct the bibliometric analysis of the shortlisted literary works. A co-occurrence network map for the keywords was created to view the topics of research and their interconnection in the field of BIM-based multidisciplinary coordination as shown in figure-A V-1.

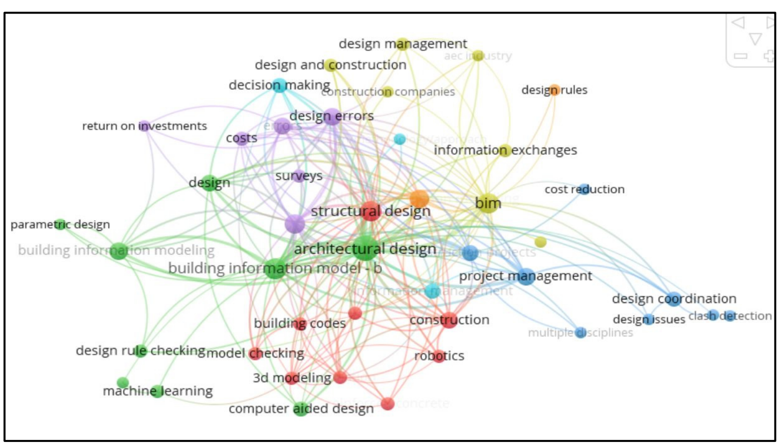

Figure-A V-1 Most prominent topics of research and their interconnection.

The network map highlights the most frequent topics of research related to multidisciplinary coordination and clash management as well as providing insights into the scope of potential research directions. It can be observed from the map that there has been significant research focused on the economic impact of design errors, building code compliance, and automated clash detection. However, there is a lack of comprehensive studies pertaining to clash avoidance. For the final stage of the review, qualitative analysis was adopted where the relevance of the literature is determined by comparing the contents of all 86 shortlisted works. First, the literary works that directly address clash management, causes of clashes, and design errors in BIM-based coordination and collaboration were selected. The documents were then analyzed carefully to identify and extract information for the next step. Subsequently, they were coded based on the specific cause of design clash and the clash management technique they discuss to further identify the potential solutions for the said cause of clash. The total number of papers shortlisted in Stage 3 of the mixed-methods systematic review was 25.

- **Identifying causes of clashes**

The most prominent causes of clashes or conflicts in BIM-based multidisciplinary coordination, according to multiple scientific publications, are discussed in this part. Previously, Tommelein and Gholami (2012) classified clashes based on their existence into (i) hard clashes, (ii) soft clash, and (iii) time clash (Tommelein & Gholami, 2012). Afterward, Akponeware and Adamu (2017) reviewed the factors influencing hard and soft geometric clashes (Akponeware & Adamu, 2017). This work identified 12 drivers of clashes and underlined the scarcity of experts, designers working in isolation, and design errors as the most important among them (Akponeware & Adamu, 2017). Other important causes mentioned in this work included failing design rules, the use of different file formats, and discrepancies in 3D modeling. Mehrbod et al. (2019) specified design discrepancy, design error, and missing items as the causes of design coordination issues (Mehrbod, Staub-French, Mahyar, et al., 2019), design error being the most frequent cause in the study. Elyano and Yuliastuti (2021) corroborated this in their case study where they found design errors causing 52.36% of the detected clashes which were mostly between structural vs MEP components (Elyano & Yuliastuti, 2021).

Design inconsistency caused 39.13% and design discrepancy caused 8.51% of detected clashes, and these clashes were mostly between structural, MEP, and precast components (Elyano & Yuliastuti, 2021). This work will address the most prominent causes of clashes identified from contemporary literature via a coding classification while discussing potential clash avoidance strategies. These causes of clashes are: (i) lack of experts, (iii) designers working in isolation, (iii) design errors, (iv) failing of design rules, and (v) discrepancy in design and 3D models as highlighted in figure-A V-2.

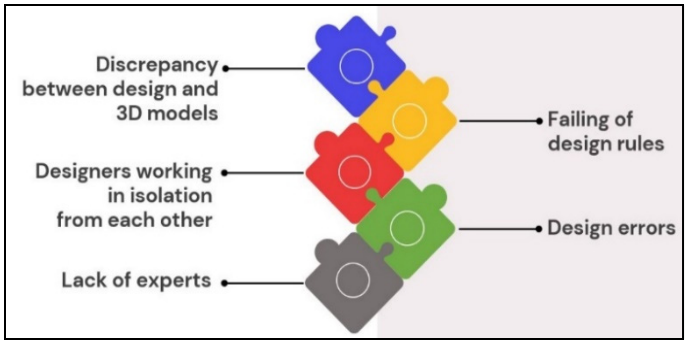

Figure-A V-2 Most prominent causes of clashes identified from literature via coding classification.

Potential clash avoidance strategies

Strategies that can help reduce the clashes in light of the studied literature are discussed in this section.

- **Lack of experts**

Akponeware and Adamu specified that the lack of experts involved in the BIM-based design process is one of the main cause of clashes according to researchers (Akponeware & Adamu, 2017). To increase the BIM expertise of professionals in the construction industry, many studies recommend educating students on BIM-based collaboration platforms and coordination process during their training. Tayeh, Bademosi, and Issa elaborated that the integration of BIM-based collaboration in the construction industry has made it crucial to include BIM-centric education in construction management and engineering training (Tayeh et al., 2019). This will ensure the success of aspiring professionals by increasing their skill level as well as ensuring proper communication and exchange of information across construction projects. The authors studied the integration of collaborative learning platform in BIM education and documented student's feedback that identified remote real-time collaboration, ease to resolve communication errors, and availability of information in a single repository as some of the most important benefits of such platforms (Tayeh et al., 2019). Students also specified that such platforms could speed up the model coordination significantly. The authors deduce that such exercises during the training period have the potential of improving the learning experience of future experts. Additionally, researchers emphasized the necessity of skill-developing programs, such as intensive training or workshops in the workplace where experienced professionals can share their expertise to increase the level of understanding and knowledge about BIM (Evans & Farrell, 2020). Alongside BIM training, addressing the lack of knowledge about coordination issues faced by team members can be another promising approach. Mehrbod et al. attempted to define a taxonomy of design coordination issues that would assist team members in gaining a better understanding of such issues as validated by industry professionals (Mehrbod, Staub-French, Mahyar, et al., 2019).

- **Designers working in isolation**

According to Akponeware and Adamu, workplace silos or designers working in isolation is one of the primary causes of clashes (Akponeware & Adamu, 2017). Complications in the relationship between team members, such as lack of trust and communication gaps between team members can drive them to work on their own in the crucial preliminary stages of design. To solve this the researchers proposed an open-work-in-progress (OWIP) stage in the common data environment instead of the traditional work-in-progress phase where all disciplines participating in the collaboration can have secure access to the design and provide feedback (Akponeware & Adamu, 2017). To improve the communication within the team Adamu, Emmitt & Soetanto proposed a social BIM framework and tested four distinct types of collaboration protocols ranging from low to high levels of shared situational awareness within the team (Adamu, Emmitt & Soetanto, 2015). The protocol offering maximum shared situational awareness enabled members to communicate with each other over the BIM platform and improves efficiency (Adamu, Emmitt & Soetanto, 2015).

- **Design errors**

Several groups of researchers recognized design errors as one of the most frequent causes of clashes. As explained by Lopez and Love, in the case of an error an unforeseeable or chance intervention takes place (Lopez & Love, 2012). Researchers had previously deduced that the mean direct and indirect costs for design errors were revealed to be 6.85% and 7.36% of contract value with errors leading to schedule delay being the most detrimental (Lopez & Love, 2012). This finding makes design errors a significant hindrance for efficient construction process. Johansson et al. studied the impact of BIM in preventing errors and determined that even though the knowledge of a potential issue and solution of the issue is located in the organization, there is no 'matchmaking' between these two (Johansson et al., 2014). Wong et al. after studying the linkage of BIM adoption and error reduction, found clash detection and design coordination to be the two most crucial factors in design error reduction (Wong et al., 2018). Formerly, Al Hattab and Hamzeh appraised the use of social network theory and simulation to compare traditional versus BIM/Lean-based environments for design error management (Al Hattab & Hamzeh, 2015). The researchers reasoned that, errors are resolved faster in a BIM/Lean network as individuals detect and resolve errors by frequent checking and communication. According to Al Hattab and Hamzeh, addressing the root causes of human-based errors despite the progress of BIM-based automated checking procedures is important for reducing design errors. The team should analyze the root cause, find the solution, and record lessons learned as defects are detected maintaining a continuous learning attitude and instilling a quality-at-bay principle (Al Hattab & Hamzeh, 2015).

- **Failing of design rules**

Tommelein and Gholami defined the lack of specificity on how specialty systems are to be developed relative to others to avoid occupying each other's space as failure of design rules and identified it as one of the root causes of hard clashes (Tommelein & Gholami, 2012). Many researchers in recent years are studying different applications of artificial intelligence to mitigate such failures which in turn can significantly reduce hard clashes in design. For example, Song et al. investigated deep learning based natural language processing (NLP) techniques for translating design rule sentences into a computer-readable data structure (Song et al., 2020). In this work, a deep learning model was trained to extract the predicate-argument structure (PAS) from the building design rule sentences, and the trained models were used in the rule interpretation process. Here, the computer analyzed building design rule sentences using a bidirectional long short-term memory model to extract the logical elements. As stated by Song et al. this approach has the potential to expand the scope of BIM-enabled rule checking where natural language based design requirements exist (Song et al., 2020).

- **Discrepancy in design and 3D models**

Akponeware and Adamu had identified several causes of clashes from existing literature that can be labeled as discrepancies in the 3D modeling stage of BIM-based collaboration. Use of low or wrong level of detail (LOD), design uncertainty, 3D model objects exceeding allowable clearance, and the use of 2D drawing instead of 3D models are notable among such drivers of clashes (Akponeware & Adamu, 2017). To resolve the issue of low or wrong LOD, the construction industry has started incorporating LOD standards. Some renowned LOD matrixes are being introduced by the United States Army Corps of Engineers (USACE), American Institute of Architects (AIA), and BIMForum. These matrixes provide standards to be referenced by the contract and the BIM execution plan.

Regarding design uncertainty, Tommelein and Gholami went on to state that the use of placeholders by designers might end up causing a hard clash with other systems or components when the exact component intended for the space is uncertain (Tommelein & Gholami, 2012). While contemporary literature does not address this issue separately, open, and constant availability of communication channels between members of the team might help to reduce such clashes. Shared situational awareness among team members can empower them with visual access to the early-stage model and improve the quality of information exchange (Adamu, Emmitt & Soetanto, 2015). Furthermore, in their work, Tommelein and Gholami also raised concerns about soft

clashes caused by 3D objects exceeding allowable clearance and components not maintaining minimum clearance from each other (Tommelein & Gholami, 2012). Even though some BIM-based coordination tools still struggle to identify soft clashes, researchers have discussed several promising approaches in recent years. In their 2021 work, Mangal et al. investigated the usage of BIM and a two-stage genetic algorithm (GA) to automate clash-free optimization of steel reinforcements in reinforced concrete (RC) structures (Mangal et al., 2021). In this work, the first stage GA focused to generate clash-free steel reinforcement layout designs. Afterward, the second stage GA optimized the size of steel reinforcement by exploring different diameter combinations of steel reinforcement and minimizing the overall steel consumption. Mangal et al. estimated that this same method can be customized and employed for solving similar design optimization problems such as member sizing optimization (Mangal et al., 2021). Additionally, Li et al. presented an alternative approach to rebar design optimization with a hybrid metaheuristic algorithm and BIM (Li et al., 2021). This approach identifies activities related to the manufacture and assembly of rebar, then proposes a multi-objective cost design formulation that includes the design code requirements. The authors also proposed the use of a hybrid genetic algorithm incorporated with Hooke and Jeeves's method for rebar clash avoidance and optimization (Li et al., 2021).

The final cause of clashes this study will discuss is the use of 2D drawings instead of 3D models. Akponeware and Adamu mentioned that mandating designers to adhere to a 3D standard can have a positive impact on the issue however this does not address the frequent design errors (Akponeware & Adamu, 2017). Contemporary researchers propose the use of cloud BIM for real-time collaboration and easy data exchange within the project team which reduces the possibilities of design errors as well (Onungwa et al., 2021). Onungwa et al. conducted a case study of digital modeling to identify seamless communication, real-time progress monitoring, and visualization of files as some of the benefits of cloud BIM technology (Onungwa et al., 2021). Mostafa et al. explored the most significant BIM opportunities and specified seamless and timely information exchange' among key project stakeholders via a BIM system as the most critical success factor (Mostafa et al., 2020). Bhonde et al. went on to add that the use of virtual reality with traditional drawings can be viable for improving the quality of design (Bhonde, 2019).

Conclusions

This review summarizes current literature that discusses the causes of clashes in BIM-based multidisciplinary coordination and the clash avoidance strategies ranging from shared situational awareness to supervised and hybrid machine learning frameworks. It is also summarized via this review that the most prominent causes of clashes directly occur during the preliminary phases of multidisciplinary coordination which are generating the speciality models and federated models. Researchers emphasize the importance of documenting lessons learned within the organization, so that team members can access the information in need and clashes can be avoided. However, there is still no guideline for such documentation. Thus, design teams still struggle with unwanted design errors and discrepancies which increase the number of clashes. Our study points towards future research directions for developing guidelines for proper standardized documentation of lessons learned during multidisciplinary coordination to avoid unwanted design errors and clashes.

The Bibliography section is presented at the very end of the thesis.

ANNEX VI

METHODS TO DEVELOP A COMPREHENSIVE RULE-BASED CLASH AVOIDANCE SYSTEM BASED ON EXPERT OPINION

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Abstract

Achieving efficacy and economy is an ongoing pursuit for the Cana-dian construction industry. However, obstacles in Building Information Model-ling (BIM) based multidisciplinary coordination and the substantial number of clashes in the federated model hamper BIM-based practices to optimize the benefit of this collaborative use of technology. As the first step in resolving this problem, different groups of researchers have pointed out the most impactful obstacles to BIM coordination and the causes of clashes. Other investigators have recommended different approaches for mitigating the identified obstacles and causes of clashes. The natural next step for increasing efficiency in the con-struction industry is identifying the most effective solution framework to avoid coordination obstacles, thus reducing the number of clashes to be resolved. In the earlier stage of this work, consolidated overviews of solution frameworks were formulated that draw connections between the obstacles and causes of clashes, their solutions, and the phases of BIM coordination where they have the most effect. However, whether the proposed frameworks apply to the con-struction industry in its current state is yet to be determined. This step is neces-sary to ensure that any proactive avoidance strategy devised, based on the pro-posed framework will be optimally impactful for the construction industry. This paper describes the process of validating the proposed frameworks formulated in the earlier stage of this research in addition to developing a methodology for effective clash avoidance. This work will assist researchers to understand the process followed to identify the most effective proactive clash avoidance strate-gy in addition to the preliminary stages to develop a robust data collection method and workflow of a recommendation system based on BIM experts' opinions.

Introduction

The construction industry strives for increasing the efficiency of construction projects with the help of Building Information Modeling (BIM). The success of a BIM-enabled project depends largely on the multidisciplinary coordination that sets the tone of the project. And BIM-based multidisciplinary coordination remains a critical, complex process that confirms that the building system members are well-defined and not causing any interference among themselves and ensuring compliance with all necessary project criteria. Thus, BIM coordination calls for impeccable teamwork from all its stakeholders, including designers, engineers, contractors, and owners (Meem & Iordanova, 2022a). This requirement poses some challenges for the traditional construction industry, known for its notorious resistance to change. The challenges or obstacles in BIM-based multidisciplinary coordination range from lack of technical support in terms of clash or conflict management, interoperability, and collaboration via common data environment to organizational culture and team-related obstacles, such as lack of trust and confusion regarding BIM roles and responsibilities (Meem & Iordanova, 2022a). Additionally, the increas-ing number of identified clashes between systems of different disciplines remains one of the principal factors that affect the efficiency of BIM-based multidisciplinary coor-dination. Such clashes of conflicts are identified as a waste in the production system (Tommelein & Gholami, 2012). Researchers have identified the causes of obstacles and clashes in BIM coordina-tion as the first step in resolving these problems. Recent years have seen many at-tempts to find reliable solutions for overcoming the obstacles in multidisciplinary coordination in addition to a surge of automatic clash detection tools and clash filtra-tion strategies. The second step of this endeavor was identifying the most effective solution framework to avoid coordination obstacles, thus reducing the number of clashes to be resolved. Previously, we have formulated consolidated overviews of solution frameworks that draw connections between the obstacles and causes of clashes, their solutions, and the phases of BIM coordination where they have the most effect (Meem & Iordanova, 2022a). The next step of this work is to determine whether the proposed frame-works apply to the Construction industry in its present state. This will ensure that any proactive avoidance strategy devised, based on the proposed frameworks will be op-timally impactful for the current industry context. This paper describes the process of validating the proposed frameworks presented in (Meem & Iordanova, 2022a) in addition to collecting the most important design rules to be followed while creating the BIM model. Studies conducted to identify the obstacles of the BIM coordination process and clash man-agement often collect data from BIM professionals regarding the efficacy of their findings or solution. However, this approach did not result in fruitful clash manage-ment solution as it views the BIM coordination as a separate stage from the planning and design phase of the project. This work is the first work of its kind which will attempt to find the most effective approach for validating the findings regarding ob-stacles in BIM coordination and design rules collection which will involve inputs from BIM professionals along with all other prominent actors in the BIM coordina-tion process (architects, MEP, and structural engineers). This will ensure that a holis-tic solution can be reached for proactive clash avoidance starting for the very first stages of developing the BIM execution plan and design overcoming the segmented and reactive clash management practice prevalent in the industry and research.

The objectives of this work are: (i) to develop the methodology of devising an ef-fective proactive clash avoidance strategy, (ii) to devise the most effective method for acquiring validation of our proposed framework based on the opinion of industry experts, (iii) to propose the preliminary workflow of a recommendation system based on our prior findings to achieve clash avoidance. The terms ‘obstacles’ and ‘barriers’ both are used in this work to identify the hindrances in the BIM coordination process. Additionally, both the terms ‘clash’ and ‘conflict’ are used interchangeably to signify clashes in the BIM model. The paper is organized as follows: Section 2 briefly pre-sents an overview of our previous works, solution frameworks drawing connections between the causes of clashes obstacles, their solutions, and the phases of BIM coor-dination where they have the most effect. Section 3 discusses the proposed methodol-ogy for developing a proactive recommendation system for clash avoidance including the tools and techniques for validating the previously proposed frameworks men-tioned in Section 2 with the help of industry experts. Finally, Section 4 explains our proposed preliminary workflow for the recommendation system in addition to sum-marizing future work.

Background overview

To increase the efficiency of BIM coordination via clash avoidance it is important to understand the most impactful root causes of clash, how they are intertwined with other prominent obstacles of BIM coordination, and which part of the BIM coordina-tion process is the most affected by these problems. This section presents the over-view of our previous studies and their results. Previously, we have identified and un-derstood the impact of the most important obstacles in BIM coordination with the help of a mixed-method systematic literature review (Meem & Iordanova, 2022). The main categories of ob-stacles in BIM coordination are i) process, ii) actor, iii) task, iv) context, and v) team (Oraee et al., 2017). The ‘Process’ category includes obstacles regarding necessary tools and resources for coordination. To overcome this, holistic and automated clash management tech-niques have been recommended by researchers (Hu et al. 2019). Coordination team member’s knowledge and skill-related obstacles fall under the ‘Actor’ category, to overcome which proper documentation of lessons learned from each BIM-based coordination project is highly recommended. The unavailability of the necessary information at the right time is the most prominent barrier under the ‘Task’ category and increased situa-tional awareness in the team is the most promising strategy to mitigate this. The in-dustry’s lack of willingness to adapt to BIM standards and tools is another barrier that can be identified as a ‘Context’ obstacle. Increased usage of cloud-based BIM collab-oration platforms in practice is helping to overcome this problem. Finally, lack of trust and impaired relationships among team members is a barrier under the ‘Team’ category for which researchers recommend breaking down the ‘work silo’ culture in addition to a much more open ‘Work-in-progress’ stage (Akponeware & Adamu, 2017).

In the systematic literature review, we identified the stage of the BIM-based design coordination most affected by each obstacle category. According to Figure-A VI-1, where obstacle categories and the proposed solution frameworks are color-coded according to the different timeline stages of the BIM design coordination phase, they affect the most, it can be seen that ‘Process’ obstacles affect coordination strategy, model gen-eration, and clash detection stage. From this analysis, it can be stated that the identified BIM collaboration obstacles mostly affect the initial stages of BIM-based design coordination. If the ‘specialty model generation’ and ‘federated model creation’ phas-es are affected by obstacles, they can hinder the efficiency of coordination as well as the other phases of the construction project.

Thus, it is necessary to figure out what can be done to alleviate the obstacles from the BIM model creation phases for in-creasing the efficiency of BIM coordination.

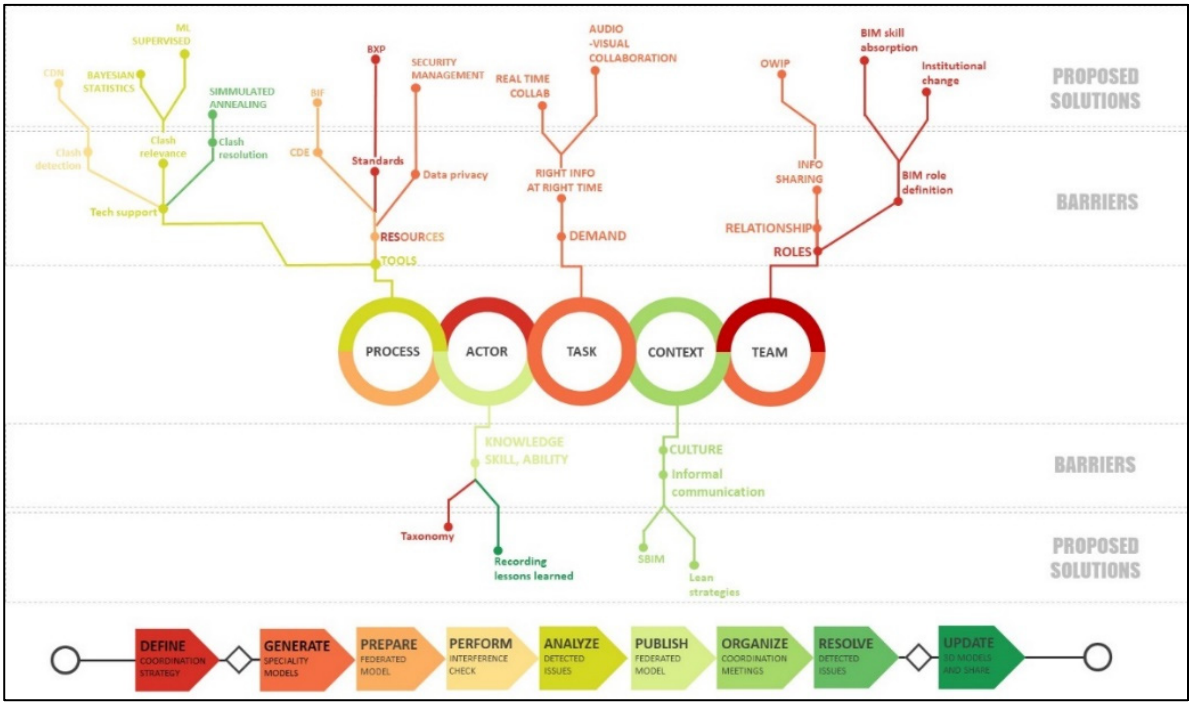

Figure-A VI-1 Interrelation between BIM collaboration obstacles

After identifying the most vulnerable stages of BIM coordination we studied the causes of clashes researchers have identified till now alongside the clash avoidance strategies that range from shared situational awareness to supervised and hybrid ma-chine learning frameworks (Meem & Iordanova, 2022b). The most prominent causes of clashes identified in this work are: (i) lack of experts, (iii) designers working in isolation, (iii) design er-rors, (iv) failure of design rules, and (v) discrepancy in design and 3D models.

To overcome 'the lack of experts in the industry', Tayeh, Bademosi, and Issa rec-ommend the integration of collaborative learning platforms in BIM education (Tayeh et al., 2029). Lack of trust and communication gaps between team members can drive them to 'work in isolation' in the crucial preliminary stages of design, increasing the risk of clashes in design can be overcome by increased shared situational awareness accord-ing to Adamu, Emmitt & Soetanto (Adamu et al., 2015). Among the recognized causes of clashes, 'de-sign errors' is the one that impacts the contract value by causing delay the most. To mitigate this Al Hattab and Hamzeh address the root causes of human-based errors, finding the solution, and record lessons learned as defects are detected maintaining a continuous learning attitude and instilling a quality-at-bay principle (Hattab & Hamzeh, 2015). Another cause of clash researchers highlight is 'the failing of design rules'. To overcome this researchers are considering deep learning-based natural language processing (NLP) techniques for translating design rule sentences into a computer-readable data struc-ture (Song et al., 2020). The last cause of clashes in BIM coordination is ‘discrepancies in design and 3D models’. Use of low or wrong level of detail (LOD), design uncertainty, 3D model objects exceeding allowable clearance, and the use of 2D drawing instead of 3D models, all these issues can be considered ‘discrepancies in design’. Recent years have seen increased incorporation of LOD matrixes in the industry which is reducing problems related to wrong LOD. Design uncertainty is something that can be addressed by increased shared situational awareness (Adamu et al., 2015). Additionally, a two-stage ge-netic algorithm (GA) to optimize clash-free design (Mangal et al., 2021), and a hybrid metaheuristic algorithm in conjunction with BIM (Li et al., 2021) have been explored to overcome the problem of 3D model objects exceeding allowable clearance. Finally, mandating designers to adhere to a 3D standard and the use of cloud BIM for real-time collaboration and easy data exchange within the project team have proven to have an impact on design errors due to reluctance to shift to BIM (Onungwa et al., 2021). From studying the causes of clashes and clash avoidance strategies till now we observed that the most prominent causes of clashes directly occur during the preliminary phases of multidisciplinary coordination (Meem & Iordanova, 2022b). This finding corroborates our previous finding (Meem & Iordanova, 2022a) and highlights the importance of ‘documenting lessons learned’ within the organization and its implementation in fu-ture projects. So that team members can access the information in need and clashes can be avoided. Our background studies solidify the idea that any approach to proac-tively reduce the number of clashes in the BIM model should be based on the ‘documented lessons learned and best practices for design and model creation’. Existing studies regarding clash avoidance and automated design optimization approach the clash avoidance reactively. Furthermore, the approaches rely on building codes gen-erally, which primarily focuses on checking code compliance after the clash has al-ready happened in the BIM model (Mangal et al., 2021 ; Li et al., 2021). In contrast, our approach leverages the best practices and lessons learned that are proven to be efficient for clash avoidance. The focus of this work is to encompass expert knowledge regarding clash avoidance with the help of interview questionnaires which are channeled towards the most fre-quent types of clashes faced by BIM professionals. Therefore, this work has the po-tential to complement the existing clash management strategies which rely on build-ing code-based design optimization and automatic clash resolution.

Developing the methodology for clash avoidance

Previously, the importance of proper documentation and implementation of best prac-tices and design rules learned during each project was identified (Meem & Iordanova, 2022a ; 2022b). The goal of this work is to develop the methodology of devising an effective proactive clash avoidance strategy that is optimized to be applied to the construction industry in its current state. The optimization will be done via the most effective design rules and best practices collected from the industry professionals. The experts will further iden-tify the design assistance features they deem useful in a clash avoidance system. This section will deliberate on the process of the methodology development.

- **Defining clash avoidance:**

Researchers have studied the idea of a proactive antidote to clashes in the past years. Akponeware and Adamu have recommended clash avoidance to be used as a proactive approach instead of reactive clash detection and resolution (Akponeware & Adamu, 2017). Pedo et al. defined clash avoidance as an effort to avoid the existence of coordination issues dur-ing the design process (Pedo et al., 2021). Lin and Huang see clash avoidance as a method that seeks to avoid the occurrence of clashes through cooperation and coordination (Lin & Huang, 2019). As the first step of developing an efficient clash avoidance strategy, this work defines the term ‘clash avoidance as a ‘proactive process’ where steps are taken to avoid spa-tial overlaps and semantic conflicts in BIM models. Clash avoidance is to be exer-cised throughout the model construction process. Starting from the first stage of de-signing to the last moment, techniques and strategies for clash avoidance can be im-plemented for practical results.

- **Clash avoidance methodology:**

Goal and objectives:

Since clash avoidance can be a proactive approach that can be exercised throughout the modeling process via BIM authoring tools, the goal of developing a clash avoid-ance approach can be achieved with a system that will integrate the best practices, design rules, or lessons learned that will help reduce clashes. This system can actively assist the designer throughout the modeling process to implement these rules. A de-tailed diagram of developing this clash avoidance methodology is provided in Figure -A VI-2. The objectives to achieve the goal of developing this clash avoidance system are: (i) identifying the design rules that will help to avoid clashes in BIM models, (ii) specifying and encoding the identified design rules to be used in the system, (iii) de-veloping the prototype for the integrated rule-based clash avoidance system.

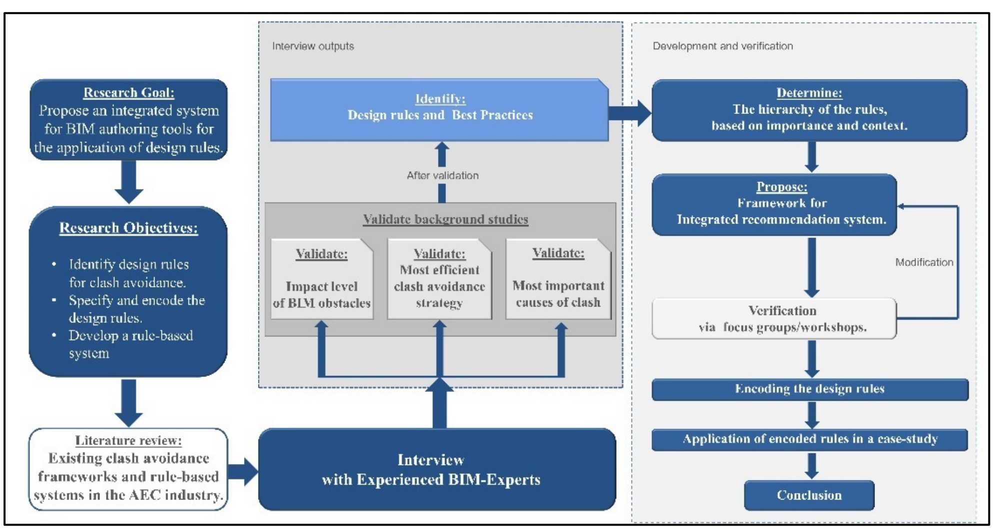

Figure-A VI-2 Methodology for developing a recommendation system

Literature review:

Previously extensive studies regarding the causes of clashes, clash avoidance strate-gies and rule-based design optimization approaches have been studied for this work. The findings from this review were briefly explained in section 2 Background over-view. Among the works that explore the application of rule-based systems to optimize design and code compliance, Vaidyanathan et al. propose an approach that allows for building system design and engineering to be generated based on functional rules so the design has minimal clashes and coordination issues (Vaidyanathan et al., 2015). In another work, Sydora and Stroulia describe a simple domain-specific language for computationally repre-senting interior design rules and a method for evaluating the rules against the BIM models (Sydora & Stroulia, 2020). Ismail et al. state in their work that the challenge in automatic compli-ance systems is not on how new approaches can be developed, but on how to select and integrate the existing approaches, in other words, the techniques (Ismail et al., 2017).

Interview with experienced BIM experts:

The next stage of the work focuses on collecting validation for the findings till now from experienced industry professionals. In recent years, BIM adoption and practice norms in the industry is changing at a fast pace. Many theories that were thought to be promising several years ago do not apply to the construction industry in its current state. Thus, this stage is imperative to determine the applicability of the conclusions of our previous works. This step also ensures that any clash avoidance approach at-tempted based on the previous works will be optimally impactful. To collect the max-imum amount of information from industry professionals the interview sessions are designed to be conducted via one-on-one video conferences and focus groups. Each one-on-one session will require 70-90 minutes and the focus groups will require 120 minutes. To avoid any potential bias, the participants to be approached consist of BIM coordinators, BIM specialists, BIM team leaders, architects, structural and MEP engi-neers, who are currently working in different architectural and engineering consulta-tion practices. It was also ensured that the selected participants have at least 5 years of experience working in BIM-enabled projects alongside having significant BIM coor-dination expertise. It was determined that the total number of participants should be around fifteen to ensure the diversity and richness of the qualitative data to be collect-ed from the interviews. The interview is designed to be semi-structured where a set of forty-four predetermined questions will exist and the interviewee will be able to an-swer in their own words. Additionally, the interviewer can probe areas based on the respondent's answers or ask supplementary questions for clarification (Easwaramoorthy & Zarinpoush, 2006). An ex-cerpt of the interview questionnaire is provided in the appendix. Due to space limita-tion all the questions are not provided.

Interview outputs:

The data collected from the interviews will validate the findings of our background study. The outputs of the interview will also determine the actual impact level of the identified BIM obstacles (Meem & Iordanova, 2022a). Furthermore, the outputs will also establish the most important causes of clashes and the most efficient clash avoidance strategy from the identified causes of clashes and strategies (Meem & Iordanova, 2022b) in the context of the current state of the construction industry. During the interview individual participants will provide their subjective ratings of the impact of BIM obstacles and causes of clash in addition to the efficacy of existing clash avoidance strategies. Then these factors will be orga-nized in order of precedence based on the subjective ratings received from the ex-perts. Once the background studies are validated the design rules and best practices to be followed during the modeling phase will also be collected from the same BIM experts.

Development and verification:

Once the design rules and best practices are collected from the BIM experts, the hier-archy of the rules will be determined based on the design context and importance. During the interview, the experts will provide a preliminary idea about the importance of each rule they mention. This score will be used to further filter the rules and their hierarchy determination based on the type of building and the building system they apply to. Based on the selected rules the framework for the integrated recommenda-tion system will be iterated. At this stage, the same group of experts will once again be approached to verify the findings and reiterate the rules in addition to the proposed framework via focus group or workshop. Consulting the same group of experts for this verification may introduce some bias in the work. However, given the time and resource constraints the panel of experts are kept the same for verification purposes. Efforts were made to select participants from different organizations and disciplines to minimize the organizational and professional bias. To develop the prototype of the proposed rule-based system, three of the collected rules will be encoded. In the final step, the encoded rules will be applied to a case study to understand the impact of the collected rules.

Preliminary workflow of the recommendation system

In figure-A VI-3, a simplified diagram is shown that depicts the proposed preliminary work-flow of the recommendation system. This workflow will be further refined based on the collected rules with the help of BIM experts. This section will briefly describe some basic functionalities of the proposed system and how it is intended to interact with the user.

The collected design rules and best practices will be encoded into the system as the knowledge base and the facts from the database will be compared against it. The facts in the database will be collected from the BIM authoring tool user interface as the BIM modeler works on the model. The encoded design rules will have a condition or an antecedent and an action or a consequent part. The condition part, being a logical test will need to be satisfied for the action part to be executed. For spatial relationship rules, such as the required clearance in the ceiling space for ducts, the dimension in the BIM model must satisfy the minimum required dimension saved in the condition section of the rule. If the model dimension is less than the requirement, the action (i.e.: Error prompt) will be executed. After launching the BIM authoring tool, the designer will have the option to review the best practice and design rules in the form of a tutorial.

Each design decision made by the designer is identified as an operator decision and will be checked against the knowledge base. In case of error prompts, summarized explanation regarding the rule will be provided. The designer can either accept the explanation of the system against their decision or disregard it. When the prompt is overridden, the system will provide the designer with more explanation to calibrate the designer's trust in the system. The error prompt and further explanation of the overridden rules will be facilitated by the explanation module. The overridden rules will also be saved in a report to be overviewed by the team leader or manager. Addi-tionally, the option to add to or edit the knowledge base will be available for the team leader or manager.

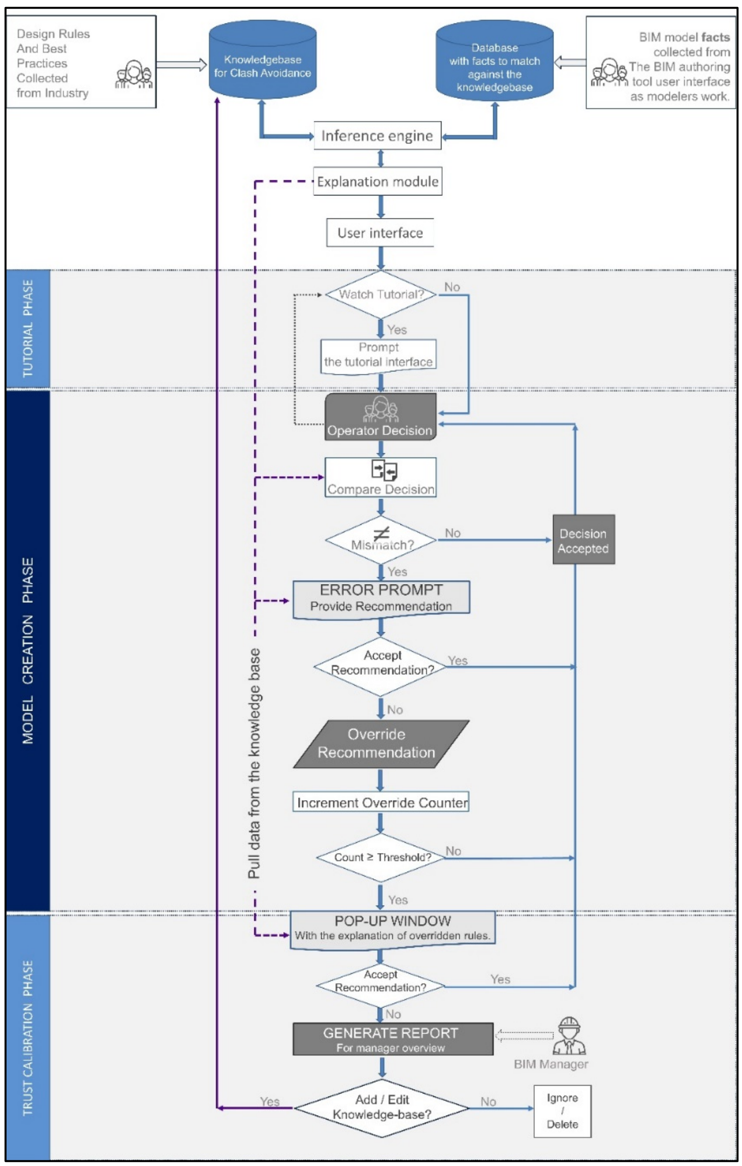

Figure-A VI-3 Preliminary workflow
of the proposed recommendation system

Conclusion

This work details the process of validating our past work to identify the most impact-ful obstacles to BIM coordination and to understand the impact of the causes of clash-es in the context of the current industry. Additionally, this work also details the meth-odology for developing a clash avoidance system that will be integrated within BIM authoring tool to be used as an assistant to designers during the BIM model creation phase. Since the BIM model creation phase is the most vulnerable step of BIM coor-dination, such a system is expected to help designers avoid clashes much better along-side ensuring the proper implementation of lessons learned. In the future, the de-scribed methodology will be used to extract qualitative data from industry BIM pro-fessionals. The most important rules and best practices collected from the interviews will be documented and encoded to create a prototype of the proposed recommenda-tion system. Which will then be tested within a case study to acquire a clear idea about the efficacy of such a system. This work will help researchers understand the process followed to identify the most effective proactive clash avoidance strategy in addition to the preliminary stages to develop a robust data collection method and workflow of a recommendation system based on BIM experts opinions.

The Bibliography section is presented at the very end of the thesis.

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