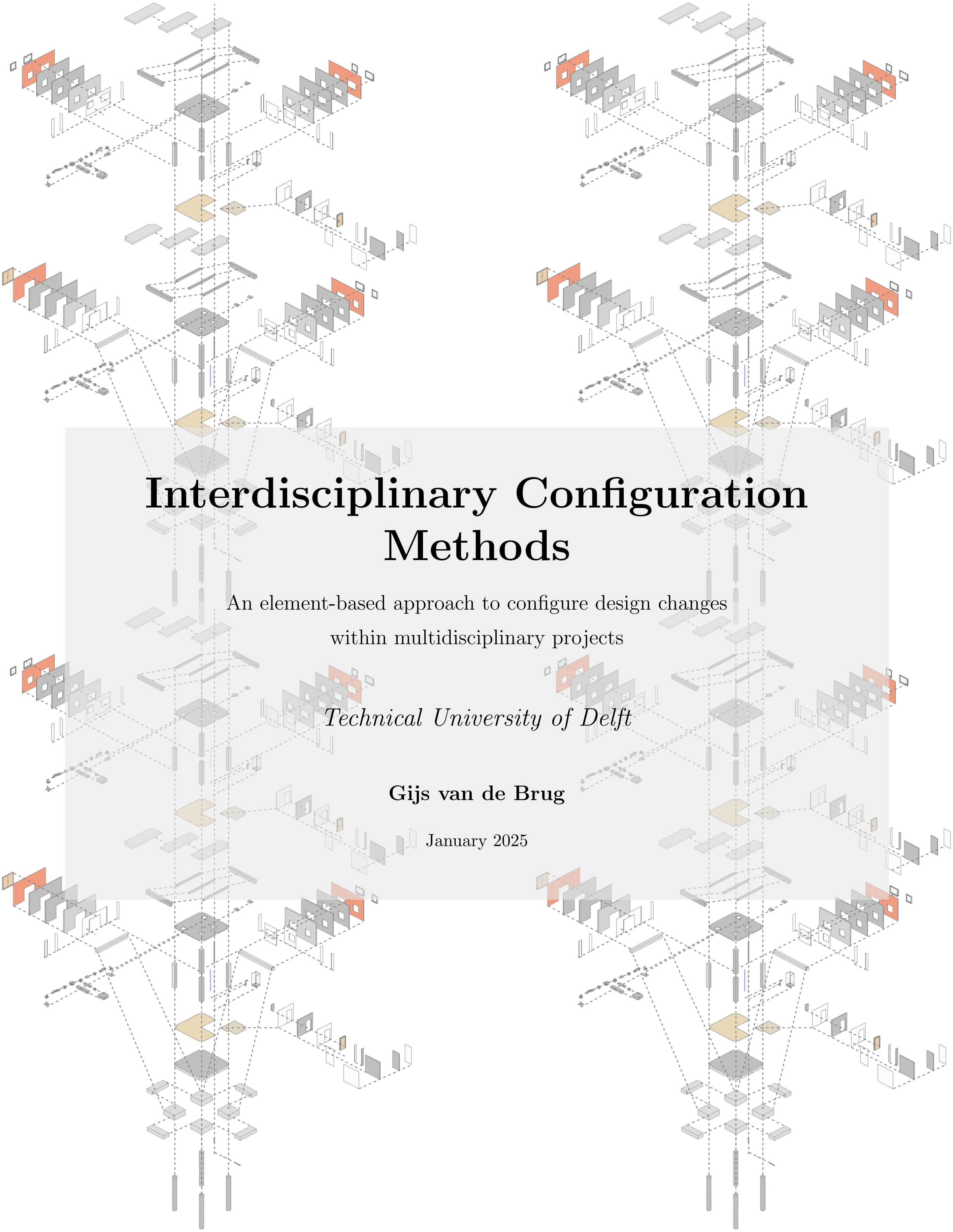


Interdisciplinary Configuration Methods

An element-based approach to configure design changes
within multidisciplinary projects

Technical University of Delft

Gijs van de Brug

January 2025

Colophon

Research Title: Interdisciplinary Configuration Methods,
An element-based approach to configure design changes
within multidisciplinary projects
Document Type: Graduation Thesis
Date: January 2025
Author: B.G. (Gijs) van de Brug

University: Delft University of Technology
Faculty: Faculty of Civil Engineering and Geosciences
Master Track: Construction Management & Engineering (CME)
Student Number: 5500621

Graduation Committee:

Chairman: Dr. M. (Martijn) Leijten
TU Delft, Faculty of Technology, Policy and Management
First Supervisor: A. (Anna) Batallé Garcia
TU Delft, Faculty of Architecture and the Built Environment, Design & Construction Management
Second Supervisor: Dr. Ir. R. (Ranjith) Kuttantharappel Soman
TU Delft, Civil Engineering & Geosciences, Integral Design & Management
Third Supervisor: Dr. Ir. G.A. (Sander) van Nederveen
TU Delft, Civil Engineering & Geosciences, Integral Design & Management
Company Supervisor: Ir. I. (Ingrid) Bolier
Witteveen+Bos, Project Management

Graduation Company:
Witteveen+Bos
Blaak 16
3011 TA Rotterdam
The Netherlands
+31 (0) 10 244 28 00

University:
Delft University of Technology
Mekelweg 2
2628 CD Delft
The Netherlands
+31 (0) 15 278 91 11

Abstract

The construction industry relies on multidisciplinary teams, each working within its own configuration framework to achieve shared project goals. As projects grow increasingly complex, the scale and interconnectivity of configurations expand, leading to a higher likelihood of clashes between components. This complexity makes effective Configuration Management (CM) increasingly challenging. Over the past two decades, Building Information Modeling (BIM) has emerged as a promising solution to manage configurations in complex construction projects. However, systematic integration of CM within BIM remains insufficient.

To address this gap, this research aims to explore how Model-Based Systems Engineering (MBSE) can enhance configuration processes within a BIM environment. The primary objective of the study is to develop and demonstrate a structured approach that leverages MBSE to visualize and manage interdependencies between building components across different disciplines, thereby improving the integration of CM in BIM workflows.

The main research question driving this study is: How can engineers in a BIM environment leverage MBSE to visualize and manage interdependencies between building components across different disciplines? To support this research, the study addresses the following sub-questions:

1. What existing MBSE methods can be adapted to manage design changes in a BIM environment?
2. How can a mock-up prototype be developed to illustrate the practical implementation of MBSE in BIM?
3. What are the potential applications of MBSE for estimating the impact of design changes in real-world construction projects?

Key findings highlight MBSE's transformative potential to improve decision-making in complex construction projects. By integrating BIM with MBSE, engineers can visualize and analyze interdependencies, enabling early conflict detection, enhancing multidisciplinary collaboration, and streamlining the change management process. Real-time updates and automated simulations further support effective impact analysis. The Design Structure Matrix (DSM) offers a systematic framework to anticipate the cascading effects of design changes across subsystems while improving cost and risk estimations.

Despite its advantages, MBSE implementation faces significant challenges, including technical barriers, tool integration issues, scalability, accessibility, and organizational resistance to change. This research offers actionable recommendations to address these challenges, such as standardizing processes, adopting incremental implementation strategies, promoting cross-disciplinary training, and enhancing BIM tools with MBSE features. Ultimately, this research demonstrates how MBSE, when integrated with BIM, can transform CM practices by improving efficiency, reducing errors, and enhancing collaboration between different disciplines during design changes.

Keywords: Building Information Modeling (BIM), Model-Based Systems Engineering (MBSE), Configuration Management (CM), Design Structure Matrix (DSM), Multidisciplinary Teams, Interdisciplinary Collaboration, Change Management, Construction Projects, Impact Analysis, Prototype, Simulation.

Preface

Before delving into the dissertation, I would like to share a few words with the reader. Over the past seven months, I had the privilege of working on my graduation thesis at the office of Witteveen+Bos. This experience has been pleasant, not only because of the knowledge I gained but also due to the support from my colleagues. Their guidance and joy made even the longest days of research and experimentation more manageable.

When I applied for a graduation position at Witteveen+Bos, Ingrid Bolier responded with great enthusiasm, setting the tone for a collaborative and inspiring journey. During my master's program in Construction Management and Engineering (CME) at Delft University of Technology, I developed an interest in project management, collaboration, and systematic engineering. I wanted to integrate these topics, and with the help of Ranjith Soman and Sander van Nederveen, I was introduced to Configuration Management and Element-Based approaches within BIM. This exploration opened my eyes to the potential of Model-Based Systems Engineering for enhancing Building Information Modeling during the design phase of multi-disciplinary construction projects.

To complete my thesis committee, Anna Batelli Garcia graciously offered her expertise and provided invaluable weekly feedback. As chairman, I selected Martijn Leijten, whose courses on project and process management resonated closely with the subject of my dissertation. I am deeply grateful to all committee members for their constructive feedback and support throughout this process. Additionally, I extend my heartfelt thanks to my family and friends for their genuine interest in and reflections on my work.

The journey to this thesis began with a search for a topic that connected to my previous experiences. Coming from an architectural background with extensive use of Revit, I identified BIM as a logical starting point. BIM has always struck me as an important tool for driving innovation in construction projects. Through discussions with project managers from various companies, I explored how BIM could be applied to address management challenges, such as handling design changes. Conversations with Ranjith Soman guided me towards the realms of configuration and change management. These insights made me revisit and refine my thesis proposal, eventually envisioning a BIM tool designed to enhance configuration processes. My familiarity with Revit and its potential for systematic, model-based approaches further enhanced my curiosity and drive.

Throughout this journey, I was fortunate to meet many supportive colleagues at Witteveen+Bos who contributed to my project in various ways. Whether they shared insights from their own projects or engaged in conversations during lunch, their support made this experience feel fulfilling. I was particularly encouraged by the enthusiasm they showed for my research topic. Many colleagues recognized how the findings could have practical applications in their workflows, which motivated me to continue my research.

This dissertation represents not only an academic achievement but also a reflection of the collective effort and inspiration provided by the people around me. I am profoundly grateful for the opportunities and support that made this journey possible.

Executive summary

Introduction

Context

Engineering projects are inherently complex, characterized by interconnected components and multidisciplinary interactions. These complexities arise from differentiation and interdependencies (Baccarini, 1996). Managing such complexity requires innovative approaches to configuration. Traditional tools, such as BIM, have made significant moves in this regard but require further enhancement through the integration of advanced MBSE methodologies.

Complexity in engineering is shaped by the diversity and interdependence of project components and disciplines, resulting in emergent behaviors that are difficult to predict or control (Sandars & Goh, 2020). In construction, these complexities manifest in stakeholder coordination, evolving requirements, and design changes (M. Sun et al., 2006).

Configuration refers to the structured arrangement and management of system components, ensuring system integrity and traceability throughout its life-cycle (Jensen et al., 2012). In construction, the configuration is critical for synchronizing multidisciplinary interactions, resolving design changes, and managing the life-cycle of building systems (Reefman, 2022). Effective configuration processes rely on maintaining consistency, tracking changes, and supporting seamless collaboration across teams (Guess, 2021).

BIM initially aimed to improve visualization, reduce errors, and enhance coordination among project disciplines (Azhar, 2011)(Borrmann et al., 2018). However, challenges persist in utilizing BIM for CM, particularly in bridging multidisciplinary dependencies and maintaining data integrity (Mangialardi et al., 2017)(Langroodi & Staub-French, 2012). Advanced MBSE methods present opportunities to address these gaps.

MBSE replaces document-centric practices with model-centric frameworks, enabling centralized and consistent management of configurations (Madni & Sievers, 2018). It supports cross-disciplinary collaboration by consolidating multiple configurations into unified models, reducing inconsistencies, and improving traceability (Reefman, 2022). MBSE is especially effective in managing interdependencies between project components, ensuring changes in one area are reflected across the system (Graignic et al., 2013). In this research the following MBSE methods will be explored; DT, DTH, and DSM.

DTs offer real-time virtual representations of physical assets, enhancing monitoring, simulation, and validation processes (Grieves, 2019) (Segovia & Garcia-Alfaro, 2022). DTHs complement DTs by providing a continuous flow of historical and future data across configurations, ensuring traceability and configuration control throughout the project life-cycle (Chown & Blyler, 2018) (Reefman, 2022). Together, they bridge the gap between design models and real-world implementation, enhancing decision-making and collaboration (Madni & Sievers, 2018).

The DSM provides a matrix-based approach to visualize and manage dependencies between project components, offering clarity on information flows and potential bottlenecks (Eppinger & Browning, 2012). By integrating DSM with MBSE, teams can map dependencies and track the impact of design changes across disciplines (Chen & Whyte, 2020). Although traditionally used in industries like aerospace, DSM is underutilized in construction, despite its potential for improving coordination and constructability (Senescu et al., 2012).

Research aim & questions

Problem statement

Engineering projects, particularly in the construction sector, are characterized by their complexity and interdisciplinary nature. Managing design changes across multiple disciplines is challenging due to the lack of efficient methods to visualize and analyze interdependencies between components. While BIM serves as a collaborative tool, it lacks robust integration with MBSE principles and tools.

Main Research Question

How can engineers in a BIM environment use MBSE to visualize interdependencies between building components across different disciplines and analyze the impact of design changes during the critical design phase?

Sub-Research Questions

1. State of the art: Understanding existing methods
    - *What are the current methods available for configuring and managing design changes within the context of MBSE in construction projects?*
        - Define MBSE in the context of BIM,
        - Explore and evaluate existing MBSE configuration methods.
2. Practical implementation: Prototype development
    - *How can MBSE methods be practically implemented in a BIM environment to estimate and visualize the impact of design changes on interrelated components across multiple disciplines?*
        - Develop a prototype BIM tool incorporating MBSE principles.
        - Create practical implementation guidelines.
3. Demonstration and validation: Real-world application
    - *How can MBSE be applied to estimate the impact of design changes across disciplines in real-world engineering projects, and what are the practical challenges?*
        - Validate the prototype through collaboration with W+B.
        - Identify technical and organizational challenges and propose solutions for broader MBSE adoption in BIM.

Methodology

This research employs a mock-up prototype demonstration approach to explore the integration of MBSE methods within BIM to enhance multidisciplinary coordination and manage design changes effectively. The methodology is structured into three phases, each designed to address specific research questions and contribute to the study's objectives.

1. **Phase I: Literature review:** A comprehensive literature review establishes the theoretical foundation by exploring existing MBSE configuration methods and their relevance to BIM. The focus is on identifying gaps in current practices and understanding their role in visualizing interdependencies in construction projects. This phase addresses the first SQ and informs the subsequent prototype development.
2. **Phase II: Prototype development:** Based on insights from the literature review, a prototype BIM model is developed using Revit. The model integrates MBSE principles, DSM, DTs, and DTHs to simulate and visualize element dependencies, enabling analysis of design change impacts across multiple disciplines. This phase addresses the second SQ and results in a conceptual tool that demonstrates how MBSE can enhance decision-making in complex projects. Practical guidelines for implementation in real-world scenarios are also developed.

3. **Phase III: Demonstration and validation:** The prototype is presented to multidisciplinary professionals in focus group sessions, including engineers and project managers at W+B. Feedback is collected and analyzed to assess the prototype's usability, effectiveness, and alignment with industry needs. This phase addresses the third SQ and validates the practical application of MBSE in BIM environments, refining the prototype and developing an actionable framework for broader industry adoption.

Findings

SQ 1: MBSE methods for CM within BIM

MBSE extends the principles of SE by prioritizing models as the core medium for system development, offering significant benefits for the AEC industry. MBSE methods were identified as effective tools for managing the complex configurations required in multidisciplinary projects. These methods complement traditional BIM practices by integrating system-level insights with physical modeling, allowing teams to map interdependencies, simulate design changes, and enhance collaboration. While MBSE methods can improve communication, decision-making, and design knowledge transfer, challenges such as model accuracy, reliance on standardization, and integration with real-world validation were recognized as critical factors for success. Together, these methods provide a framework that bridges the gap between technical and functional elements in construction projects, fostering more coordinated and efficient workflows.

SQ 2: Practical implementation of MBSE methods within BIM

To explore the practical application of MBSE methods, a prototype was developed and tested, integrating key features to enhance configuration management in BIM environments. This prototype incorporated dependency mapping through DSM, real-time analysis via DT, and change tracking using DTH. Additional features, such as automated alerts and compatibility with Revit, demonstrated the prototype's ability to improve communication and collaboration across disciplines. The prototype provided a structured, three-step guideline for managing design changes: tracking successive changes, communicating changes across disciplines, and assessing the impacts of design modifications. These steps enabled teams to proactively identify conflicts, evaluate alternative solutions, and maintain alignment across project phases. The findings validated the practical feasibility of MBSE tools, offering actionable insights for improving decision-making and interdisciplinary coordination in construction projects.

SQ 3: MBSE methods in real-world engineering contexts

The study examined how MBSE methods could be applied in real-world multidisciplinary construction projects, highlighting both opportunities and challenges. MBSE's strengths included early conflict detection, enhanced collaboration, and streamlined workflows supported by real-time data sharing. Visualization of interdependencies and simulation of design changes enabled proactive decision-making, minimizing errors and inefficiencies. However, technical barriers such as data management requirements, modeling standards, and tool compatibility posed significant challenges. Organizational obstacles, including resistance to change and communication gaps between technical and non-technical teams, further limited seamless adoption. To address these issues, the study recommended scalable tools, standardized protocols, and interdisciplinary training to ensure smoother integration of MBSE practices.

RQ: MBSE integration in BIM for CM

In response to the main research question, the study concluded that MBSE methods, when integrated with BIM, significantly enhance the ability of engineers to visualize interdependencies and analyze the impact of design changes. By leveraging tools like DT, DTH, and DSM, engineers can create dynamic models that provide real-time insights into multidisciplinary configurations. These methods facilitate early conflict detection, improve collaboration, and enhance decision-making, driving better project outcomes. However, achieving the full potential of MBSE in BIM environments requires addressing technical and organizational challenges through standardized processes, incremental adoption strategies, and the development of advanced tools. This integration supports smarter, more efficient construction practices, bridging the gap between theoretical advancements and practical applications in the AEC industry.

Conclusion

This study highlights the potential of MBSE methods integrated with BIM environments to revolutionize configuration management in multidisciplinary construction projects. By leveraging tools such as Digital Twins, Digital Threads, and Design Structure Matrices, engineers can enhance the visualization of interdependencies, manage design changes effectively, and foster collaboration across disciplines. The findings underscore the transformative impact of MBSE in improving project efficiency, reducing errors, and streamlining workflows. However, the successful adoption of these methodologies requires addressing technical and organizational challenges, including standardization, scalability, and interdisciplinary training.

Broader implementation of MBSE in construction projects can enable a shift toward smarter, more data-driven decision-making, aligning design and operational objectives seamlessly. To achieve this, companies must prioritize the establishment of clear guidelines for MBSE integration, invest in robust data management and version control systems, and provide comprehensive training to project teams. Additionally, adopting scalable tools and piloting MBSE-enabled BIM workflows in real-world scenarios will help validate their effectiveness and identify areas for refinement.

Future research should explore alternative MBSE techniques, assess scalability for large and complex projects, and investigate organizational factors influencing adoption. Studies on advanced data management technologies, such as blockchain and AI, could further enhance the reliability and integration of MBSE within BIM environments. Tailoring MBSE tools to industry-specific needs and the unique challenges of smaller firms will ensure accessibility and relevance across the construction sector. By addressing these research gaps, the construction industry can fully harness the potential of MBSE to deliver innovative, efficient, and resilient projects.

Table of Contents

Abstract i

Preface ii

Executive summary vii

1 Introduction 1
- 1.1 The LEGO anecdote 1
- 1.2 Context 2
  - 1.2.1 Complex projects 2
  - 1.2.2 Configuration 2
  - 1.2.3 BIM & configuration 3
- 1.3 Literature review of BIM configuration methods 4
  - 1.3.1 Model-Based Systems Engineering (MBSE) 4
  - 1.3.2 The role of Digital Twin (DT) and Digital Thread (DTH) in MBSE 4
  - 1.3.3 Using the Design Structure Matrix (DSM) to visualize DTHs 5
  - 1.3.4 Integration 5
- 1.4 Summary and research framework 6
- 1.5 Research gap 8
- 1.6 Aims, questions and contributions 9
- 1.7 Research scope 10

2 Methodology: Prototype Demonstration 11
- 2.1 Introduction 11
  - 2.1.1 Phase I: Literature review – Exploring MBSE Methods for Configuration 13
  - 2.1.2 Phase II: Prototype development – Structuring BIM Dependencies 13
  - 2.1.3 Phase III: Demonstration and validation – Real-World application 14
- 2.2 Data Collection and analysis 15
  - 2.2.1 Phase I: literature review – Exploring MBSE Methods for Configuration 15
  - 2.2.2 Phase II: Prototype development – Structuring BIM dependencies 15
  - 2.2.3 Phase III: Demonstration and Validation – Practical feedback and guideline development 16
- 2.3 Deductive and inductive 17
- 2.4 Quantitative and qualitative 17

3 Current state of MBSE methods within BIM 18
- 3.1 Introduction 18
- 3.2 Systematic thinking & MBSE 19
  - 3.2.1 What is SE 19
  - 3.2.2 Model-Based Systems Engineering (MBSE) 22
- 3.3 MBSE & BIM 24
  - 3.3.1 What is BIM 24
  - 3.3.2 Difference between MBSE & BIM 24
  - 3.3.3 Implementing MBSE within BIM 25
  - 3.3.4 From multiple configurations to one unified configuration 26
- 3.4 MBSE methods 28
  - 3.4.1 Digital Twin 28
  - 3.4.2 Digital Thread 29
  - 3.4.3 Design Structure Matrix 31
  - 3.4.4 MBSE methods conclusion 34

4 Mock-up prototype: MBSE methods 35
- 4.1 Introduction 35

4.2 Context and requirements ... 36
4.2.1 Requirements ... 36
4.3 Building the prototype ... 37
4.3.1 Configuration ... 38
4.3.2 Design changes ... 39
4.3.3 Element attributes ... 39
4.3.4 Dependency types ... 40
4.3.5 Dependencies between elements ... 41
4.4 The mock-up prototype ... 42
4.4.1 Digital Twin ... 42
4.4.2 Digital Threads ... 43
4.4.3 Design Structure Matrix ... 45
4.4.4 One configuration ... 47
4.5 Practical implementation of the prototype ... 48
4.5.1 Implementation in Revit ... 48
4.5.2 Guideline ... 51
4.5.3 Creating a dependency graph in BIM ... 53

5 Demonstration analysis ... 55
5.1 Introduction ... 55
5.2 The Canvas ... 56
5.3 Demonstration Results ... 57
5.3.1 Prototype validation ... 58
5.3.2 Canvas answers analysis ... 59
5.4 Demonstration discussion analysis ... 60
5.4.1 Advantages of the prototype ... 60
5.4.2 Disadvantages of the prototype ... 61
5.4.3 Technological obstacles ... 62
5.4.4 Organizational obstacles ... 63
5.4.5 Future perspectives ... 66

6 Discussion ... 69
6.1 Research findings ... 69
6.2 Interpretations from the research ... 73
6.3 Implementations ... 74
6.4 Limitations of the research ... 76

7 Conclusion and recommendations ... 77
7.1 Conclusion ... 77
7.2 Recommendations & further research ... 81

References ... 82

A Phase I ... 85
A.1 Keywords ... 86

B Phase II ... 89
B.1 Mock-up prototype ... 90
B.2 Practical guideline ... 92

C Phase III ... 93
C.1 The canvas ... 94
C.2 Prototype validation ... 99
C.3 Discussion VS literature ... 100
C.4 Problems from practice and solutions from theory ... 104

List of Abbreviations

ACC	Auto-desk Construction Cloud
AEC	Architecture, Engineering, and Construction
AI	Artificial Intelligence
BIM	Building Information Modeling
CM	Configuration Management
CM2	Configuration Management (Version 2)
DSM	Design Structure Matrix
DT	Digital Twin
DTH	Digital Thread
HVAC	Heating, Ventilation, and Air Conditioning
IFC	Industry Foundation Classes
ISO	International Organization for Standardization
MBSE	Model-Based Systems Engineering
MEP	Mechanical, Electrical, and Plumbing
ROI	Return on Investment
RQ	Research Question
SE	Systems Engineering
SoS	System of Systems
SQ	Sub-Question
TOE	Technical Organizational External
V&V	Verification and Validation
W+B	Witteveen + Bos

List of Figures

1.1 The assemblies of the LEGO Darth Vader helmet 1
1.2 Theoretical background framework 7
1.3 Research context scope 10

2.1 Research method 12
2.2 Deductive vs inductive 17

3.1 The V-diagram (Reefman, 2022) 20
3.2 Every phase has its own configuration Reefman (2022) 27
3.3 Different configurations: (a) Design and (b) Production Reefman (2022) 27
3.4 Digital thread linking changes across configurations. 30
3.5 Example of a DSM showing dependencies between project components across multiple disciplines. Each cell indicates a dependency, with filled cells representing connections that may affect other components if modified. 31

4.1 Configurations 38
4.2 Design changes 39
4.3 Element attributes 39
4.4 Different types of dependencies 40
4.5 Dependencies between elements 41
4.6 Digital Twin prototype 42
4.7 Elements per configuration 43
4.8 Configuration of elements and DTHs 44
4.9 Configuration diagram 45
4.10 Zoom in configuration diagram detail 46
4.11 One configuration 47
4.12 How the DSM translates to BIM 48
4.13 Digital Twin, Digital Threads, and DSM in Revit 49
4.14 Showing the dependent elements 49
4.15 Zooming in on element dependencies within a discipline 50
4.16 Zooming in on element dependencies between disciplines 50
4.17 Guideline for implementation 52
4.18 Gephi dependency graph 54

5.1 Demonstration at W+B on the 15th of October 55
5.2 Discussion during the workshop session 65
5.3 Future perspectives strategies 68

B.1 Guideline for implementation 92

C.1 The Canvas for the demonstration 94

List of Tables

3.1 Comparison between MBSE and BIM 25

4.1 List of abbreviations 41

5.1 BIM Experience Table 57

A.1 Themes, Keywords, and References for the introduction 86
A.2 Themes, Keywords, and References for the research gap 87
A.3 Themes, Keywords, and References 88

B.1 Elements of the prototype and their references with integration details 90
B.2 Integration of MBSE methods in the mock-up prototype 91

C.1 Validation of requirements based on participant feedback 99
C.2 Advantages of the prototype and alignment with literature 100
C.3 Disadvantages of the prototype and alignment with literature 101
C.4 Technological obstacles and alignment with literature 102
C.5 Organizational obstacles and alignment with literature 102
C.6 Future perspectives on modeling tools and BIM protocols 103
C.7 Disadvantages of the prototype and proposed solutions 104
C.8 Technological and organizational obstacles and proposed solutions 105

Chapter 1

Introduction

1.1 The LEGO anecdote

During the weekend, I thought about getting a new LEGO set and building something. However, I realized that I did not need to get a new set and instead checked my LEGO collection to see what I could build. I found a project that included a model of Darth Vader's helmet and started working on it. Once I got the construction manual I saw that the model could be constructed in five parts, each of which was packed in a separate bag. Carefully, I took apart the model, placing each part into separate boxes as were the original bags. Such an arrangement of the parts would make it easier to put everything back together.

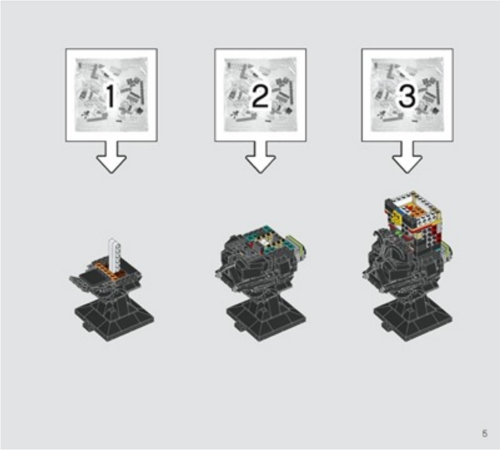


Figure 1.1: The assemblies of the LEGO Darth Vader helmet

Upon starting the process of reconstruction, I noted that every bag had its own system and was able to stand alone from the rest. The assembled constituents were practically interchangeable so that they could be viewed or built simultaneously. If there was a change or a need for some repair, you could find the particular place affected and go about fixing it without touching the model as a whole. Still, all LEGO elements within any of the sub-assemblies had some connection with each other, and even though the connection was weak sometimes it still meant that if one element was altered it would have some effect on other elements depending on how much depth the alteration was made.

This experience led me to think about the parallels with building construction. In this analogy, the Darth Vader helmet model represents a building, with its various sub-structures akin to different components such as the main structure, exterior elements, interior spaces, and MEP systems.

Consider a scenario where a change is needed in the building's façade. By referencing the assembly manual for the exterior elements, one can determine how to implement the change, identify the connected components, and understand the interdependencies. This process mirrors the concept of CM in construction, where managing the relationships and dependencies between various building components is crucial. CM ensures that changes are systematically planned, tracked, and implemented, minimizing disruptions and maintaining the integrity of the overall project.

Just as with the LEGO model, where modifications are restrained to specific sections, CM in building construction allows for targeted changes. This approach not only enhances efficiency but also ensures that the impact of changes is well understood and controlled.

1.2 Context

1.2.1 Complex projects

Engineering projects are inherently complex due to the multitude of interacting components that give rise to emergent behaviors (Sandars & Goh, 2020). These systems are composed of many parts and involve complex interactions where behaviors emerge unpredictably from the way the elements intertwine. Managing such complexity involves recognizing that outcomes are not straightforward and that the system's behavior is shaped by these interactions, often in ways that are difficult to foresee or control (Z. Sun et al., 2016).

The defining feature of complex engineering projects is the interconnectedness and interdependence of different elements. For instance, in construction projects, the coordination between multiple stakeholders—architects, engineers, contractors, and project managers—results in a network of interrelated components. These components influence one another in ways that are unpredictable, creating challenges in managing project teams, aligning stakeholder interests, and adapting to evolving project requirements. As a result, the complexity often leads to unexpected outcomes, requiring a flexible management approach rather than reliance on predefined processes (Sandars & Goh, 2020).

Complexity in projects also arises from the variety and diversity of elements, which Baccarini (1996) refers to as differentiation. Differentiation is split into vertical and horizontal categories: vertical differentiation refers to the depth of hierarchical structures within an organization, while horizontal differentiation refers to the breadth of different departments or disciplines involved in the project (Baccarini, 1996). Along with differentiation, Baccarini (1996) highlights interdependence as a key aspect of complexity, where project elements depend on one another. There are three types of interdependencies: pooled, where components operate independently but contribute to a common goal; sequential, where one element's output becomes the input for another; and reciprocal, where components are mutually dependent on each other (Baccarini, 1996).

In engineering projects, complexity is commonly categorized into three areas: Technical, Organizational, and External complexities, according to the TOE framework (Bosch-Rekveldt et al., 2014). Technical complexity arises from the use of advanced technologies, materials, and processes such as BIM, which require specialized expertise and integration. Organizational complexity refers to the internal dynamics within the project, including communication flows, coordination among teams, and goal alignment across disciplines. Finally, external complexity deals with factors outside the project, such as regulations, economic conditions, and social expectations, all of which can significantly impact project success.

As projects grow in scale and complexity, managing design changes becomes increasingly difficult. Design changes are often one of the major causes of delays and errors in construction projects. While BIM has been widely adopted to enhance coordination and collaboration, there is still a lack of integration of more advanced CM methods, such as MBSE. These methods offer the potential to improve the management of design changes, helping to mitigate the risks associated with complex projects and avoid costly overruns and delays (Cha & Kim, 2020) (Eftekhari et al., 2022) (Reefman, 2022) (Bano et al., 2012) (Wood & Ashton, 2009).

1.2.2 Configuration

Configuration refers to the arrangement and organization of components or elements of a system to ensure that it functions as intended (Jensen et al., 2012). In a broader sense, configuration involves maintaining system integrity, ensuring proper operation, and supporting change control (Jensen et al., 2012).

It is often applied in various fields, such as engineering, IT, construction, and product design. There are several key aspects of configuration, they are listed as follows. Firstly, configuration involves specifying the individual components or elements that make up the system. Secondly, configuration includes parameters and attributes of these components. Thirdly, are the relationships between components, ensuring they interact correctly with each other. An example from construction is ensuring that different building systems are configured correctly to work together without conflicts. The fourth key aspect is change management, ensuring that any changes to the system or its components are tracked, controlled, and documented. This is to prevent unauthorized or unintended changes that could negatively affect the system's performance. Lastly, life-cycle management plays a key role in configuration as it is a continuous process that spans the entire life-cycle of a system, from its initial design to end decommissioning (Reefman, 2022).

1.2.3 BIM & configuration

There are several reasons behind BIM and its conceptualization. Firstly, BIM was created to allow architects, engineers, and builders to create a more comprehensive, digital 3D, representation of a building. The second is to enhance the visualization and accuracy, reducing errors, and eliminating the inconsistencies that arose from using 2D drawings, which often led to costly rework during construction. The third main initial goal was to improve coordination between different disciplines involved in a project (architects, structural engineers, mechanical, MEP, contractors, client). By having a shared, central digital model, BIM allowed different disciplines to work more collaboratively and resolve clashes before construction began. Finally, BIM was intended to help reduce the time and costs associated with building projects by improving communication, detecting potential issues earlier, and reducing errors during construction through better planning (Azhar, 2011) (Borrmann et al., 2018).

BIM's original intent was largely focused on improving the design and construction process, its role in CM across multiple disciplines became more prominent as the technology and practices evolved. Despite BIM becoming more widely adopted and sophisticated, it is not optimally used as a tool for multidisciplinary coordination, change management, and life-cycle management. BIM has the potential to further develop and evolve into a platform that helps manage complex interactions and interdependencies between different project disciplines (Langroodi & Staub-French, 2012). With the digital functionality of BIM, it has the potential to facilitate CM by allowing stakeholders to track, identify, and measure the impact of changes to the design and construction (Pilehchian et al., 2015).

The CM aspect of BIM focuses on controlling changes, maintaining the integrity of data, and ensuring that all project stakeholders have access to the most current and accurate information. Recent studies suggest that though the technology is capable of more advanced configuration methods, there is a significant lack of implementation (Reefman, 2022) (Mangialardi et al., 2017). Every discipline works within its own configuration, making it hard to create one integrated configuration in which dependencies between these disciplines are shown.

BIM can be used as a configuration tool by enabling the management, control, and coordination of building elements, systems, and processes (Liu et al., 2014). It helps to ensure that all components and elements of a building are properly configured to work together harmoniously. The following methods can be used within BIM for configuration; centralized data, change management, clash detection, model federation, component configuration, standardization, interdependent systems, regulatory compliance, visualization, simulation, and as-built (Reefman, 2022).

There are notable challenges and limitations regarding configuration methods within BIM in the practical construction field. While BIM provides powerful tools for design, modeling, and coordination, the application of CM in real-world construction face several difficulties (Z. Sun et al., 2016). These challenges stem from a variety of factors, including the complexity of projects, gaps in standardization, and the collaborative nature of construction, which hinder the effective use of configuration methods in BIM (Z. Sun et al., 2016).

1.3 Literature review of BIM configuration methods

This section provides a comprehensive review of CM methods within BIM, focusing on the integration of MBSE, with DT, DTH, and eventually DSM. The methods offers advanced techniques for managing complexity and interdisciplinary coordination during the design phase.

1.3.1 Model-Based Systems Engineering (MBSE)

In the construction industry, managing complex projects has traditionally relied on document-based methods, where designs, specifications, and configurations are maintained in separate documents across multiple disciplines (Madni & Sievers, 2018). This approach often results in fragmentation, with different teams using distorting information that can easily become inconsistent, outdated, or conflicting (Reefman, 2022).

MBSE emerged as a response to these challenges, shifting from a document-centric paradigm to a model-centric one (Madni & Sievers, 2018). MBSE places models at the core of the design and development process, allowing for a more integrated, coherent, and traceable approach to managing complex projects. Unlike the document-based method, where each discipline maintains its own set of configurations, MBSE enables the consolidation of these configurations into a single, unified model. This shift eliminates the need for maintaining multiple, often conflicting, configurations and allows all stakeholders to work from a consistent model (Reefman, 2022). By centralizing system-related information, MBSE enhances traceability, consistency, and error detection.

One of the key benefits of MBSE is its ability to handle the intricate dependencies between various components and systems. Complex projects involve interactions across multiple domains (Graignic et al., 2013)—such as structural, mechanical, electrical, and architectural, that must be carefully coordinated. MBSE provides a framework for modeling these interactions in a unified system, ensuring that design changes in one discipline are properly accounted for in others, thereby minimizing risks and inefficiencies (Graignic et al., 2013).

1.3.2 The role of Digital Twin (DT) and Digital Thread (DTH) in MBSE

DT technology has become a cornerstone in the advancement of MBSE by enabling real-time, virtual representations of physical assets (Segovia & Garcia-Alfaro, 2022). In construction projects, DT provides an accurate and dynamic model of the building or infrastructure, allowing continuous monitoring, simulation, and optimization (Grieves, 2019). By integrating DTs with MBSE, project teams can visualize the current state of the project in real-time, simulate possible design changes, and assess their impacts before implementation (Reefman, 2022). This real-time feedback loop not only enhances decision-making but also strengthens the V&V processes that MBSE supports (Madni & Sievers, 2018).

The DTH further complements MBSE by creating an unbroken flow of data that connects all aspects of a project from its inception to completion and beyond (**reefmand**). Although the DT represents the current state of the project, the DTH provides the historical and future data necessary to trace changes, maintain configuration control, and link various stages and configurations of the project (Reefman, 2022). In MBSE, DTH ensures that every design modification is traceable across all configurations. This flow of data is essential for maintaining consistency in all disciplines, ensuring that changes made in the DT are accurately reflected in the execution of the project (Chown & Blyler, 2018).

By combining the DT and DTH, MBSE can bridge and connect virtual models and real-world implementation. This integration ensures that all stakeholders have access to up-to-date information, allowing faster decision-making, better risk management, and overall improved project outcomes (Madni & Sievers, 2018).

1.3.3 Using the Design Structure Matrix (DSM) to visualize DTHs

While MBSE, together with DTs and DTHs offer handy tools for managing complex construction projects, the DSM provides a complementary method for visualizing and managing dependencies between project components (Eppinger & Browning, 2012). DSM is a matrix-based tool that represents the relationships between elements of a system, focusing on information flows rather than workflows (Eppinger & Browning, 2012). It has been applied in various fields, including construction, where it can enhance project management based on constructability principles. Its simplicity and ability to organize data flow make it a valuable tool for managing complex projects across different project management approaches, including traditional, hybrid, and agile methodologies (Piccirillo et al., 2017).

In construction projects, the interactions between different systems are often highly interdependent. Design changes in one area can have significant downstream impacts on others, leading to delays or cost overruns if not properly managed. DSM allows project teams to map these interdependencies explicitly, helping to identify critical connections and potential bottlenecks in the design process (Yassine, 2004).

When integrated with MBSE, DSM can be used to visualize how DTHs connect different components and configurations over time (Chen & Whyte, 2020). For instance, as changes are made to the DT, the DSM can illustrate how those changes ripple through the project, highlighting the relationships between different systems of disciplines. This visualization makes it easier for project teams to manage iterative design changes, prioritize critical tasks, and ensure that dependencies are properly addressed across all configurations (Lindkvist et al., 2013).

1.3.4 Integration

The integration of MBSE methods within BIM offers transformative potential for managing configurations of complex construction projects (Chen & Whyte, 2020). However, while the theoretical advantages of these methods are well established, their practical implementation in the construction industry remains limited and challenging. Despite its potential, there is no clear path for integration (Pavalkis, 2016).

In practice, one of the main barriers to adopting MBSE and its associated technologies is the fragmentation of data and workflows across disciplines (Zou et al., 2020). Construction projects often involve multiple stakeholders, each working with their own set of tools, standards, and practices. The integration of MBSE into BIM requires a high level of collaboration and data sharing across these diverse teams, which is not always easily achieved. In particular, MBSE's promise of consolidating multiple configurations into a single unified model requires consistent automation of data management practices and willingness from all parties to adopt shared models and processes (Chen & Whyte, 2020).

Furthermore, the integration of DTs and DTHs within the construction design process has several technical and organizational obstacles that impede their implementation. Technical obstacles consist of; data integration complexity, data-processing, automation, and lack of standardization (Wang et al., 2022). The following organizational obstacles are identified; cultural resistance to change, training and skill gaps, coordination across disciplines, and resource allocation (Wang et al., 2022).

The DSM, while valuable for visualizing interdependencies, is underutilized in construction compared to other industries such as aerospace and manufacturing (Senescu et al., 2012). DSM is traditionally applied in highly controlled environments where changes are meticulously planned and managed. In construction, however, the fast-paced and often unpredictable nature of projects makes it difficult to maintain up-to-date DSM models that reflect the current state of design interdependencies. Moreover, while DSM can map dependencies, it lacks the ability to dynamically adapt to real-time data, which limits its application in rapidly evolving construction projects. Senescu et al. (2012) proposed an automated approach to generate information dependency networks, aiming to reduce the time-consuming manual effort required for DSM creation.

1.4 Summary and research framework

The complexity of engineering projects can be understood through the interaction of multiple disciplines and how tasks, components, and roles differ across them. This differentiation and interdependence between the various disciplines contribute to the complexity, especially as different teams must collaborate closely (Baccarini, 1996). Sandars and Goh (2020) describe this complexity as the result of the varied elements, tasks, and roles involved in engineering projects, all of which need to be managed concurrently.

The framework in figure 1.2 outlines configuration as a core process for managing complexity. Configuration involves specifying the relationships and arrangements of project elements and managing these elements throughout the project's life cycle (Jensen et al., 2012). Configuration methods allow for the structured management of design changes while ensuring system integrity, as outlined by Guess (2021) (Guess, 2021). In particular, this framework suggests using more advanced methods such as MBSE, which centralizes models and emphasizes their use for maintaining consistency across disciplines (Madni & Sievers, 2018). MBSE structures intricate interactions between components and disciplines to manage design changes effectively (Reefman, 2022).

Further enhancing this, the framework integrates concepts like the Digital Twin and Digital Thread. The Digital Twin creates a virtual representation of physical systems (Segovia & Garcia-Alfaro, 2022), while the Digital Thread ensures consistency across configurations, providing an unbroken flow of data (Grieves, 2019). DSM is also incorporated to visualize dependencies between different project components, helping to identify potential bottlenecks or impacts from design changes (Eppinger & Browning, 2012). DSM can map interactions and improve collaboration between disciplines (Lindkvist et al., 2013).

Despite the potential benefits, the framework highlights practical challenges in applying these methods, particularly in terms of practical implementation (Senescu et al., 2012) and dealing with obstacles in collaboration and data management across multiple disciplines (Chen & Whyte, 2020). These points align with the broader literature on managing complex projects and the evolving role of CM in achieving successful project outcomes.

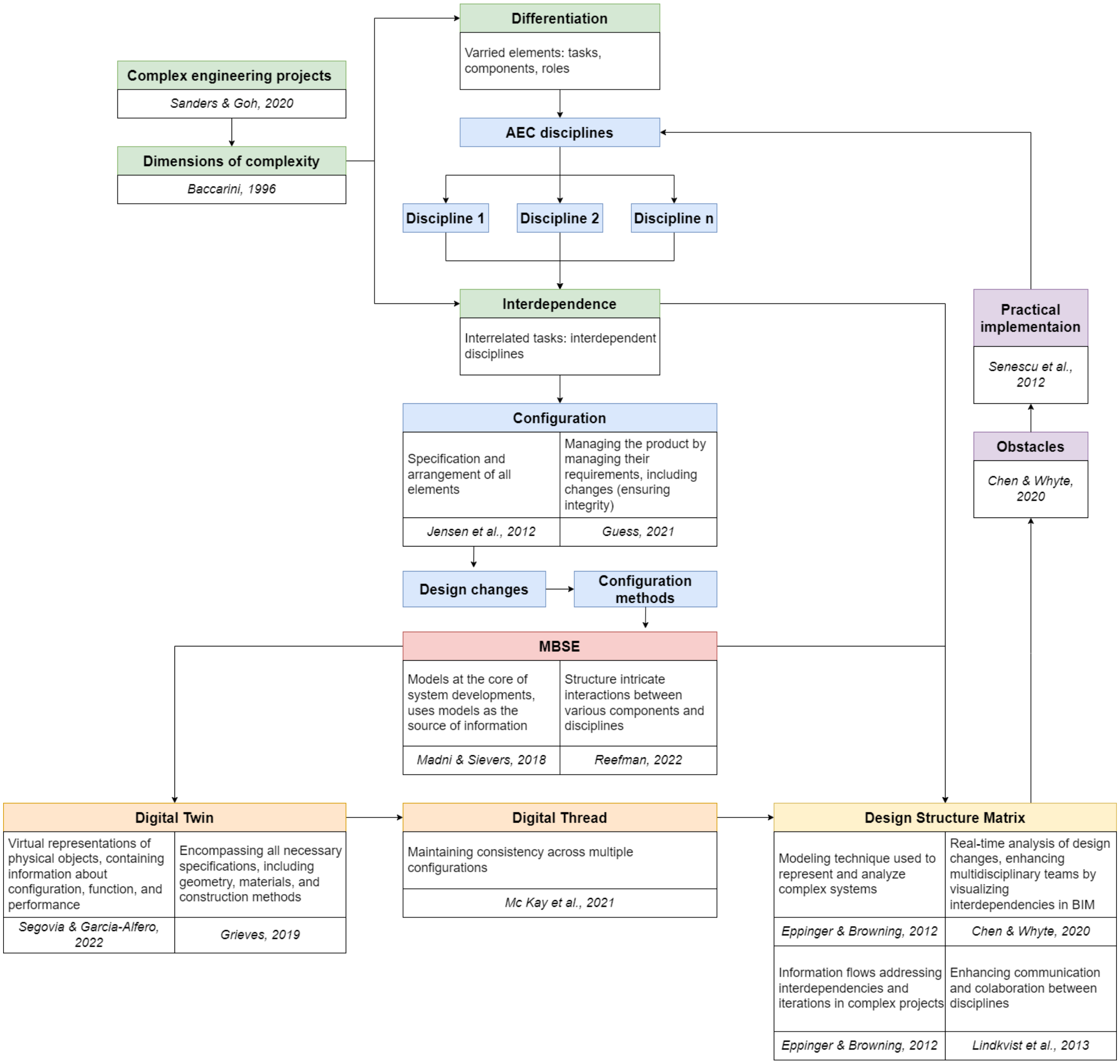


Figure 1.2: Theoretical background framework

1.5 Research gap

The LEGO anecdote from section 1.1 serves as a metaphor for CM between components, highlighting the parallel between breaking down complex systems into smaller, manageable parts and the challenges of real-world construction projects. Just as LEGO, models can be assembled and reassembled through independent sub-assemblies, complex construction projects can benefit from a systematic approach to design, where changes are localized to specific subsystems. However, this ideal is challenging to achieve in construction due to the sector's inherent complexities (Bosch-Rekveldt et al., 2014).

Fragmentation of CM across disciplines

One of the primary concerns in the construction industry is the fragmentation of CM. In contrast to the LEGO model, where sub-assemblies are neatly divided into separate, yet interconnected parts, construction projects involve multiple disciplines, each operating with its own configurations. Architects, engineers, and contractors typically use different tools, standards, and data formats, resulting in fragmented workflows. This approach results in conflicts during design changes (Eppinger & Browning, 2012) (Reefman, 2022) (Mokhtar et al., 1998)(Pilehchian et al., 2015).

Despite the promise of MBSE to consolidate multiple configurations into a unified model, achieving this in practice remains a significant challenge (Madni & Sievers, 2018). A key research gap is exploring how integrated CM can be established across disciplines in complex construction projects (Grieves, 2019).

Under-utilization of DTs and DTHs

Although DT and DTH technologies offer the potential for real-time monitoring and simulation, their practical adoption in construction remains limited (Reefman, 2022). The complexity of integrating data from the dynamic design phase with virtual models poses both technical and organizational challenges. Existing research highlights the lack of standardized methods for creating and maintaining DTHs, which are essential for connecting the disciplines' dependencies (Segovia & Garcia-Alfaro, 2022).

Limited application of DSM

While the DSM has been widely applied in industries such as aerospace and manufacturing to manage interdependencies between system components (Eppinger & Browning, 2012), its adoption in construction remains limited (Freddi & Salmon, 2018). Again, the multiple disciplines, combined with rapid design iterations, make it difficult to maintain an up-to-date DSM model that accurately reflects the evolving interdependencies between project components (Oloufa et al., 2004) (Chen & Whyte, 2020).

Research is needed to explore how DSM can be adapted to the practical field. There is a need for methods that allow DSM models to reflect changes as they occur within the design process (Chen & Whyte, 2020). Additionally, DSM methods can be integrated with DT technologies, allowing project teams to visualize how design changes ripple through different disciplines, enabling more effective design change management.

Organizational barriers to MBSE adoption

Finally, while the technical aspects of MBSE are well-researched, there is a significant gap in understanding the organizational challenges that prevent adoption (M. Sun et al., 2006). The research focuses on identifying strategies to overcome organizational resistance, and providing a change management framework to promote adoption of MBSE.

1.6 Aims, questions and contributions

Research aim

The goal of this thesis is to implement MBSE into multidisciplinary construction projects to enhance the configuration of design changes. This implementation will utilize DSM to analyze and quantify the impact of design changes on element dependencies within complex construction projects. Given the broad scope and diverse topics in the theoretical framework, this thesis will specifically focus on the integration of element dependencies within BIM models. The research will explore current MBSE methods through DTs and DTHs. The implementation framework will be validated using a prototype BIM model with integrated dependencies, which will be demonstrated to the accompanying organization of W+B in front of multiple disciplines.

Research questions

Based on the problem statement, the RQs aim to explore how designers in complex construction projects can leverage MBSE as a configuration method to enhance decision-making regarding design changes. The main RQ is:

How can engineers in a BIM environment use MBSE to visualize interdependencies between building components across different disciplines and analyze the impact of design changes during the critical design phase?

The RQ will guide the research of how MBSE methodologies can work together to streamline the design process, manage changes effectively, and ensure multi-disciplinary coordination in large-scale construction projects. To answer the main RQ, three SQs are formulated:

State of the art: Understanding existing methods

1. What are the current methods available for configuring and managing design changes within the context of MBSE in construction projects?
   - Define MBSE in the context of BIM.
   - Explore and evaluate the various MBSE configuration methods that are currently in use or proposed for managing design changes.

Practical implementation: prototype development

2. How can MBSE methods be practically implemented in a BIM environment to estimate and visualize the impact of design changes on interrelated components across multiple disciplines?
   - Develop a systematic mock-up prototype BIM tool that visualizes components and their interdependencies, incorporating MBSE requirements.
   - Create a practical implementation guideline for how this prototype can be utilized in real-world projects.

Demonstration and validation: real-world application

3. How can MBSE be applied to estimate the impact of design changes on various disciplines in real-world engineering projects, and what are the practical challenges?
   - Present and validate the prototype through collaboration with W+B, collecting insights on its practical application and effectiveness.
   - Identify potential technical and organizational challenges and explore future strategies to overcome these obstacles in the adoption of MBSE in BIM.

1.7 Research scope

This research focuses on the intersection of CM, MBSE, the Critical Design Phase, and the Construction Industry. These four interconnected domains define the scope of the study, as illustrated in the research scope diagram 1.3.

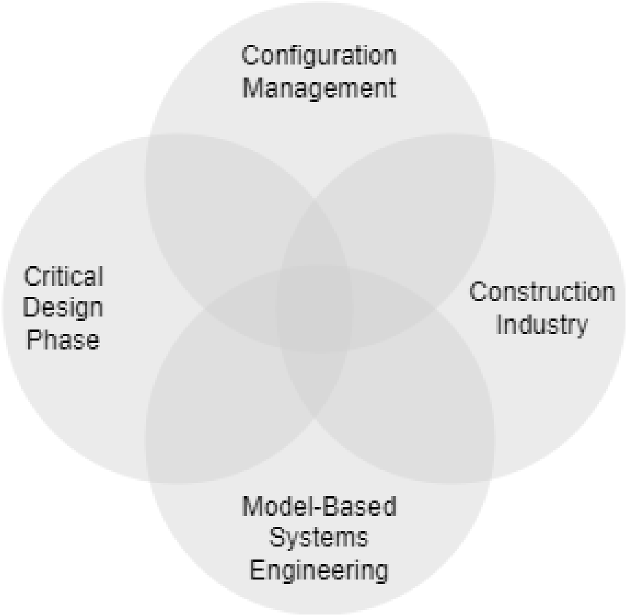


Figure 1.3: Research context scope

Configuration Management: CM serves as the backbone for maintaining consistency and traceability in complex projects. Within this research, CM has been examined as a tool for managing design change. It guarantees consistency between disciplines. and maintain the configurational integrity of a construction project during the critical design phase.

Model Based Systems Engineering: MBSE is seeking a model-driven approach that moves away from traditional document-based approaches. The research explores how MBSE can support the integration of different subsystems and disciplines. In construction projects, it promotes an integrated approach to managing complex interdependencies during the design process.

Critical Design Phase: This study limits its focus to the critical design phase. This is where key decisions determine the overall success of a construction project. Research is focused on this phase to address the challenges of interdisciplinary coordination, initial configuration management, and optimizing design workflows.

Construction Industry: The research is contextualized within the construction industry, addressing its unique challenges, such as fragmented workflows, interdisciplinary coordination, and the increasing demand for digital tools like BIM. By situating the study in this domain, it aims to provide practical insights and recommendations tailored to the industry's specific needs.

In the focal point of this research lies the intersection of CM, MBSE, the critical design phase, and the construction industry. This intersection represents a new area of study, emphasizing the integration of advanced systems engineering principles with configuration management to address the complexities inherent in early-stage construction design.

Chapter 2

Methodology: Prototype Demonstration

2.1 Introduction

This chapter outlines the research design, using a prototype demonstration approach to explore integrating MBSE methods within BIM. The study is organized into three main phases: a literature review, prototype development, and a demonstration involving focus groups. The goal is to develop practical guidelines for applying MBSE in BIM.

The first phase begins with a literature review, investigating existing MBSE configuration methods to identify those most relevant to BIM. Based on this, a prototype BIM model will be developed in the second phase, incorporating element dependencies to simulate real-world project scenarios.

In the final phase, the prototype will be demonstrated to focus groups, with professionals from various fields providing feedback. This input will be essential for refining the prototype and crafting practical guidelines for MBSE implementation in BIM.

Data will be collected and analyzed throughout these phases, combining both quantitative and qualitative approaches to ensure a comprehensive understanding. The research employs both deductive reasoning from theory and inductive insights from real-world feedback.

This methodology aims to contribute to both academic research and practical applications, enhancing the integration of MBSE and BIM in complex construction projects.

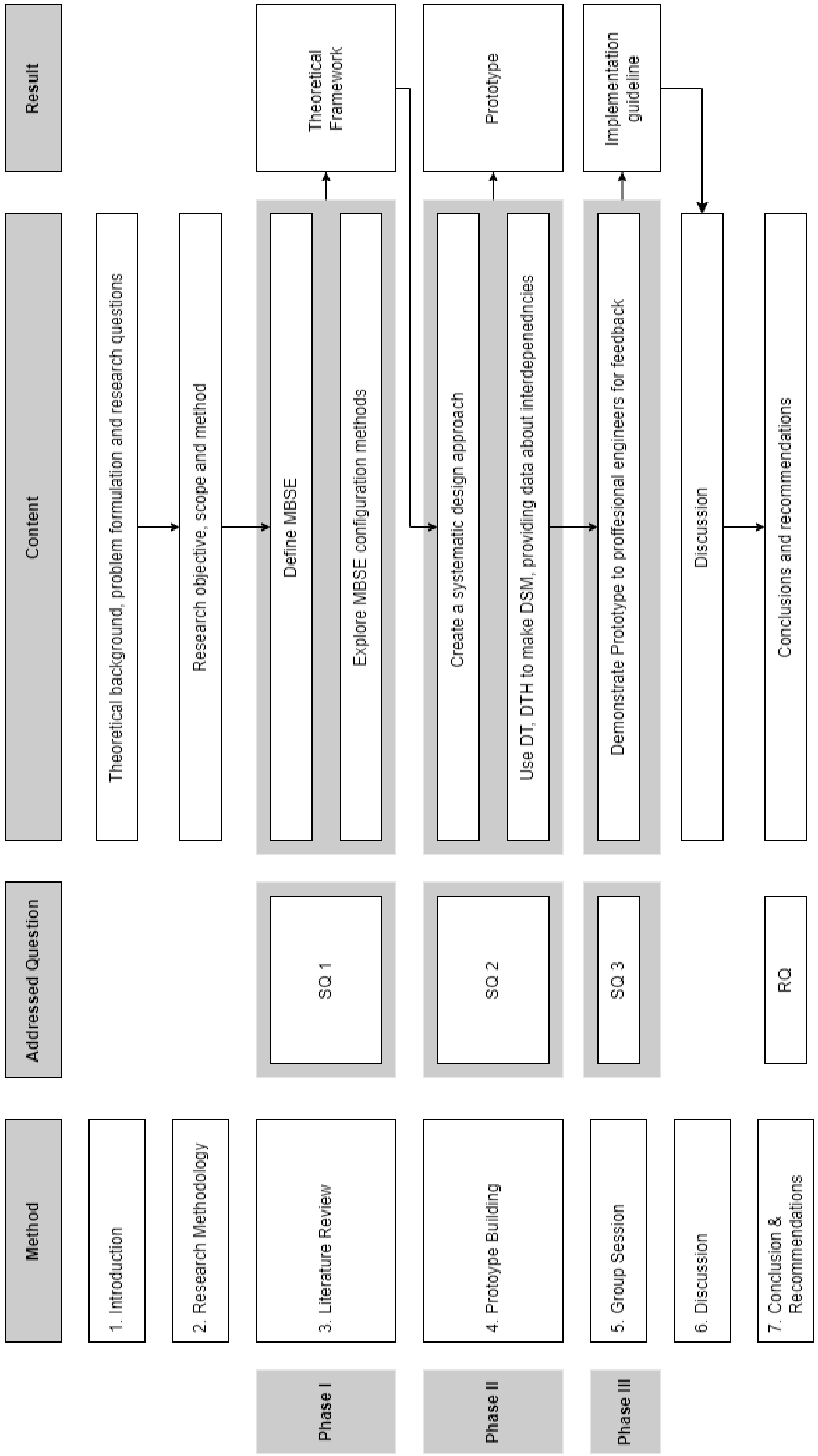


Figure 2.1: Research method

2.1.1 Phase I: Literature review – Exploring MBSE Methods for Configuration

The first phase of the research focuses on addressing the first SQ 1 by conducting a thorough literature review on the current methods of configuration within MBSE, particularly in relation to BIM environments. This review will establish the theoretical foundation needed to understand how MBSE methodologies can be integrated into multidisciplinary construction projects.

SQ 1: What are the current methods of configuration within MBSE?

To answer this question, Phase I will:

1. Define MBSE and its relevance in the context of BIM.
2. Explore existing MBSE configuration methods that can be applied to visualize interdependencies within construction projects.
3. Investigate how MBSE supports systematic design approaches and multi-disciplinary coordination.
4. Examine the role of DTs and DTHs in configuration management and their integration with MBSE frameworks.
5. Review relevant literature on DSM to understand its utility in managing design dependencies.

Expected outcome

This phase will provide a comprehensive review of MBSE configuration methods, linking them to BIM practices in the construction industry. It will also identify gaps in current literature and set the stage for developing an integrated framework for managing element dependencies in complex projects, guiding the development of a prototype mock-up in Phase II.

2.1.2 Phase II: Prototype development – Structuring BIM Dependencies

In this phase, the research moves towards addressing the second SQ. Based on the literature review in Phase I, the focus will be on developing a prototype BIM model that integrates MBSE principles to manage design changes effectively by structuring and visualizing element dependencies across disciplines. This prototype will utilize DSM, DTs, and DTHs as key components.

SQ 2: How can MBSE methods be practically implemented to estimate the impact of design changes on interrelated disciplines within complex projects in a BIM environment?

To address this question, Phase II will:

1. Develop a requirement list that applies MBSE principles to structure BIM element dependencies, ensuring these dependencies are visually represented and analyzable.
2. Create integrated DTs and DTHs to capture real-time data and the relationships between building components.
3. Use DSM as a tool for organizing and mapping interdependencies between BIM elements.
4. Prototype a BIM tool that integrates all these components, enabling designers to visualize and analyze the impact of changes across multiple disciplines.
5. Provide a practical guideline to integrate the prototype in a real-world context.

Expected outcome

The expected outcome is a mock-up prototype that conceptually demonstrates the integration of MBSE into BIM models, effectively visualizing and analyzing interdependencies. The prototype will serve as a proof-of-concept, showing how design changes can be managed more efficiently in complex construction projects, especially when dealing with multidisciplinary coordination.

2.1.3 Phase III: Demonstration and validation – Real-World application

Phase III will address the third SQ by focusing on demonstrating and validating the prototype in a real-world engineering context, particularly within W+B. The prototype will be presented to multidisciplinary teams for feedback, and its practicality in managing design changes across various disciplines will be assessed.

SQ 3: How can MBSE be used to estimate the impact of design changes across various disciplines in the real-world engineering context?

To answer this question, Phase III will:

1. Demonstrate the prototype in an interactive session with engineers from various disciplines at W+B.
2. Gather qualitative feedback from participants to evaluate the prototype's effectiveness in visualizing and analyzing element dependencies and design changes.
3. Assess the practical application of MBSE in managing interdependencies within a BIM environment, focusing on its ability to enhance decision-making processes.
4. Develop a framework for future perspectives, illustrating how MBSE can be adopted for managing design changes and interdependencies in future projects.

Expected outcome

The final outcome of this phase will be a validated prototype, demonstrating how MBSE can be practically applied to estimate and manage the impact of design changes across various disciplines. Additionally, this phase will result in a refined framework that can be adopted by W+B and other companies to mitigate risks and enhance efficiency in managing complex projects.

2.2 Data Collection and analysis

The collection and analysis of data are crucial to the development of a practical framework for integrating MBSE into multidisciplinary construction projects. The data management strategy is made to ensure that each research phase is supported by structured referencing, enabling the accurate validation of findings and the creation of a reliable framework.

2.2.1 Phase I: literature review – Exploring MBSE Methods for Configuration

In Phase I the research focuses on collecting existing theoretical knowledge and identifying gaps in MBSE configuration methods. The data collected during this phase will be only qualitative, consisting of literature sources, theoretical models, and best practices that inform the development of the framework. This phase will create a theoretical framework that will serve as a basis for developing the prototype in Phase II. The literature is gathered with tools such as Google Scholar, Elicit, and Google Search. The use of keywords per theme are highlighted in the appendix.

1. **Literature sources**: Academic journals, books, conference proceedings, and reports on MBSE, CM, and BIM.
2. **Theoretical models**: Identification and documentation of existing MBSE methods and configuration frameworks.
3. **Data analysis**: A qualitative analysis of literature sources, focusing on identifying common themes, trends, and gaps in MBSE and BIM integration methods.

2.2.2 Phase II: Prototype development – Structuring BIM dependencies

In Phase II, the research shifts towards building a prototype mock-up that integrates MBSE principles into BIM tools, focusing on structuring element dependencies and visualizing their interrelations. In this phase, the data from the previous phase will be used to create a mock-up prototype. BIM software will be used to develop the tool, this research focuses on the use of Revit to develop a BIM tool. This phase will generate a functional prototype that will serve as a proof-of-concept, demonstrating the practical application of MBSE to manage design changes across disciplines in BIM models.

1. **Literature sources**: Additional data on advanced MBSE methods and DSM (Design Structure Matrix) applications.
2. **BIM software data**: Use of BIM tools to develop and structure element dependencies in the prototype, including datasets related to spatial and functional elements.
3. **Prototype development**: Collection of data on system performance, usability, and the accuracy of dependency visualization in the prototype.

2.2.3 Phase III: Demonstration and Validation – Practical feedback and guideline development

Phase III focuses on validating the mock-up prototype in a real-world setting, through its demonstration to engineers from various disciplines. Data collection will involve gathering feedback from participants and using it to refine the prototype and finalize the practical framework. This phase will produce a validated prototype and a practical guideline for integrating MBSE into CM processes within BIM environments, designed for real-world applicability in multi-disciplinary construction projects.

1. **Feedback from demonstration**: Qualitative feedback collected through a canvas and focus group discussions with engineers and project managers at W+B.
2. **Practical application data**: Observations and data on the prototype's practical performance in visualizing element dependencies and supporting decision-making in real-world scenarios.
3. **Implementation guideline**: Data collected on the steps required to adopt MBSE into existing CM practices will be documented to create the final guideline.
4. **Data analysis**: Qualitative analysis of feedback, focusing on identifying strengths, weaknesses, and areas for improvement in the prototype. The feedback will be coded and analyzed for patterns that inform further refinement of the framework.

Overall data management and analysis strategy

The overall data management and analysis strategy is designed to ensure the accuracy, transparency, and integrity of the data collected throughout the research process. The following steps will be implemented:

1. **Data storage and security**: All data (literature, software outputs, prototype documentation, feedback) will be stored in a secure drive with access restricted to authorized personnel. Data will be backed up regularly.
2. **Data documentation**: Detailed documentation of the data collection process will be maintained, including descriptions of the methodologies, tools, and protocols used in each phase. This will ensure transparency and replicability of the research.
3. **Ethical Considerations**: Participants involved in the feedback and validation processes will provide informed consent, and their data will be anonymous to protect privacy.

2.3 Deductive and inductive

The main difference between deductive and inductive research is in the direction of reasoning and how conclusions are formed. A deductive approach starts with a theory or hypothesis, as the research begins with a general theory, idea, or framework. The goal is to test and validate this theory. An inductive approach, on the other hand, starts with observations or data. The research begins with collecting evidence or observing patterns without a predetermined theory. The goal is to develop new theories or insights based on the observed data. Deductive can be seen as top-down and inductive as bottom-up reasoning.

This research implements a deductive method as it is theory-driven and tests the theoretical framework formulated in the introduction. The study begins with a conceptual model for managing configuration information, which is derived from existing literature and guidelines, indicating a top-down approach starting from theory. The research aims to test whether systematic configuration information used in product development can be applied to construction projects. This involves verifying existing theories within a new context. The demonstration results and literature review are used to compare actual practices against the proposed model, which is a typical deductive approach to validate theoretical frameworks.

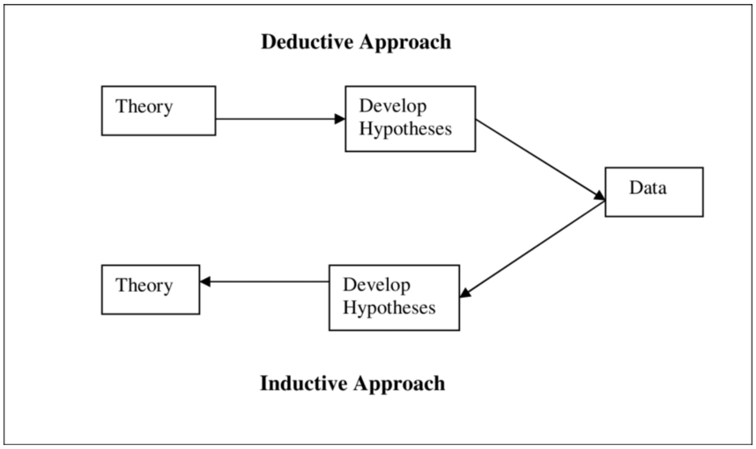


Figure 2.2: Deductive vs inductive

2.4 Quantitative and qualitative

The research will be a qualitative method, making a prototype to validate the qualitative research. A qualitative literature review, as an extensive literature study will be conducted to identify key areas of configuration applicability to construction projects. The literature review involves qualitative analysis to synthesize findings from various sources. The result of the research will manifest in the form of a framework. Developing a conceptual model for managing configuration information involves qualitative reasoning and synthesis of knowledge from the literature and guidelines.

Chapter 3

Current state of MBSE methods within BIM

3.1 Introduction

This chapter explores the current state of MBSE methods within the context of BIM, examining their roles, relationships, and the potential for integration. With the increasing complexity of modern construction projects, systematic and structured approaches to managing these complexities are gaining relevancy. MBSE offers a robust framework for handling system-level complexities, while BIM provides essential tools for managing the detailed, data-driven aspects of construction projects.

Section 3.2 focuses on Systematic Thinking & MBSE, beginning with an exploration of what is SE and how SE principles form the foundation for MBSE. The discussion then moves to MBSE itself, outlining its key concepts and benefits, particularly in managing complex systems with numerous interacting elements.

In Section 3.3, the chapter delves into the relationship between MBSE and BIM. After defining What is BIM, the chapter explores the differences between MBSE & BIM and the unique contributions each brings to project management. Furthermore, the section discusses strategies for implementing MBSE within BIM, highlighting the potential for integrated workflows. It concludes with a look at how MBSE can facilitate moving from multiple configurations to one unified configuration, streamlining project management and enhancing coherence across systems.

Section 3.4 introduces key MBSE methods that are increasingly being applied within the BIM environment. These include the concepts of the DT, which creates a virtual model of the physical project, the DTH, which ensures traceability and continuity of data throughout the project life-cycle, and the Design Structure Matrix, a method for modeling the relationships and dependencies between project components.

By exploring these topics, this chapter provides an overview of how MBSE methods can be integrated within BIM, offering potential solutions to the growing complexity and demands of modern construction projects.

3.2 Systematic thinking & MBSE

This section aims to explore the integration of MBSE as a configuration method within BIM to effectively manage and implement design changes. The integration will be discussed in the context of system engineering principles, MBSE's key characteristics, and the practical implementation of MBSE approaches, such as the DT, DTH, and DSM.

3.2.1 What is SE

SE has a multitude of definitions over the years, which built up chronologically. To understand SE, first, the definition of a system has to be established. Sub-sequentially, the definition of SE will be established. Closing this section with a brief explanation of V&V methods.

Systems

A system is defined as a set of interrelated components or subsystems that work together to achieve a common goal (Carayannis et al., 2014). Systems may involve various types of components, which interact to deliver functionality (Carayannis et al., 2014). Systems exist in various forms, from everyday examples to specialized fields like computer and information systems.

There are three types of systems, these are; simple, complex, and adaptive (Mitchell & Newman, 2002). Simple systems consist of a limited number of components and interactions, often predictable. An example of a simple system is a bicycle. Its parts (pedals, chains, wheels) interact in a straightforward way. Complex systems, on the other hand, involve numerous components with intricate interactions, where changes in one part can affect others unpredictably. An aircraft is an example of a complex system with multiple layers of interaction. Lastly, adaptive systems can change or evolve based on feedback from the environment, such as biological ecosystems (Mitchell & Newman, 2002).

Systems can exist at multiple levels of complexity, often within hierarchical structure (Clauset et al., 2008). These are called subsystems, components within a larger system that have their own function but contribute to the system's overall objective. Bringing back to the aircraft example, the engine or landing gear system are subsystems. A SoS is a set of systems working together to achieve a higher-level goal (Clauset et al., 2008). An example would be the integration of aircraft control systems, and ground operations working together.

The behavior of a system emerges from interactions between its components. These can be unpredictable due to the complexity of the interactions, especially in systems with many dependencies (Carayannis et al., 2014). Understanding system behavior is central to SE, as it allows engineers to predict how changes to one part of the system will impact the whole. Systems engineering is inherently interdisciplinary, requiring collaboration across multiple fields of expertise. Managing a system means ensuring that all these perspectives are aligned and work together to achieve the system's objectives (Carayannis et al., 2014).

Definition of SE

According to the literature summarized by Buede (2024), SE is an interdisciplinary approach that integrates both technical and management processes to ensure that complex systems meet stakeholder needs and operational requirements throughout their life-cycle. Wymore (2018) defines SE as the intellectual, academic, and professional discipline of which the principal concern is the responsibility to ensure that all requirements for bioware/hardware/-software systems are satisfied throughout the life-cycle of the system.

SE applies scientific engineering principles to transform operational needs into defined system configurations through iterative processes such as analysis, design, synthesis, evaluation, integration, and testing. It brings together various engineering disciplines, management practices, and stakeholder inputs to ensure that systems meet their intended functions and objectives.

The goal of SE is to ensure that all individual system components function together as a cohesive whole. SE addresses the complexity that arises from modern engineering projects, which involve multiple subsystems, stakeholders, and disciplines. These projects typically require balancing competing constraints such as performance, cost, reliability, safety, and schedule. SE ensures that these systems are built to fulfill their objectives (Bahill & Dean, 1996).

Verification and validation (V&V) in SE

One critical aspect of SE is V&V. Verification ensures that a system or component is built correctly and adheres to the design specifications. Validation ensures that the system fulfills the operational needs and performs as expected in real-world conditions. V&V methods make sure that systems are built according to design specifications and fulfill their intended purposes (Madni & Sievers, 2018).

Traditionally, V&V activities have been guided by the V-diagram, a sequential development and validation model. While this approach is effective, it often identifies errors late in the process, making them more difficult and costly to rectify (Reefman, 2022). The V-diagram is a fundamental concept in SE, offering a visual representation of the product development process from inception to completion (Clark, 2009). The diagram's characteristic "V" shape captures a dual process: the left side represents the top-down design approach, while the right side reflects the bottom-up realization approach. This structure helps systematically decompose complex systems into manageable components and then integrates them back into a cohesive whole.

On the left leg of the V-diagram, the process begins with defining application requirements, which lay the foundation for the entire system. This is followed by system design, where the overall architecture is developed, subsystem design, where specific functionalities are detailed, and component design, which specifies the individual parts of the system. The right leg of the V-diagram mirrors this process but focuses on the realization phase. It starts with constructing individual components, assembling subsystems, and then integrating the entire system. The final stage involves delivering the product, with rigorous testing phases to ensure that the final system meets the original design requirements. Figure 3.1 illustrates the V-diagram's sequential order, progressing from left to right (Reefman, 2022).

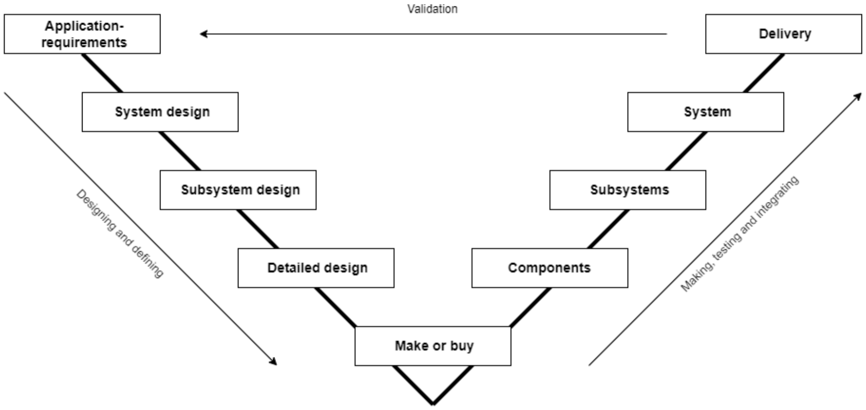


Figure 3.1: The V-diagram (Reefman, 2022)

Challenges in SE

While SE is a powerful approach for managing complexity, it has some challenges to cope with. Firstly, as systems grow in size and complexity, integrating and managing numerous components and subsystems becomes increasingly difficult (Eppinger & Browning, 2012)(Madni & Sievers, 2018). The integration process involves coordinating engineering activities at various levels to achieve a cohesive final product (Eppinger & Browning, 2012). Factors contributing to SE complexity include rapidly emerging technologies, multidisciplinary components, and the need for system resilience and adaptability (Madni & Sievers, 2018). The collaborative engineering environment adds another layer of complexity, requiring adaptation of SE approaches to distributed settings. SE must account for the interactions between these components to identify potential errors. To address these challenges, researchers have proposed methods such as documenting system decomposition, identifying component interactions, and clustering components around integration challenges (Eppinger & Browning, 2012).

Secondly, is the balancing of trade-offs, as SE often requires making difficult trade-offs between competing objectives (Parnell et al., 2021). Balancing these factors is essential for delivering a system that meets all stakeholder needs within project constraints. This process, often called trade-off analysis, requires determining the relative priority of requirements and selecting preferred alternatives (Gilb & Maier, 2005). As data availability increases, trade-off analytics will become an increasingly important tool for engineers across various domains (Parnell et al., 2021).

Lastly, communication and coordination within SE is challenging. Because SE involves multiple disciplines and stakeholders, effective communication and coordination is crucial (Au & Ravindranath, 2020). Miscommunication between teams or departments can lead to design errors, delays, or failure to meet system requirements. Studies have shown that system engineers in mediating roles can improve the probability of technical success by facilitating communication channels within design teams. To address these challenges, an integral collaboration environment between domains and across levels is key to achieving efficient and high-quality designs (Au & Ravindranath, 2020).

Benefits of SE

Despite the challenges, SE also offers significant benefits to the construction sector. First of all, SE ensures that all subsystems and components work together smoothly, reducing the likelihood of integration issues during the system deployment (Bahill & Dean, 1996).

Another key benefit is SE's emphasis on early risk identification. Through comprehensive planning, analysis, and continuous monitoring, SE enables project teams to detect potential issues at the earliest stages of the development process. This proactive risk management approach ensures that problems are mitigated or resolved before they escalate, thereby preventing costly delays and avoiding disruptions to the project timeline (Bahill & Dean, 1996).

Finally, SE's focus on aligning system requirements with stakeholder objectives throughout the entire life-cycle of the project ensures that the design is well-defined from the start. By addressing requirements iteratively and continuously verifying and validating system performance, SE helps minimize the need for costly rework. This not only saves time but also keeps projects within budget and on schedule, leading to a more efficient and reliable construction process (Bahill & Dean, 1996).

3.2.2 Model-Based Systems Engineering (MBSE)

MBSE is a modern approach to systems engineering that places models at the core of system development. Unlike traditional document-centric SE methods, MBSE uses models as the authoritative source of information throughout the system's life-cycle, from initial concept through design, implementation, and maintenance (Madni & Sievers, 2018) (Reefman, 2022). This approach is particularly beneficial in managing the complexity, maintaining consistency, and ensuring traceability in the development of large-scale systems, such as those encountered in complex construction projects.

In the context of complex construction projects, MBSE offers a structured methodology to handle the intricate interactions between various components, subsystems, and disciplines involved. Construction projects often involve numerous stakeholders, each with specific requirements and expectations. MBSE provides a coherent framework to capture these requirements, model the interactions between different system elements, and ensure that the project progresses in a coordinated and controlled manner (Reefman, 2022). The transition from document-based to model-based methods allows engineers to more effectively simulate, analyze, and optimize systems.

MBSE and CM: V&V

V&V translates from SE to MBSE, ensuring that systems are built according to the design specifications (verification) and that they meet the intended operational requirements (validation). MBSE supports V&V by providing a consistent, traceable model of the system that evolves over time, reflecting changes and updates throughout the design process. In MBSE-based V&V, models act as the central reference, enabling verification through automated model checks and consistency evaluations, and validation through simulations, and scenario analysis by digital models.

Within systems, each subsystem has its own configuration that specifies how its components are structured and how they interact within the subsystem. These subsystem configurations define the architecture, design, and operational parameters specific to each individual part of the larger system. Configuration outlines how each part of the system is arranged, connected, and interacts with others. This includes technical specifications, design features, interfaces, and the relationships between subsystems and components. For instance, in a building project, configuration might include how the HVAC system integrates with the electrical and structural systems. CM is a crucial process in SE that ensures consistency and traceability of a system's configuration, ensuring that all changes are systematically evaluated. This is critical for ensuring that the system continues to meet its requirements and functions as intended, even as changes are made during design, development, or operational phases.

MBSE uses digital models to unify and link the configurations of all subsystems into a single, integrated system configuration. Thereby, MBSE enhances CM by maintaining a single source of truth for the system's design and configuration. This helps ensure that all design modifications are properly tracked and that the system's current state is always aligned with the project's specifications and goals. The traceability provided by MBSE makes it easier to identify the impact of design changes and manage configuration baselines.

Characteristics of MBSE

MBSE centralizes all system-related information into a single, configuration-managed repository, setting it apart from traditional engineering practices that often depend on multiple, inconsistent models (Madni & Sievers, 2018). This centralization allows for the interconnection of model elements, efficient information retrieval, and reasoning about the system's design and performance. Key features of MBSE include consistency, traceability, and error identification. These key elements will be explained in the following paragraph. The first key element is consistency. When a design change is made in one part of the model, MBSE automatically propagates this change throughout the system, ensuring that all aspects of the system remain aligned. This capability is critical in complex systems where minor inconsistencies can lead to integration issues later on. The second hallmark of MBSE is traceability, as it tracks requirements, design decisions, and assumptions throughout the system development process. This makes it easier to perform rigorous V&V since each system element can be traced back to its originating requirement. Lastly, MBSE aids in error identification, as the integrated models allow for early error detection and consistency checks. By identifying potential issues earlier in the design process, MBSE reduces the likelihood of costly mistakes that could arise later in the project. These features make MBSE a powerful methodology for managing complexity (Madni & Sievers, 2018).

Benefits of MBSE

In complex construction projects, the benefits of MBSE are particularly evident. MBSE enhances communication among multidisciplinary teams, supports visualization of complex structures, and captures decisions and assumptions systematically. Madni and Sievers (2018) identified the benefits of MBSE, these are further explained in the following paragraph. One of the primary advantages of MBSE is enhanced communication. By providing a common framework and language, MBSE facilitates better interaction and understanding among architects, engineers, contractors, and other stakeholders, which is crucial in large-scale, multi-stakeholder projects. Additionally, visualization is a key benefit: MBSE models offer visual representations of the construction project, making it easier for team members to understand the structure and how various components interact. This visual clarity aids in the early identification of potential issues and provides a comprehensive understanding of the system's overall behavior. Finally, MBSE significantly improves documentation and knowledge transfer. It ensures that the rationale behind design decisions and assumptions is thoroughly documented, making it easier to conduct audits, reference decisions later in the project, and transfer knowledge to new team members. This is especially important in long-term or phased projects where consistent decision tracking is essential for maintaining system integrity.

Pitfalls and challenges

While MBSE offers numerous benefits, it also presents certain challenges that must be carefully addressed to avoid potential pitfalls (Madni & Sievers, 2018). One major issue is the risk of inaccurate models. If the model does not accurately represent the system or its operational environment, the insights and conclusions drawn from it may be flawed, leading to misguided decisions and project setbacks. Another challenge is the possibility of over-reliance on models. Solely depending on models without cross-validating them with real-world data can lead to overconfidence in the predictions they produce, increasing the likelihood of unforeseen risks or errors during project execution. Additionally, a lack of consistency and standardization across models is a concern. When different teams use inconsistent terminology, methods, or assumptions, it can lead to confusion and miscommunication, which underscores the importance of rigorous standardization processes in MBSE. Lastly, inadequate V&V is a critical issue. Without thorough V&V processes, models can generate wrong analyses, making it essential to ensure that models are rigorously tested and validated to maintain their reliability and accuracy. Addressing these challenges is important to achieve best practices, to fully realize the potential of MBSE in complex projects (Madni & Sievers, 2018).

3.3 MBSE & BIM

The integration of MBSE within BIM represents a powerful methodology for managing complex building systems throughout their life-cycle. BIM has transformed the AEC industries by creating a collaborative digital platform for managing building designs. The assumption is that when combined with MBSE, BIM's capacity to handle design configurations and system interactions can be significantly enhanced. This section will take a deeper dive into the differences between MBSE and BIM. When combining these differences, three benefits of implementing MBSE into BIM are highlighted. These benefits give validation to why it is important to explore MBSE methods in relation to BIM.

3.3.1 What is BIM

BIM is a comprehensive digital methodology that streamlines the creation, management, and exchange of information throughout the entire life-cycle of a building or infrastructure project. BIM integrates various aspects of construction, including design, cost estimation, scheduling, and project management, into a coordinated and reliable database. This centralization enhances collaboration among architects, engineers, and construction professionals by allowing them to share and access information efficiently, ensuring that all stakeholders are working with consistent, up-to-date data. BIM improves coordination across disciplines, reduces errors, and facilitates more accurate decision-making throughout the design, construction, and operation phases. It leverages relational databases that store both graphical and non-graphical (e.g., material specifications) information, providing stakeholders with detailed insights into the project at every stage. This integrated approach helps reduce waste, streamline processes, and improve cost-efficiency by minimizing rework and ensuring alignment across teams. Globally recognized for its ability to foster collaborative working environments, delivering significant benefits in communication, cost management, and long-term life-cycle management of buildings and infrastructure (Azhar, 2011) (Eastman et al., 2008).

3.3.2 Difference between MBSE & BIM

MBSE and BIM are both methodologies used to manage complex systems, but they differ in focus and scope. However, they share a complementary relationship which will be explored within this section.

As established before, MBSE is an interdisciplinary approach that focuses on the entire life-cycle of a system. Using models to represent the system's structure, behavior, and requirements, centralizing all system-related information. MBSE is concerned with the technical and functional aspects of systems, focusing on how various subsystems interact and are integrated (Madni & Sievers, 2018).

BIM, on the other hand, is primarily used in architecture, engineering, and construction (AEC) sectors to manage the design, construction, and operation of physical structures like buildings and infrastructure. BIM models serve as digital representations of the physical and functional characteristics of a facility, focusing on spatial relationships, geometry, and material specifications. They also enable stakeholders to visualize, plan, and collaborate on projects, improving productivity, quality, and efficiency while reducing costs and delivery times. It creates a centralized data model where all project stakeholders can work together effectively, incorporating data from planning and design through construction, renovation, and demolition (Azhar, 2011) (Eastman et al., 2008). The following table provides an overview of all the differences between MBSE and BIM based on the literature of Madni and Sievers (2018) and Azhar (2011).

MBSE (Model-Based Systems Engineering)	**BIM (Building Information Modeling)**
Focuses on the entire life-cycle of systems, addressing technical and functional aspects (**madni2018**).	Focuses on the design, construction, and operation of physical structures, primarily in AEC sectors (**azhar2011**).
Centralizes system-related information through models that capture system structure, behavior, and requirements (**madni2018**).	Manages the physical and spatial characteristics of buildings and infrastructure using digital representations (**azhar2011**).
Integrates subsystems and ensures their interactions and dependencies are effectively modeled (**madni2018**).	Facilitates the design and planning of buildings, incorporating geometry, spatial relationships, and materials (**azhar2011**).
Applied in domains like aerospace, defense, and automotive to manage complex system integration (**madni2018**).	Applied in architecture, engineering, and construction to streamline project management and collaboration (**azhar2011**).
Enhances collaboration across disciplines by providing a unified system model that captures functional aspects (**madni2018**).	Provides a centralized platform where stakeholders collaborate on project details throughout the building life-cycle (**azhar2011**).
Models system behavior and performance, focusing on logical interactions between subsystems (**madni2018**).	Models physical structures, focusing on the geometry, spatial layout, and material specifications (**azhar2011**).

Table 3.1: Comparison between MBSE and BIM

When using MBSE with BIM, the two can be used together to enhance the design and management of construction projects. MBSE can provide a systems-level perspective for managing and integrating the configurations of the subsystems or disciplines that must interact within a physical infrastructure (Madni & Sievers, 2018), while BIM models the physical aspects of that infrastructure (Azhar, 2011). MBSE can be effectively applied within the BIM environment to improve the management of building systems, enabling a model-centric approach to design. While BIM traditionally focuses on the 3D modeling of physical structures, MBSE brings in a systematic method for managing the engineering aspects of building systems.

3.3.3 Implementing MBSE within BIM

There are several ways in which MBSE can enhance BIM, particularly in complex construction projects where multiple systems and disciplines need to be integrated effectively.

Firstly, as established from multiple sources, MBSE allows for better integration of complex building systems and their dependencies within the wide range of interconnected systems. MBSE provides a framework for modeling these technical systems and their interactions, ensuring that their dependencies are understood and managed effectively (Madni & Sievers, 2018)(Graignic et al., 2013) (Eppinger & Browning, 2012) (Yassine, 2004)(Chen & Whyte, 2020). This level of integration is often difficult to achieve through BIM alone, which primarily focuses on the physical layout and structure of the building (Azhar, 2011) (Eastman et al., 2008).

Secondly, MBSE enhances BIM by ensuring that changes to design configurations are consistently and accurately reflected across the entire system model. In large-scale construction projects, design modifications are inevitable, and any change made to one subsystem can have a ripple effect on others. MBSE's model-centric approach enables automatic updates across all related components whenever a change is made. This reduces the risk of inconsistencies between different models and subsystems, a common problem when relying solely on traditional document-based methods (Madni & Sievers, 2018).

Finally, MBSE facilitates better coordination between the various disciplines involved in building projects through the use of a unified system model (Au & Ravindranath, 2020) (Madni & Sievers, 2018). Traditionally, these disciplines often work in silos, each using its own set of tools and processes. MBSE breaks down these silos by providing a shared framework where all stakeholders can contribute to and access the same system model. This improves communication and collaboration, as everyone is working from a single, integrated source of truth (Reefman, 2022). This one source of Truth can also be related to one configuration, defined by Guess (2021). It also helps bridge the gap between the physical design aspects managed by BIM and the technical performance aspects managed by MBSE.

In conclusion, the implementation of MBSE within BIM offers significant advantages for managing the complexities of modern construction projects. By providing a robust framework for integrating technical systems and their dependencies, MBSE addresses the challenges that BIM alone cannot handle, such as managing intricate system interactions and dependencies. MBSE's ability to reflect design changes consistently across the entire system model minimizes the risk of inconsistencies, ensuring that all subsystems remain aligned throughout the project life-cycle. Additionally, MBSE enhances collaboration and communication by offering a unified model that breaks down disciplinary silos, enabling all stakeholders to work from a shared source of truth. This integration ultimately bridges the gap between BIM's physical design focus and MBSE's technical and functional system management, leading to more efficient, coordinated, and resilient building systems.

3.3.4 From multiple configurations to one unified configuration

Configurations refer to the arrangement and interconnection of various components or subsystems within a larger system. In the context of SE, a configuration includes not only the physical and functional aspects of these components but also their relationships and interactions within the entire system (Jensen et al., 2012). As systems become more complex, managing configurations effectively becomes crucial. This includes handling design variations, dependencies between subsystems, and the impact of changes across the entire system. By employing MBSE methodologies, organizations can systematically manage these configurations (Madni & Sievers, 2018).

In the development of complex projects, different disciplines maintain their own specific configurations, each designed to meet their unique requirements or specifications (Freddi & Salmon, 2018). Figure 3.2 demonstrates how various phases within a project life-cycle (such as function, system, design, production, maintenance, and demolition) each have distinct configurations. These configurations adhere to the specialized demands of each phase, allowing for tailored approaches that meet specific objectives and challenges. By structuring each phase according to its unique requirements, this approach enables a more focused and effective handling of complex projects, ensuring that every stage is managed with precision and clarity (Reefman, 2022). This principle applies not only across project phases but also within various AEC disciplines, such as structural engineering, mechanical systems, architectural design, and facility management. Each discipline develops and uses configurations that reflect its specialized processes, tools, and outcomes (Reefman, 2022).

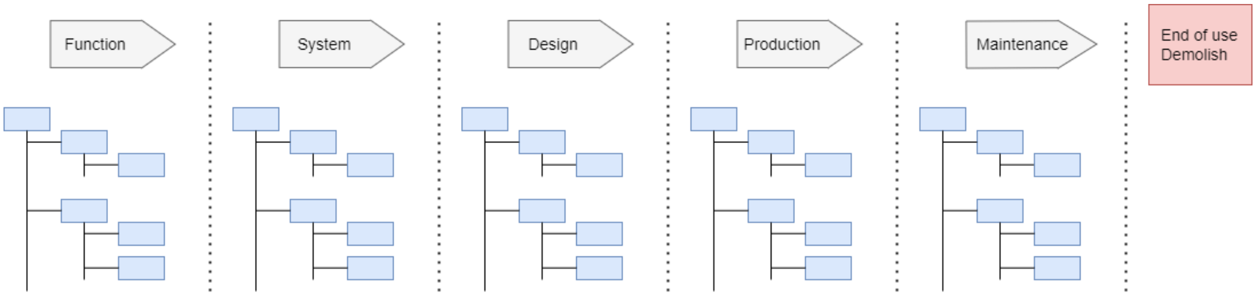


Figure 3.2: Every phase has its own configuration Reefman (2022)

As illustrated by Reefman (2022), these discipline-specific configurations can be seen, for example, in the development of a bicycle. During the design phase, the mechanical engineering team focuses on a configuration that details the brake system, including components such as the brake disc and brake caliper 3.3 a. Meanwhile, the manufacturing team has specific configurations that emphasize the physical assembly of these parts, like how the brake disc is attached to the axle, along with other production-related components 3.3 b. These separate configurations reflect the distinct concerns and focus areas of each discipline.

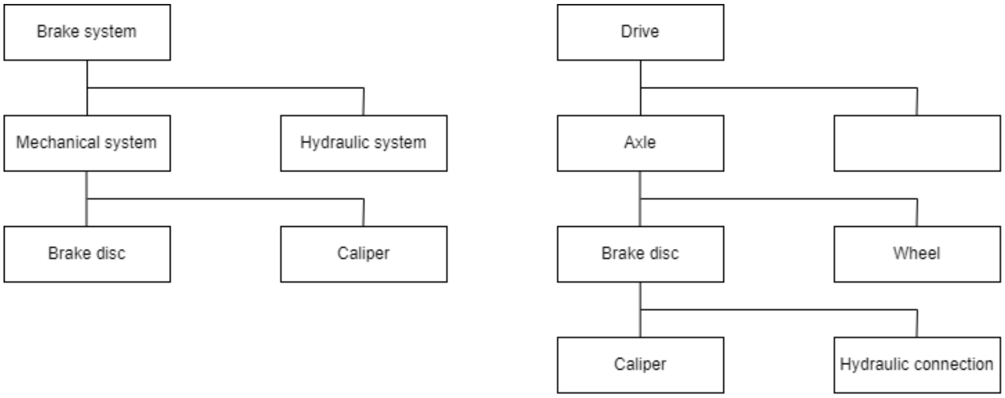


Figure 3.3: Different configurations: (a) Design and (b) Production Reefman (2022)

While these discipline-specific configurations address the specialized needs of each team, they also lead to inefficiencies and misalignment. To streamline this process, Guess (2021) proposes a unified configuration called CM2. Instead of maintaining separate configurations for design, engineering, and manufacturing, CM2 encourages the creation of a single, consistent product structure that is shared and used by all disciplines throughout the product's development. This unified configuration ensures that all disciplines are working with the same data and are aligned with their objectives, reducing the risk of miscommunication and enhancing collaboration.

This shift from multiple discipline-specific configurations to one unified configuration offers several key benefits. First, it simplifies the management of product data by eliminating the need to maintain and synchronize multiple, parallel configurations. This reduces the likelihood of errors or discrepancies that can occur when different teams work with outdated or inconsistent information (Guess, 2021). Second, it improves change management by ensuring that any modifications made by one discipline are automatically reflected across all areas, allowing for a more agile and responsive development process (Madni & Sievers, 2018). Finally, a unified configuration makes better communication and collaboration between teams possible, as all stakeholders have access to the same information and are working towards a common goal (Reefman, 2022).

3.4 MBSE methods

MBSE provides a framework to manage the complexities of modern product development and configuration management. Key methodologies within MBSE, such as the DT, DTH, and DSM, are essential for creating an integrated and cohesive theoretical framework. These methods offer practical tools for managing configurations across various disciplines, ensuring the alignment of design, production, and operational stages. In this section, these methodologies will be explored in detail and how they contribute to the overall MBSE approach.

3.4.1 Digital Twin

DT technology provides a virtual representation of physical objects or systems, incorporating essential data such as geometry, materials, and functionality. In the AEC industry, DTs enable the integration of multiple disciplines by serving as a unified and continuously updated configuration model, which reflects the real-world conditions of the project (Segovia & Garcia-Alfaro, 2022).

When initiating the design process, defining the product's appearance, functionality, and performance is critical. Previously managed with physical drawings and texts, today, this process relies on digital datasets such as 3D models, PDFs, and other virtual tools. The accumulation of digital product data throughout the development cycle allows for real-time tracking and modification (Reefman, 2022).

Digital Twins excels at managing interdisciplinary collaboration by synchronizing configuration data across architectural, engineering, and mechanical systems. As all teams work from a shared, real-time model, DTs help prevent miscommunication, outdated designs, and errors caused by isolated changes in one discipline that are not reflected in others (Reefman, 2022). Effective CM ensures that various representations of the same product remain consistent, especially when changes occur (Tiwari & Franklin, 1994).

Digital Twin in the development process

Throughout the development process, the DT acts as the single source of truth (Guess, 2021). Any changes to the design are first made in the DT, ensuring alignment between the digital and physical counterparts. This ongoing process allows for real-time monitoring, simulation, and control, supporting efficient decision-making at every project stage (Segovia & Garcia-Alfaro, 2022).

DTs enable project teams to simulate different design scenarios and assess their impacts before construction begins. By allowing simulations of alternative materials, structural systems, or energy models, DTs provide insights into the performance, sustainability, and cost-effectiveness of design choices. These simulations aid in detecting and resolving potential conflicts early (Reefman, 2022).

MBSE and Digital Twin integration

MBSE complements DTs by enhancing their ability to manage the complexity of large construction projects. MBSE provides formalized models to capture system behaviors, requirements, and design specifications, ensuring that the DT remains aligned with stakeholder needs (Madni & Sievers, 2018).

MBSE strengthens the DT framework by facilitating requirement traceability and design validation. As changes are made, MBSE ensures that all modifications are accurately reflected across the integrated DT, allowing teams to continuously validate that designs meet performance and functional criteria (Madni & Sievers, 2018). This approach helps manage the complexity of large construction projects, ensuring alignment across all disciplines.

Application of Digital Twin

The critical design phase plays a key role in determining the project's overall success. During this phase, DTs serve as a central CM tool by incorporating design data from all AEC disciplines into a single digital model. This centralized approach ensures that stakeholders from the different disciplines work with consistent and up-to-date information, minimizing errors and enhancing collaboration (Grieves, 2019).

The ability to simulate and analyze different design scenarios during the critical design phase is one of the most significant advantages of Digital Twins. By simulating the performance of various materials or structural systems under different conditions, DTs help project teams make more informed decisions. Moreover, early detection of potential design conflicts reduces the risk of costly adjustments during construction (Reefman, 2022). Identifying interdisciplinary clashes early helps streamline construction and prevents delays.

3.4.2 Digital Thread

A DTH is a comprehensive, connected flow of data that links all phases of a product or system's lifecycle, from the initial requirements through to the final delivery. This data flow provides full traceability of changes across various configurations, ensuring that modifications are consistently reflected throughout the entire system. In the AEC industry, where multiple disciplines work together on complex projects, a DTH is essential for maintaining consistency across configurations, ensuring data integrity, and facilitating communication between stakeholders (Reefman, 2022).

Linking configuration data across disciplines

As design changes are introduced in complex AEC projects, managing their impact on various configurations can become challenging. The DTH concept ensures that any design modification, regardless of where it originates, is accurately propagated across all relevant configurations within the different disciplines (McKay et al., 2021). This section outlines how a design change is managed and linked across various configurations:

1. **Change identification:** The process begins by identifying which elements in the structural configuration (Configuration 1) are affected by a design change, such as an adjustment from design A1 to design A2.
2. **Cross-disciplinary impact:** The next step is identifying corresponding elements in related disciplines, such as the architectural configuration (Configuration 2), that are impacted by the change. Virtual links are created between modified elements across different configurations.
3. **Updating subsequent configurations:** The process continues across other configurations (e.g., mechanical, electrical), ensuring that every related element is consistently updated. This structured approach ensures changes are accurately reflected across all configurations involved in the project (Reefman, 2022).

By implementing a DTH, each design modification is consistently traced through different configurations. This prevents miscommunication and design inconsistencies that can arise from isolated changes within a single discipline. The DTH supports continuous validation, ensuring that every change aligns with the overall system requirements and is reflected in all subsequent configurations (Madni & Sievers, 2018).

The digital link: Connecting requirements to configurations

In AEC projects, the DTH concept facilitates coordination across disciplines, each with its own configuration needs and datasets. For example, architects, engineers, and contractors often work with discipline-specific models that include their own set of configurations and design elements. As shown in Figure 3.4, the DTH connects these various configurations, linking initial project requirements to the evolving design and construction stages (Reefman, 2022).

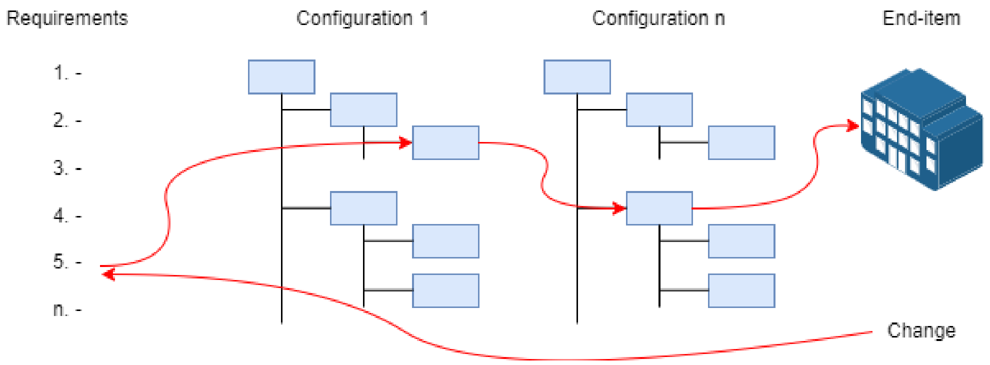


Figure 3.4: Digital thread linking changes across configurations.

In practice, this means that when requirements are updated, such as a change in material specifications or regulatory compliance, all related configurations across the architecture, engineering, and construction disciplines are updated in real-time. This dynamic flow of information ensures that each discipline remains aligned with the most current requirements.

The DTH enhances decision-making by allowing project members to verify that each requirement is accurately reflected across the different models. For instance, if a structural engineer modifies a load-bearing wall design, the updated configuration will instantly alert other disciplines, such as architecture or interior design, of changes that may impact their plans. This continuous feedback loop maintains consistency, minimizes errors, and allows the project to move forward more smoothly and efficiently, as all stakeholders can rely on synchronized, up-to-date information across their respective models (Madni & Sievers, 2018).

Following the Digital Thread in complex projects

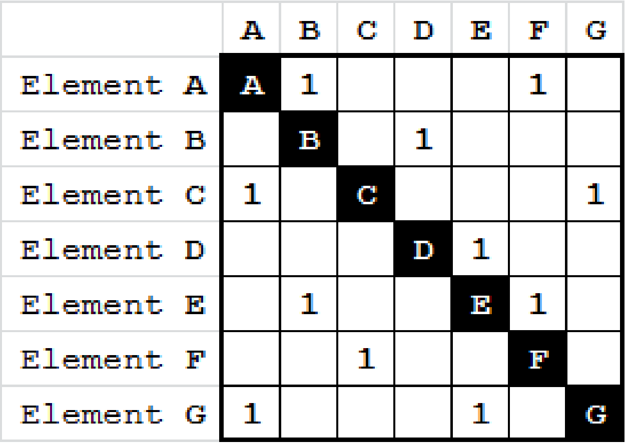
To effectively manage the impact of design changes in a complex project, it's crucial to trace the consequences of any alteration throughout all configurations. This process involves identifying affected components across configurations and determining the status of those components within the project life-cycle (Langroodi & Staub-French, 2012). The following steps outline the process of tracking design changes:

1. **Trace affected components:** Identify all components affected by a specific design change, along with their attributes in all configurations. Current BIM tools face challenges in identifying these dependencies automatically, requiring a more computational approach to track these changes.
2. **Determine component status:** Assess the design, procurement, or construction status of each impacted component. The project's 4D model, which represents time-related data, should be updated regularly to reflect the actual construction status.
3. **Impact assessment:** Evaluate the change's impact based on the current status of the affected components. This evaluation can be quantitative (cost estimates) or qualitative (assessing impact severity). Integration with 5D models (cost-related data) may be necessary to provide a complete understanding of the impact (Langroodi & Staub-French, 2012).

While BIM tools offer significant advantages for managing large-scale projects, their current capabilities to automatically identify dependencies across configurations remain limited (Pilehchian et al., 2015). Integrating computational methods with BIM tools could enhance the ability to track design changes effectively across disciplines, improving automation and accuracy in handling complex configurations (Langroodi & Staub-French, 2012). Frameworks for integrating CM with BIM have been developed, focusing on managing potential changes to IFC-based models and distributing change information among team members (Liu et al., 2014). These efforts aim to enhance the ability to track design changes effectively across disciplines, improving automation and accuracy in handling complex configurations within BIM-based project delivery processes.

3.4.3 Design Structure Matrix

The Design Structure Matrix (DSM) is a powerful modeling technique used to represent, analyze, and manage complex systems by mapping the dependencies between their components. It has been applied across a wide range of industries, including product architecture, organizational structures, and processes, and is especially useful in construction projects that involve multiple disciplines. DSM's compact format, visual nature, and analytical power make it an effective tool for simplifying and understanding complex interdependencies (Eppinger & Browning, 2012).



	A	B	C	D	E	F	G
Element A	A	1				1	
Element B		B		1			
Element C	1		C				1
Element D				D	1		
Element E		1			E	1	
Element F			1			F	
Element G	1				1		G

Figure 3.5: Example of a DSM showing dependencies between project components across multiple disciplines. Each cell indicates a dependency, with filled cells representing connections that may affect other components if modified.

As illustrated in Figure 3.5, a DSM is structured as a square matrix, where each row and column represents a specific component of the system. Interdependencies between components are indicated in the matrix cells; a filled cell signifies a dependency between the intersecting components. In multidisciplinary projects, DSM helps visualize how changes in one component can impact others across various fields, such as structural, mechanical, or electrical systems.

Unlike workflow-based models, DSM emphasizes information flows and interactions, focusing on interdependencies and iterative processes common in multidisciplinary project environments (Yassine, 2004). DSM can be enhanced by integrating multilevel data, providing a more detailed understanding of interactions between various components and tasks (Eppinger & Browning, 2012). Algorithms such as partitioning, clustering, and simulation further enhance its utility for managing the planning and execution of complex projects.

The DSM methodology follows a structured five-step approach to architectural modeling and analysis. This approach consists of the following steps: Decompose, Identify, Analyze, Display, and Improve. First, decomposition involves breaking down the system into its components or subsystems, which helps in understanding the system's structure at various hierarchical levels. Next, Identify focuses on documenting the relationships and interactions between these elements, enabling a deeper insight into the system's interdependencies. In the analysis step, the DSM rearranges the elements and their relationships to uncover the underlying patterns and assess their implications on the structure of the system. The Display step then visualizes the DSM model, highlighting features of particular relevance or interest to stakeholders. Finally, Improve involves using the insights gained from the DSM analysis to refine and enhance the system's structure, thus closing the feedback loop (Eppinger & Browning, 2012).

Recent advancements in DSM include its integration with digital tools like BIM and DTs, allowing for more efficient tracking of changes in complex systems. This digital-DSM approach enables real-time management of interdependencies, offering a structured method to analyze and visualize relationships between system components (Chen & Whyte, 2020).

Using DSM to link dependencies across disciplines

In complex construction projects, design changes can affect multiple components across various disciplines, making it difficult to predict the full impact of a single modification. DSM helps visualize these interdependencies by mapping relationships between elements—whether they are tasks, components, or teams. This is particularly helpful in the critical design phase when changes need to be understood and managed across all involved disciplines (Chen & Whyte, 2020).

According to Eppinger and Browning (2012), DSM's ability to model both direct and indirect relationships reveals hidden dependencies that might otherwise go unnoticed. By using DSM, project teams can see the broader implications of a design change, thereby managing complexity more effectively.

One of the strengths of DSM is its support for iterative work processes. In the critical design phase, changes in one part of the system often trigger cascading modifications elsewhere. DSM helps teams track these changes, reducing the need for rework by visualizing how changes in one discipline may affect others (Yassine, 2004). For example, in a construction project where structural and mechanical systems are tightly integrated, a change in the placement of a beam could impact the routing of HVAC ductwork. DSM visualizes these interdependencies, helping teams anticipate potential conflicts before they occur.

Change management with DSM

By modeling how changes to one component affect others, DSM enables project managers to foresee potential risks and plan accordingly. As demonstrated by Chen and Whyte (2020), integrating DSM with BIM allows for real-time tracking of design changes, offering immediate feedback on how these changes will propagate throughout the project. This capability is especially valuable in large, complex construction projects where even small changes can have significant ripple effects. DSM ensures that project teams have a clear understanding of these effects, allowing them to make informed decisions and reduce the risk of costly delays.

In addition to tracking changes, DSM also helps prioritize tasks by highlighting components that have the most dependencies. This makes it easier for project managers to focus on areas that are most likely to cause delays or bottlenecks. By managing both information flows and workflows, DSM enables teams to prioritize critical tasks, reducing the likelihood of rework and keeping the project on schedule (Fayez et al., 2003). For example, if a key structural component is linked to several other systems, any changes to that component must be addressed first to prevent cascading delays throughout the project.

Enhancing communication and collaboration

One of the main causes of design change disruptions is poor communication between disciplines. DSM mitigates this by providing a shared framework for understanding project interdependencies. By visualizing the relationships between different components and teams, DSM helps ensure that all stakeholders are aware of how their work impacts others.

This shared understanding is crucial for large construction projects where multiple disciplines must work together. According to Lindkvist et al. (2013), effective communication and collaboration are key to managing complex interdependencies, and DSM serves as a valuable tool for fostering this coordination.

DSM also aids decision-making by offering a clear, visual representation of how changes in one area of the project will affect other areas. By providing this holistic view, DSM helps project teams make informed decisions, ensuring that changes are implemented efficiently and with minimal disruption to the overall project timeline.

Practical implementation of DSM in construction projects

To effectively use DSM in construction projects, a structured approach is necessary. Below is a step-by-step guide for implementing DSM to manage interdependencies across disciplines:

1. **Identify project components:** Break down the project into distinct configurations and elements for each discipline. Assign unique identifiers to each component to ensure traceability.

2. **Map dependencies:** Use DSM to map the dependencies between components, representing them as rows and columns in the matrix. This step visualizes how changes in one element affect others across different disciplines.

3. **Analyze the matrix:** Analyze the DSM to identify critical dependencies, feedback loops, and potential conflicts. This analysis helps teams understand how design changes propagate through the system.

4. **Continuous monitoring:** Update the DSM continuously throughout the project life-cycle to reflect evolving dependencies. This ensures that project teams can adapt to changes as they arise.

Consider a commercial construction project with multiple disciplines, such as structural, mechanical, and electrical engineering. A design change in the structural beam might affect the placement of HVAC ducts and electrical conduits. Using DSM:

- The project team identifies the beam, ducts, and conduits as distinct components.
- Dependencies between these components are mapped, revealing how a change in the beam's position could impact the routing of ducts and conduits.
- The DSM is continuously updated as changes occur, ensuring that the impact of each change is fully understood and managed across disciplines.

The DSM is a valuable tool for managing the interdependencies of components across disciplines in complex construction projects. By visualizing these relationships, DSM helps teams anticipate the impact of design changes, improve communication, and prioritize critical tasks. When integrated with digital tools like BIM, DSM becomes even more powerful, enabling real-time tracking and management of changes. This structured approach reduces the risk of rework, enhancing project efficiency.

3.4.4 MBSE methods conclusion

In MBSE, the DT, DTH, and DSM each play a crucial role in ensuring efficient and cohesive CM for complex AEC projects. These methodologies complement one another, forming an integrated framework that aligns requirements, design, and construction stages across disciplines.

The DT provides a virtual, continuously updated representation of physical assets, allowing stakeholders to track real-world changes and simulate potential scenarios. Acting as a centralized configuration model, the DT ensures that all teams have access to accurate and up-to-date project data, which is essential for collaboration and error prevention (Reefman, 2022). By simulating various design choices, DTs enable project teams to make data-driven decisions, reduce errors, and improve overall project efficiency (Guess, 2021).

The DTH connects all configurations of the project, linking requirements to configurations in real-time. This connection ensures traceability and consistency across design changes, as updates in one discipline are automatically propagated to all others. The DTH enables project teams to maintain alignment with evolving requirements, reducing the risk of inconsistencies across the various configurations managed by each discipline (Madni & Sievers, 2018). As a result, the DTH improves decision-making and reduces costly delays that may arise from isolated changes (McKay et al., 2021).

The DSM complements DT and DTH by mapping dependencies and interdependencies across system components. DSM's visual and analytical capabilities allow project teams to understand the cascading effects of design changes, prioritize tasks, and manage interdependencies. This approach enhances project planning by clarifying how a change in one configuration impacts others, which is especially beneficial in projects with tightly integrated systems (Eppinger & Browning, 2012). DSM's ability to model relationships across project elements improves communication and coordination, allowing teams to anticipate potential conflicts and manage project complexity (Chen & Whyte, 2020).

Together, DT, DTH, and DSM create a cohesive MBSE framework that supports real-time data sharing, effective change management, and efficient collaboration across AEC disciplines. By integrating these methods, project teams can optimize workflows, reduce rework, and achieve consistency from initial design to final construction. This approach not only improves project outcomes but also supports the industry's move toward a more interconnected and data-driven future (Segovia & Garcia-Alfaro, 2022).

Chapter 4

Mock-up prototype: MBSE methods

4.1 Introduction

This chapter focuses on the development of a BIM tool designed to integrate element dependencies, thereby enhancing the tracking of design changes across AEC disciplines. The prototype is built upon the theories of the previous chapter regarding MBSE and its implementation in BIM. From exploring the current state of MBSE methods within BIM, a foundation has been established for understanding the systematic thinking required to manage multi-faced projects. This chapter is structured to explain how the prototype is built. The chapter will first explain the functionality of multi-disciplinary projects and the characteristics of design changes. The following section highlights the different element dependency types. The next section describes how the prototype model is structured, based on theories from DT, DTHs, and DSM. Finally, the chapter concludes with the practical implementation of the prototype. In this final section, a practical guideline will explain how the prototype would work in an BIM environment.

4.2 Context and requirements

Large, multi-disciplinary projects are characterized by their complexity, involving numerous interacting elements that span across different fields of expertise (Sandars & Goh, 2020). As project size and scope increase, so does the need for precise integration of various components from multiple disciplines. Effective integration becomes essential to ensure that all elements work cohesively toward the project's overarching objectives, especially as complexity increases and the potential for unpredictable interactions becomes more pronounced (M. Sun et al., 2006). The complexity of such projects presents a significant technical challenge, particularly in coordinating interactions across disciplines (Baccarini, 1996).

This prototype mock-up is developed within a multi-disciplinary project framework that includes Architecture, Structural Engineering, and MEP, collectively known as the AEC disciplines. Each of these disciplines brings its own unique set of requirements, technical specifications, and specialized knowledge illustrating the differentiation and interdependence that characterize complex projects (Baccarini, 1996). Effective coordination among these disciplines is essential for achieving a unified design, as each discipline's contributions are interdependent and must align with the overall project goals.

In such a project, each field operates with distinct configurations that outline their requirements, constraints, and design goals. These configurations need to be integrated into a comprehensive design framework, as they define how each element will function and interact within the final structure. Inevitably, design changes arise due to evolving requirements, unexpected challenges, or improvements in design strategy. Such changes can have cascading effects across the different disciplines, making it essential to adopt a coordinated approach that ensures modifications in one area do not adversely impact others. MBSE as an advanced CM method provides tools for managing these interdependencies and mitigating the risk associated with design changes (Bano et al., 2012; Cha & Kim, 2020; Eftekhari et al., 2022; Reefman, 2022).

4.2.1 Requirements

To effectively use MBSE principles for visualizing interdependencies between building components across disciplines and analyzing the impact of design changes, the prototype should adhere to the following requirements:

1. **Interdisciplinary dependency mapping**
    - *Requirement*: Enable mapping and visualization of dependencies between structural, architectural, MEP systems, and other building components.
    - *Purpose*: Categorize dependencies (e.g., spatial, functional, analytical) to clarify relationships within and across disciplines, fostering coordination.
    - *Reference*: (Reefman, 2022), (McKay et al., 2021), (Chen & Whyte, 2020).
2. **Change tracking and version control**
    - *Requirement*: Include tools for logging successive design changes, recording their impact on interconnected elements.
    - *Purpose*: Maintain a clear, accessible record of dependency changes over time, preserving design integrity and facilitating effective change management.
    - *Reference*: (Madni & Sievers, 2018).
3. **Real-time impact analysis**
    - *Requirement*: Provide real-time visualization of design changes and their potential impacts on component stability, functionality, and other dependencies.
    - *Purpose*: Facilitate proactive responses by alerting teams to significant changes and visualizing affected areas to prevent conflicts.
    - *Reference*: (Tiwari & Franklin, 1994).

4. **Automated alerts and notifications**
    - *Requirement*: Implement a notification system that automatically alerts relevant teams of changes impacting their areas, with visual cues on affected components.
    - *Purpose*: Enhance interdisciplinary communication and ensure timely responses by directing attention to relevant impacts.
    - *Reference*: (Langroodi & Staub-French, 2012), (Segovia & Garcia-Alfaro, 2022).
5. **Integration with existing BIM tools**
    - *Requirement*: Ensure compatibility with BIM tools such as Revit for seamless import, update, and export of model data.
    - *Purpose*: Maintain project continuity, allowing dependency maps and impact analyses to function within the Revit environment for consistency.
    - *Reference*: (Grieves, 2019).

These requirements are structured to establish an efficient, user-friendly prototype that leverages MBSE to visualize dependencies, support impact analysis, and enhance real-time interdisciplinary coordination, ultimately advancing change management in complex building projects.

4.3 Building the prototype

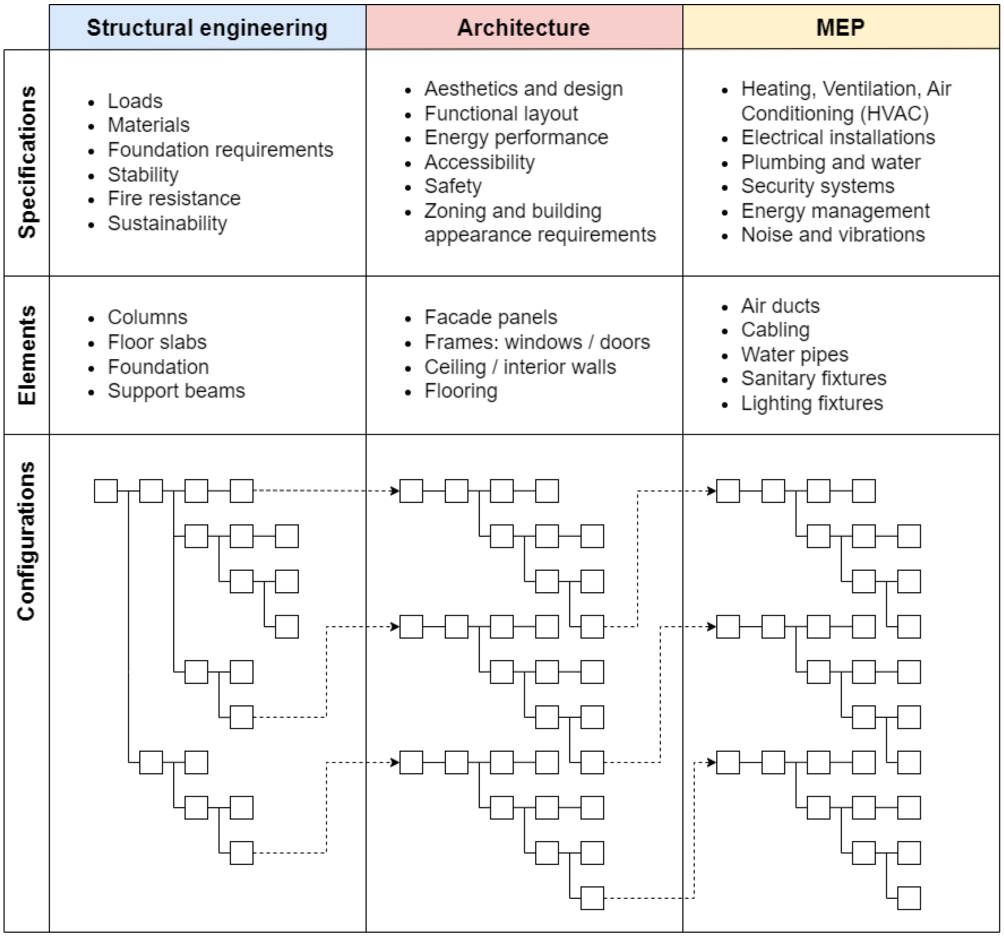
In constructing this mock-up prototype, several key elements are involved, including configurations, design changes, element attributes, dependency types, and inter-element dependencies. Configurations refer to the arrangement of elements specific to each discipline, ensuring that structural, architectural, and MEP requirements are met. This is in line with the approach discussed by Jensen et al. (2012), who highlights the importance of configuration in modular construction systems.

Design changes, such as additions, modifications, and deletions, provide flexibility for updating the prototype as the design progresses. As Langroodi and Staub-French (2012) and Pilehchian et al. (2015) point out, each element in the configuration has attributes that define its geometry, position, and specifications, which outline its physical and functional characteristics. Dependency types define how elements are interconnected, helping to predict the impact of design changes on the overall structure, as discussed by Liu et al. (2014) in their framework for managing change within BIM.

Finally, inter-element dependencies ensure that changes in one component are consistently reflected across related components, supporting a cohesive multi-disciplinary design process. This aligns with Reefman (2022) insights on configuration management, where dependencies play a critical role in maintaining functional alignment across different disciplines. Mangialardi et al. (2017) also emphasize the need for managing dependencies to ensure consistent data flow and avoid conflicts.

4.3.1 Configuration

Configuration refers to the arrangement and organization of components or elements within a system to ensure proper functionality, system integrity, and support for change control, as Jensen et al. (2012) discuss. In the context of the mock-up prototype, every discipline maintains its own unique configuration. These configurations are composed of a list of specifications and associated elements, providing a blueprint for organizing and integrating components within each discipline, which enables effective interdisciplinary collaboration and alignment (Jensen et al., 2012). Figure 4.1 illustrates these distinct configurations across disciplines, highlighting how elements are arranged within each configuration to meet specific functional and design objectives.



	Structural engineering	Architecture	MEP
Specifications	• Loads • Materials • Foundation requirements • Stability • Fire resistance • Sustainability	• Aesthetics and design • Functional layout • Energy performance • Accessibility • Safety • Zoning and building appearance requirements	• Heating, Ventilation, Air Conditioning (HVAC) • Electrical installations • Plumbing and water • Security systems • Energy management • Noise and vibrations
Elements	• Columns • Floor slabs • Foundation • Support beams	• Facade panels • Frames: windows / doors • Ceiling / interior walls • Flooring	• Air ducts • Cabling • Water pipes • Sanitary fixtures • Lighting fixtures
Configurations			

Figure 4.1: Configurations

4.3.2 Design changes

Design changes are a crucial aspect of the mock-up prototype, enabling adaptability and refinement during the development process. According to Langroodi and Staub-French (2012), there are three primary types of design changes: addition, modifications, and deletion. Additions allow new elements to be incorporated into the mock-up, modifications involve updating existing elements to enhance or alter their functionality, and deletions remove elements that are no longer needed or viable within the design. Each type of change impacts the configuration and dependencies between elements, necessitating careful management to ensure consistency. Figure 4.2 visually represents these different types of design changes, demonstrating how each type may affect the prototype's structure.

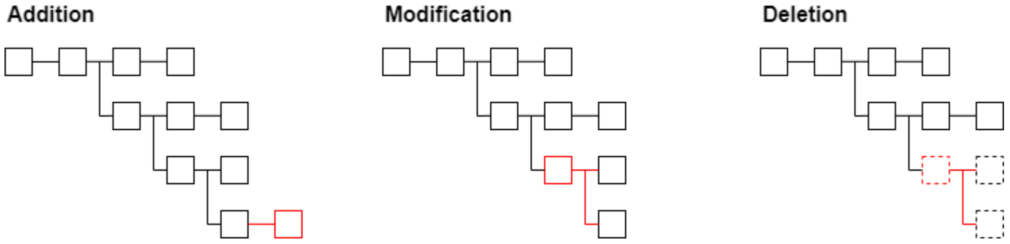


Figure 4.2: Design changes

4.3.3 Element attributes

According to Langroodi and Staub-French (2012), each element within a configuration has three primary attributes that define its characteristics: Geometry, Position, and Specification. Geometry specifies the physical shape and size of the element, position indicates its location within the structure, and specification provides details regarding its material, functionality, and performance requirements. These attributes are fundamental in determining how each element contributes to the overall configuration and how they interact with other components. Figure 4.3 illustrates these essential attributes, highlighting their role in shaping the building prototype.

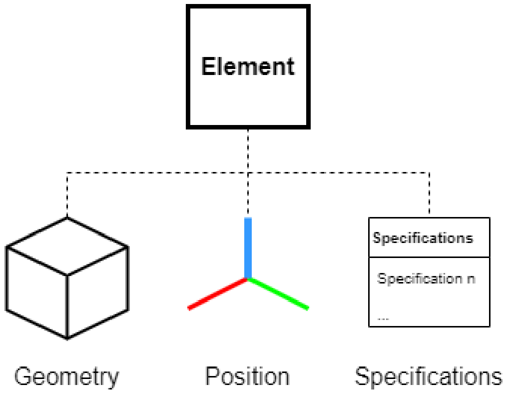


Figure 4.3: Element attributes

4.3.4 Dependency types

Dependencies between elements in a system are crucial for ensuring that different components work together cohesively. These dependencies are broadly divided into two main categories: Spatial and analytical dependencies. Each type represents unique relationships that dictate how elements interact, rely on each other, or support the overall structure and functionality of the building. (Langroodi & Staub-French, 2012).

Spatial dependencies describe physical relationships between elements, focusing on their relative positioning and structural connections. For instance, the Connected To (CT) dependency indicates a direct physical link between two elements, often essential in forming structural frameworks. Supported By (SPB) represents dependencies where one element provides structural support for another, as in the case of beams supported by columns. Adjacent To (AT) describes elements placed next to one another without a direct connection, while Surrounded By (SRB) signifies an element enclosed by another, such as a pipe within a wall. These spatial dependencies ensure that elements are positioned and interconnected to support the overall structural design.

Analytical dependencies, on the other hand, represent relationships based on functional, structural, or regulatory requirements. Structural Integrity (SI) ensures that elements contribute collectively to the building's stability. Mechanical Interaction (MI) involves dependencies requiring mechanical interaction, such as moving components. Architectural Consistency (AC) ensures design coherence, Electrical Relationship (ER) involves electrical connectivity, and Operational Requirement (OR) defines dependencies based on regulatory or functional standards, such as safety requirements. Figure 4.4 depicts these dependency types, emphasizing their roles in creating a cohesive, well-integrated design.

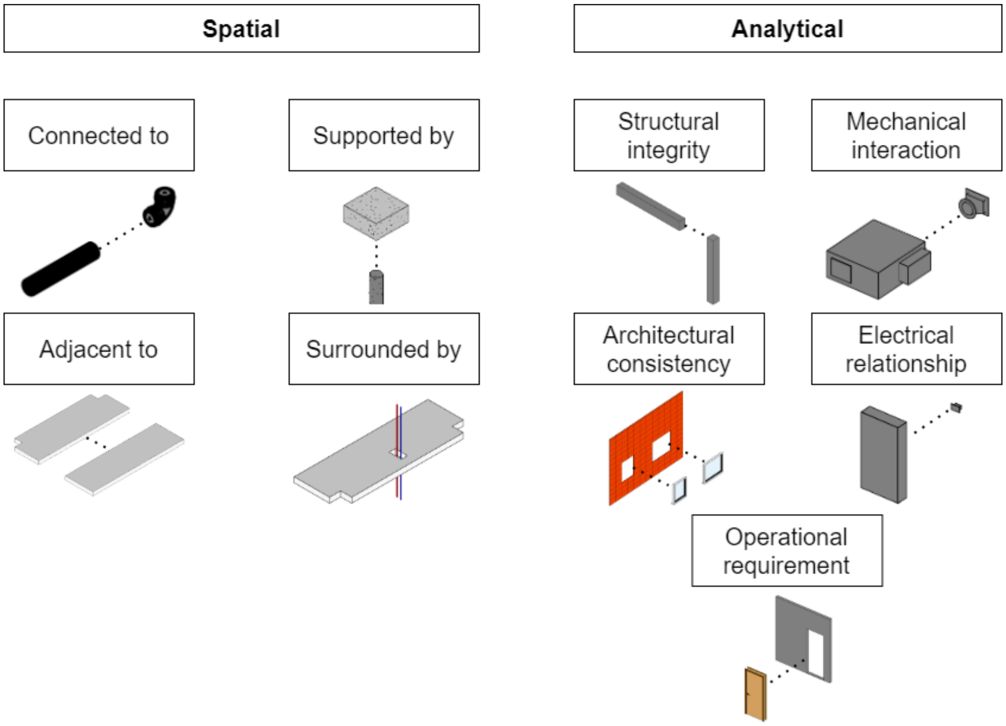


Figure 4.4: Different types of dependencies

4.3.5 Dependencies between elements

In the mock-up prototype, elements are interdependent, relying on various types of relationships to function cohesively as part of the overall structure. These dependencies between elements can impact how changes in one part of the design affect others, which contributes to understanding how modifications propagate through the system. Langroodi and Staub-French (2012) summarizes these dependencies, as shown in table 4.1. The table lists abbreviations that categorize and describe these dependencies. The Type category identifies basic design change actions—ADD for additions, MOD for modifications, and DEL for deletions. Each of these actions has specific implications for the prototype's configuration, influencing whether elements are introduced, adjusted, or removed entirely.

Category	**Abbreviation**	**Description**
Type	ADD	Addition
	MOD	Modification
	DEL	Deletion
Spatial Dependency	CT	Connected To
	AT	Adjacent To
	SPB	Supported By
	SRB	Surrounded By
Analytical Dependency	SI	Structural Integrity
	AC	Architectural Consistency
	MI	Mechanical Interaction
	ER	Electrical Relationship
	OR	Operational Requirement

Table 4.1: List of abbreviations

Figure 4.5 shows a schematic representation of two connected elements, labeled Element 1 and Element 2, highlighting how specific attributes in each element interact according to defined dependency types. Each element is associated with three primary attributes: Geometry, Position, and Specifications. These attributes establish relationships between the elements, demonstrating how each attribute depends on the other to maintain coherence within the prototype design.

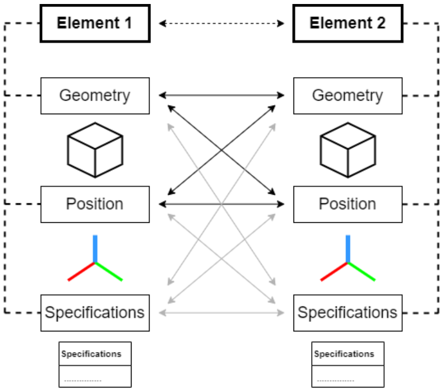


Figure 4.5: Dependencies between elements

4.4 The mock-up prototype

This section presents a mock-up prototype for a digital twin in a multidisciplinary project context. The model consists of three discipline configurations: Structural Engineering, Architectural Design, and MEP systems. These configurations are displayed in three views—Exterior, Interior, and Section—to provide a comprehensive understanding of the building's structure and functionality.

4.4.1 Digital Twin

Figure 4.6 illustrates a fragment of the project, demonstrating the DT concept with discipline-specific configurations. DT technology provides a virtual representation of physical structures, integrating essential data such as geometry, materials, and functionality, which is crucial in the AEC industry for creating a unified and continuously updated configuration model (Segovia & Garcia-Alfaro, 2022). The structural discipline includes the structural framework and foundational components essential for supporting the building's physical structure. The architectural design focuses on the architectural layout, spatial planning. and aesthetic design of the building. The Mechanical, Electrical, and MEP configuration incorporates the necessary systems for building functionality, including HVAC ducts, electrical systems, and plumbing installations. This multi-disciplinary digital twin approach allows for effective coordination across structural, architectural, and MEP configurations (Reefman, 2022).

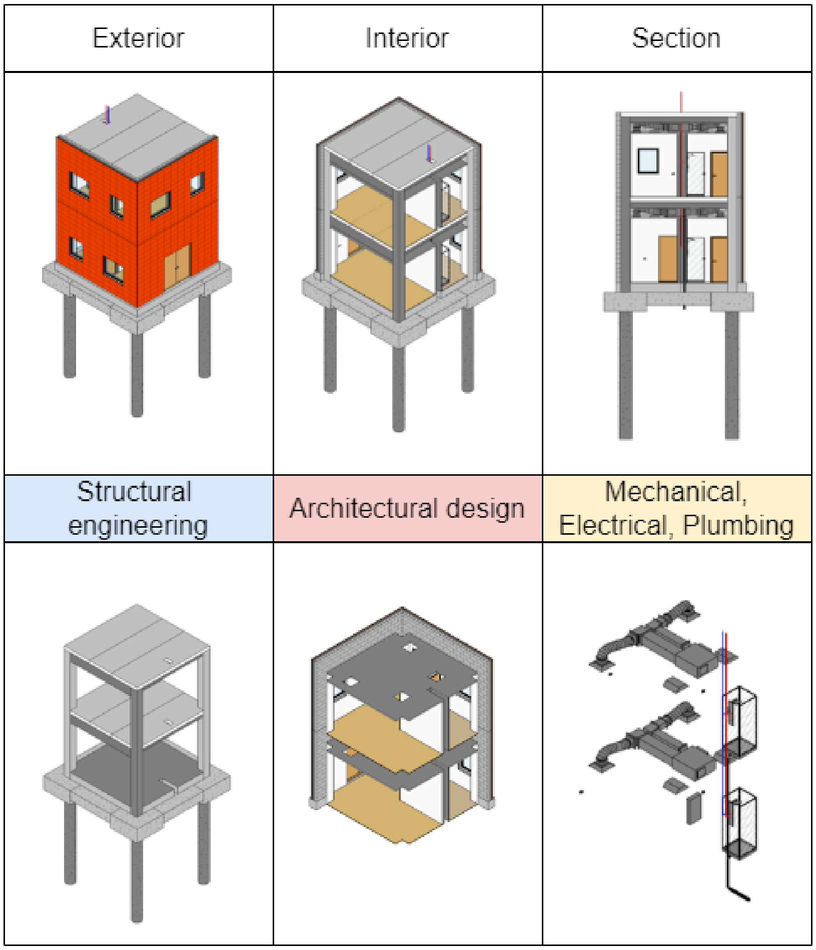


Figure 4.6: Digital Twin prototype

Each discipline configuration within the DT consists of individual elements, each with a unique code, allowing for precise identification and tracking throughout the design, construction, and maintenance phases (Guess, 2021). This system of unique codes facilitates effective coordination across disciplines, ensuring that every element can be referenced accurately throughout the design, construction, and maintenance phases.

As shown in figure 4.7; structural engineering includes coded elements representing foundational and load-bearing structures, such as beams, columns, and other supporting components. Architectural design contains elements that define the spatial and aesthetic aspects of the building, including walls, doors, and windows, allowing for accurate configuration tracking (Madni & Sievers, 2018). One element here is highlighted as an example to show the code of one such element. Lastly, the MEP comprises components essential for building operations.

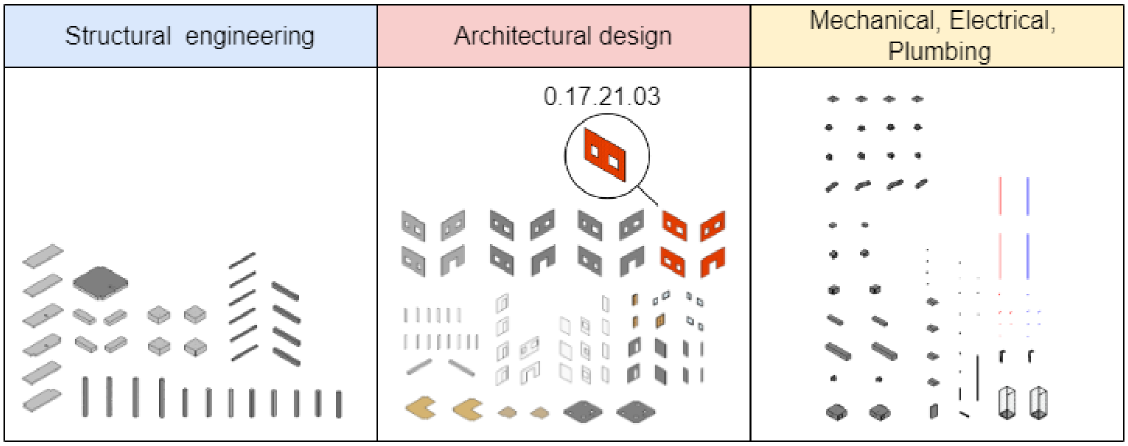


Figure 4.7: Elements per configuration

4.4.2 Digital Threads

DTH represents the connections and dependencies between elements across different discipline configurations within the DT (Reefman, 2022). Each element in Structural Engineering, Architectural Design, and Mechanical, Electrical, and MEP is interconnected through these threads, allowing data to flow seamlessly across disciplines. This interconnected framework ensures that any modification or update in one configuration is reflected in others. Through the DTH, any design change in one configuration is accurately propagated to related configurations in other disciplines (McKay et al., 2021).

Each discipline configuration within the DT has its own unique structure that defines how elements are connected based on specific functional requirements (Segovia & Garcia-Alfaro, 2022). For instance, the structural engineering configuration organizes elements like beams, columns, and slabs based on load-bearing relationships and stability requirements, prioritizing alignment to maintain the building's structural integrity. This structure facilitates change management by ensuring that updates in load-bearing elements are systematically linked across all configurations.

The Architectural Design configuration organizes elements such as walls, doors, and windows to form spatial layouts and aesthetic structures. Connections here are based on spatial relationships and visual continuity, emphasizing the building's form, user flow, and appearance rather than structural load distribution.

In the MEP (Mechanical, Electrical, and Plumbing) configuration, elements are connected according to the building's operational needs. This structure links ducts, pipes, and electrical conduits in a way that prioritizes efficient service routing and access for maintenance. The connections within this configuration ensure that essential systems are integrated without interfering with other structural or architectural elements.

As shown in figure 4.8, each configuration has a distinct connection layout that supports its specific purpose, while DTHs provide cross-disciplinary links that ensure coordination and coherence across the entire digital twin model (Pilehchian et al., 2015). To enable the cross-disciplinary links, the DTH connects the elements within each discipline by establishing dependencies and relationships that reflect the overall project requirements and objectives (Madni & Sievers, 2018).

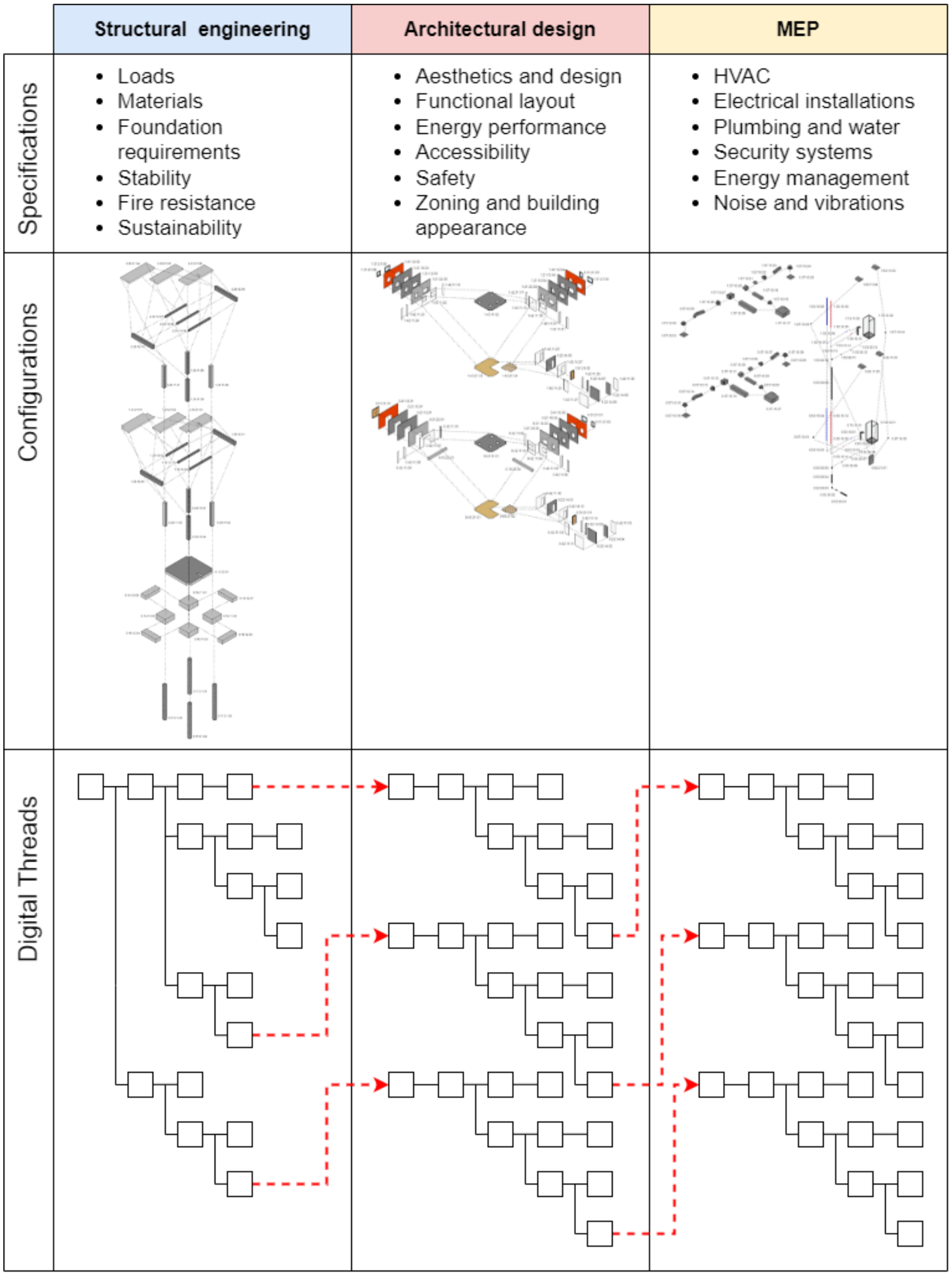
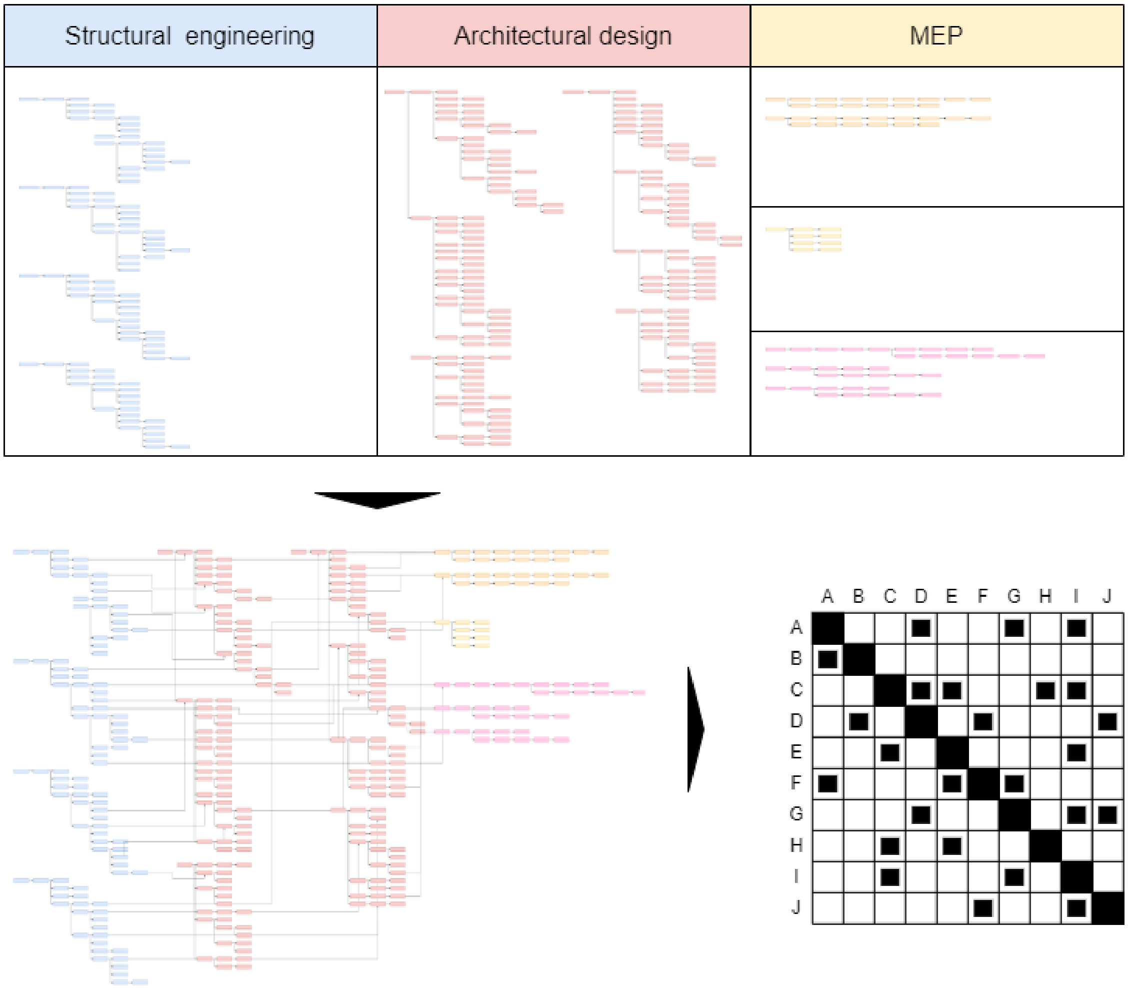


Figure 4.8: Configuration of elements and DTHs

4.4.3 Design Structure Matrix

The DSM is a tool used to represent and analyze the interdependencies between elements in a multidisciplinary BIM model. In Figure 4.9, the DSM is organized by discipline. The DSM is structured as a matrix, where each row and column represents an element within the different configurations. Connections between elements within the same discipline and across different disciplines are illustrated, enabling project managers and engineers to see where dependencies and interactions occur. This visualization aids in understanding how a change in one element might impact others, both within and outside its discipline (Eppinger & Browning, 2012).



	A	B	C	D	E	F	G	H	I	J
A	■			■			■		■	
B	■	■								
C			■	■	■			■	■	
D		■		■		■				■
E			■		■				■	
F	■				■	■	■			
G				■			■		■	■
H			■		■			■		
I			■				■		■	
J						■			■	■

Figure 4.9: Configuration diagram

Figure 4.10 offers a zoomed-in view of the configuration, focusing on a specific fragment of the structural engineering configuration. This detailed view shows how individual elements, represented by unique identifiers, are connected. Each connection signifies a dependency or interaction, whether structural, spatial, or analytical. By examining these connections, stakeholders can gain insight into how design modifications in one part of the configuration could cascade through related components, potentially impacting elements in the architectural or MEP configurations (Chen & Whyte, 2020) (Segovia & Garcia-Alfaro, 2022) (Yassine, 2004).

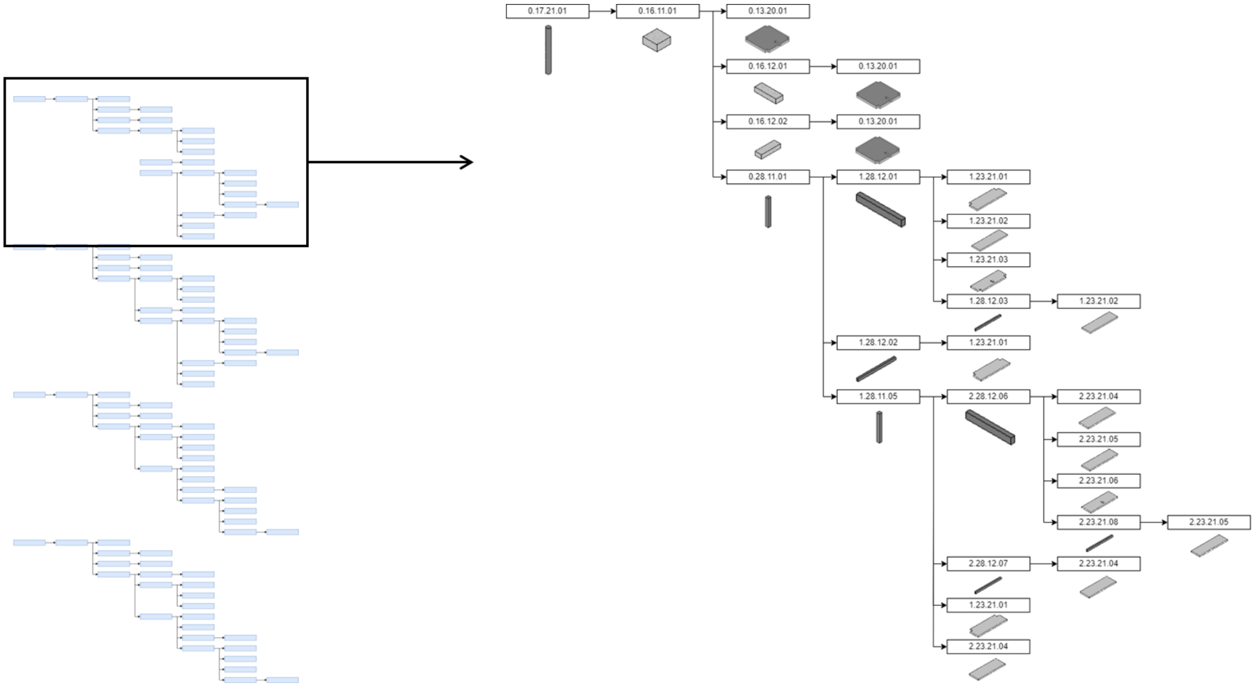


Figure 4.10: Zoom in configuration diagram detail

Together, the DSM diagrams provide a comprehensive overview of the project's configuration structure, supporting efficient change management and interdisciplinary coordination. The detailed fragment emphasizes DSM's utility in tracking dependencies, ensuring that all necessary updates are accounted for as design changes occur across the project (Lindkvist et al., 2013). This structured approach to managing interdependencies helps streamline workflows and minimizes the risk of conflicts arising from poorly coordinated design changes across disciplines (Fayez et al., 2003). By visualizing these relationships, DSM enables project teams to make informed decisions and enhance overall project efficiency.

4.4.4 One configuration

The integration of multiple configurations from various disciplines results in a unified configuration, as depicted in figure 4.11. This unified structure combines elements from Structural Engineering, Architectural Design, and MEP into a single, interconnected system (Guess, 2021).

The diagram on the left illustrates how individual components from each discipline are spatially organized in a three-dimensional arrangement. This spatial layout visually represents the physical relationships and dependencies between components, laying the foundation for a more cohesive design process (Jensen et al., 2012).

On the right, the configurations from each discipline are merged into a detailed tree-like structure. Each color-coded branch represents a different discipline, with nodes and connections symbolizing the relationships and dependencies between individual elements (Madni & Sievers, 2018). By connecting these configurations, the model provides a comprehensive overview of how various systems and elements interact, ensuring that changes in one discipline are properly aligned with others. This unified configuration enables enhanced coordination, reduces the risk of conflicts, and promotes more efficient communication across disciplines (Guess, 2021).

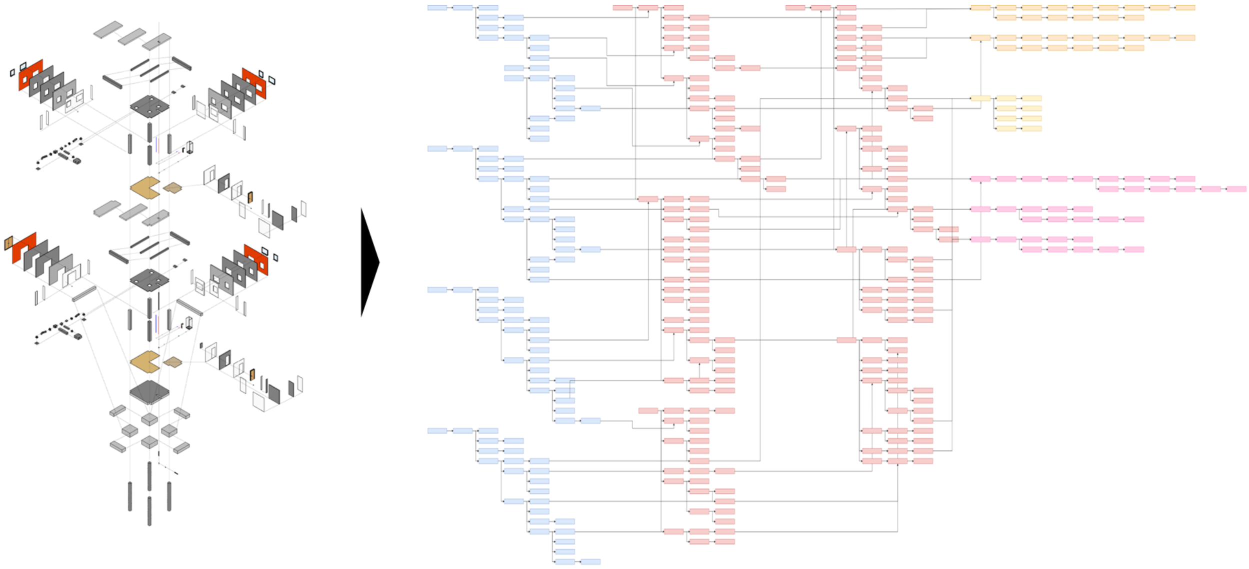


Figure 4.11: One configuration

4.5 Practical implementation of the prototype

The DSM can be practically implemented within a BIM environment to facilitate the integration and coordination of various disciplines in a single digital model. Using a tool like Autodesk Revit, this prototype can be developed into a functional BIM tool, as shown in Figure 4.12. This aligns with the DSM's role in enhancing project management through visualization of interdependencies and promoting constructability (Eppinger & Browning, 2012)(Lindkvist et al., 2013)(Yassine, 2004).

The diagram on the left represents a building model that encapsulates various structural, architectural, and MEP elements. By translating the DSM configuration into a BIM environment, these elements can be organized and managed in a way that promotes collaboration among stakeholders (Azhar, 2011)(Borrmann et al., 2018). The DSM framework (right side of figure 4.12 is transformed into a hierarchical structure that is easy to navigate within the BIM tool, providing a visual representation of the dependencies and interactions between components.

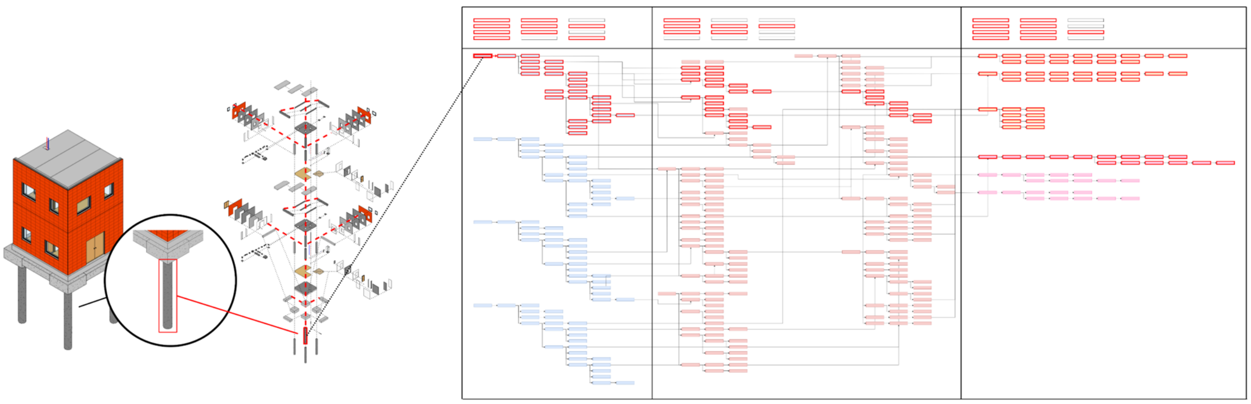


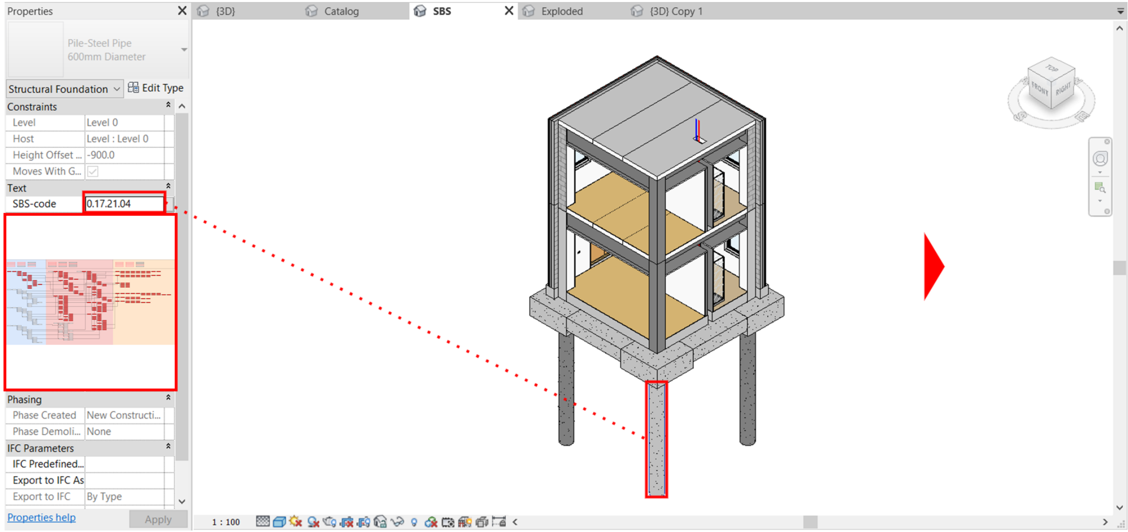
Figure 4.12: How the DSM translates to BIM

This implementation enables architects, engineers, and other professionals to work in a coordinated manner, as changes made to any element are automatically updated across the relevant parts of the model, preserving the integrity and accuracy of the project (Liu et al., 2014)(Pilehchian et al., 2015). It also allows for a streamlined workflow where interdependencies are respected, reducing errors and ensuring the accuracy of the design (Langroodi & Staub-French, 2012)(Reefman, 2022). By using DSM within BIM, project teams can manage complexity effectively, ensuring that each aspect of the design aligns with the overall project objectives.

4.5.1 Implementation in Revit

The integration of DTs, DTHs, and DSM within Revit aims to enhance coordination across AEC disciplines. By embedding these elements, users can visualize complex interdependencies between building components and streamline design changes. As Grieves (2019) describes, DT technology provides a virtual counterpart to physical elements.

Figure 4.13 showcases the DT implementation in Revit, where the DSM is linked to specific elements within the model. As noted by Langroodi and Staub-French (2012), the tracking of interdependencies via a DTH helps manage the impact of changes across various systems, ensuring that all affected components are identified. In this case, selecting an element, such as the column marked in red, reveals how changes to that element might affect others, thus providing real-time insights into the broader implications of design decisions. This interactive setup supports a more integrated design approach, enhancing the collaboration described by Segovia and Garcia-Alfaro (2022) and Reefman (2022) in terms of linking disciplines and tracking dependencies through a shared, real-time model.



Pile-Steel Pipe
600mm Diameter

Structural Foundation

Constraints	
Level	Level 0
Host	Level : Level 0
Height Offset ...	-900.0
Moves With G...	☑
Text	
SBS-code	0.17.21.04
Phasing	
Phase Created	New Constructi...
Phase Demoli...	None
IFC Parameters	
IFC Predefined...	
Export to IFC As	
Export to IFC	By Type

Figure 4.13: Digital Twin, Digital Threads, and DSM in Revit

The Element Dependencies Matrix shown in figure 4.14 visually represents these dependencies, illustrating how specifications and design choices are interlinked across different project layers. As Madni and Sievers (2018) points out, the MBSE approach that underpins the DT can aid in ensuring that design, performance, and stakeholder needs are consistently integrated. The matrix in Revit is color-coded to distinguish between structural, architectural, and MEP dependencies, offering a clear visual reference. The blue and red sections represent distinct categories, allowing stakeholders to quickly identify critical dependencies, and facilitate design modifications in line with the project's evolving requirements. This graphical interface not only simplifies decision-making but also provides a detailed yet easily navigable overview of element interdependencies, as described by Tiwari and Franklin (1994) in the context of configuration management.

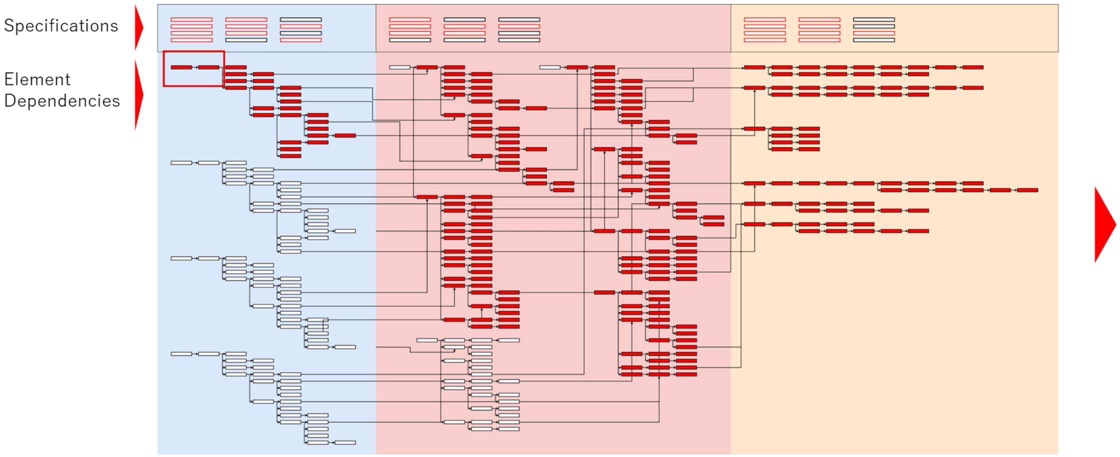


Figure 4.14: Showing the dependent elements

Figure 4.15 demonstrates the concept of element dependencies within a single discipline by focusing on various spatial and analytical relationships, as described by Langroodi and Staub-French (2012). This visualization aids in the assessment of design choices on structural integrity and mechanical interactions within a particular discipline. As Liu et al. (2014) and Chen and Whyte (2020) emphasize, such dependencies are critical in ensuring the stability and performance of the system. By zooming in on specific elements, users can assess the impact of design choices on structural integrity and mechanical interactions within a particular discipline, providing a focused analysis of dependencies that are critical to the stability of that system. This allows users to make discipline-specific adjustments and understand their impact in a controlled scope.

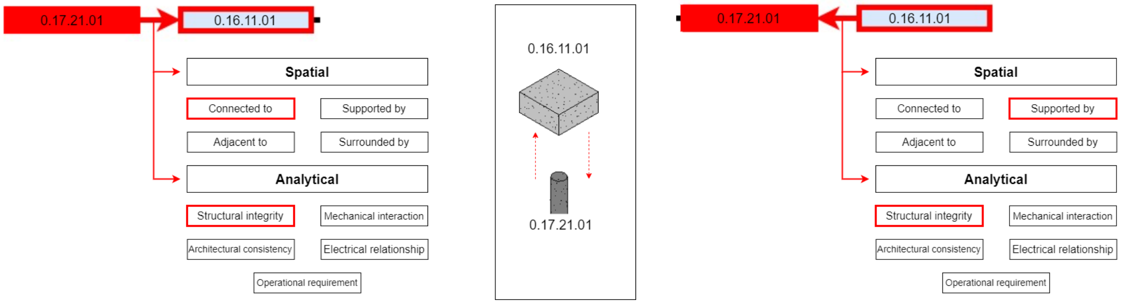


Figure 4.15: Zooming in on element dependencies within a discipline

Figure 4.16 expands on this concept by illustrating dependencies between elements across different disciplines. This cross-disciplinary view highlights how interconnection design elements influence each other, not just within a single discipline but across structural, mechanical, and spatial systems. As noted by McKay et al. (2021), this approach is essential for identifying and resolving interdisciplinary conflicts early in the design process. In this example, the dependencies span both spatial and analytical aspects, with elements classified as being surrounded by or adjacent to others, while also fulfilling structural or operational requirements. The early identification of such dependencies is critical for effective project management and coordination, ensuring that changes in one discipline (e.g., architectural) do not unintentionally disrupt another (e.g., MEP systems), as described by Guess (2021) and Segovia and Garcia-Alfaro (2022).

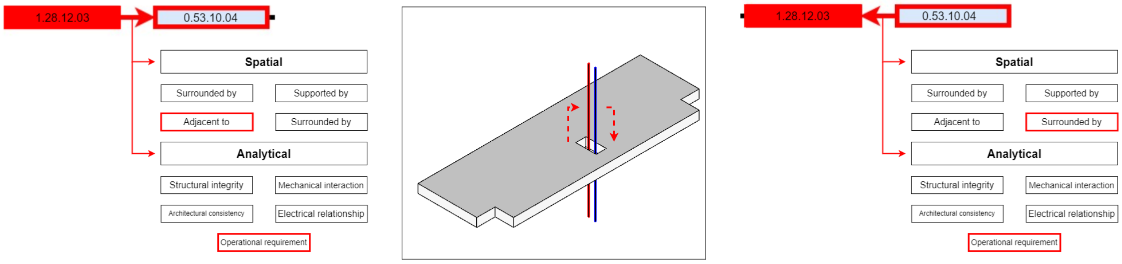


Figure 4.16: Zooming in on element dependencies between disciplines

4.5.2 Guideline

Incorporating insights from the mock-up prototype discussed earlier in the chapter, this approach enhances the management and coordination of design changes within a BIM environment like Revit. As highlighted by Grieves (2019) and Langroodi and Staub-French (2012), the integration of DTs and DTHs within Revit enables real-time tracking of design changes and facilitates the seamless flow of information across different disciplines. The prototype serves as a practical tool to visualize and simulate dependencies between building elements, allowing teams to understand how changes propagate across different disciplines and facilitating a more cohesive design process.

The mock-up prototype provides a tangible example of how the outline process can be implemented in real-world scenarios. Its role is especially valuable in visualizing dependencies and changes across building elements, helping teams anticipate and manage the ripple effects of design modifications. This integration strengthens each phase of the guideline by providing a structural framework for understanding and managing complex interdependencies, as discussed by Segovia and Garcia-Alfaro (2022) and McKay et al. (2021), who emphasize the importance of early identification and resolution of interdependencies in complex projects.

Step 1: Track successive changes with the prototype

Through the prototype, design teams can effectively identify and trace modifications across interconnected elements, using dependency mapping to assess the reach and impact of each change. For instance, when simulating a modification such as moving a shower tray, the prototype demonstrates how this change affects other components like pipes, walls, and structural supports. As Madni and Sievers (2018) points out, the use of MBSE methods, supported by DTs, helps visualize and track such interdependencies, ensuring that the cascading effects of design changes are properly understood. The mock-up enables users to explore various scenarios, examining how spatial, functional, or analytical dependencies influence the surrounding elements. This approach enhances the team's ability to manage risks associated with design modifications by providing a clear map of affected components, as advocated by Chen and Whyte (2020).

Step 2: Identify and communicate changes to other disciplines

The interdisciplinary framework of the prototype facilitates communication by providing real-time visual feedback across teams. When a change is implemented within one aspect of the prototype, alerts and visual cues highlight affected elements in other disciplines, ensuring relevant teams are informed of potential impacts. This visual representation of dependencies clarifies complex relationships between components, enabling each discipline to understand the extent of the change and adjust their designs as needed. The role of real-time data in improving interdisciplinary communication is emphasized by Reefman (2022), who underscores the value of synchronized models in reducing errors and improving team collaboration. Such real-time communication strengthens collaboration and ensures that all disciplines are aware of any interconnected impacts, aligning with the findings of (Liu et al., 2014) on the critical need for integrated project workflows.

Step 3: Assess the impact of the design change

Evaluating the broader consequences of design changes is streamlined with the prototype's visualization capabilities, which allow teams to see how proposed modifications affect stability, safety, and functionality across systems. For example, spatial conflicts between mechanical, electrical, and MEP systems and structural or architectural elements can be identified early in the design process. The prototype enables users to experiment with alternative solutions, assessing each option's impact and effectiveness before selecting the most viable approach. As noted by Tiwari and Franklin (1994) and McKay et al. (2021), the ability to visualize potential conflicts across disciplines at an early stage significantly enhances decision-making, ensuring that all factors, whether spatial or analytical, are taken into account. This capability supports efficient conflict resolution and ensures the coordinated alignment of design changes.

Enhancing the change management process with prototype insights

Insights from the mock-up prototype provide a practical layer to the outlined steps, supporting a hands-on framework for managing design changes. By automating notifications, visualizing dependencies, and allowing interdisciplinary assessments, the prototype reinforces the importance of a structured approach to change management. As Grieves (2019) and Segovia and Garcia-Alfaro (2022) note, such a system enables continuous monitoring and adjustment, facilitating a flexible yet controlled design process. Additionally, it functions as a training tool, enabling team members to practice implementing the guideline in a controlled environment, thereby enhancing their preparedness for real-world application.

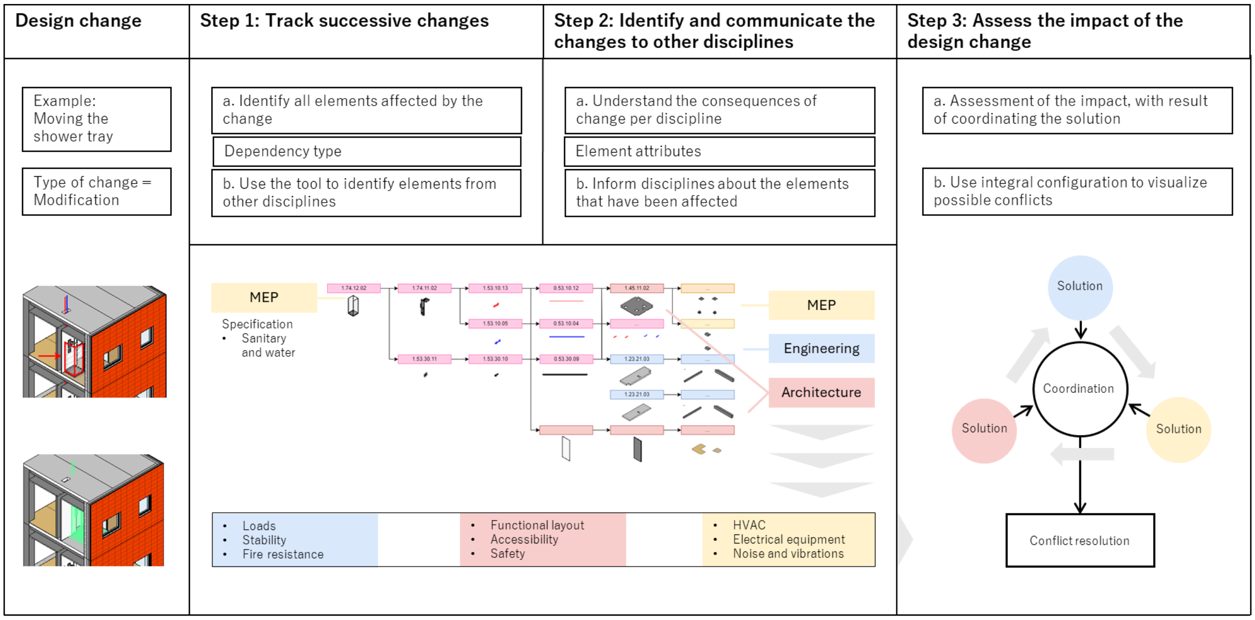


Figure 4.17: Guideline for implementation

4.5.3 Creating a dependency graph in BIM

Developing a dependency graph in a BIM environment requires a systematic process that combines data extraction, rule definition, and visualization. The first step is to extract data from the BIM model using software tools like Autodesk Revit or Navisworks (Ismail et al., 2018). These tools provide access to detailed information about model elements, including their IDs, categories (e.g., walls, beams, ducts), locations, and other attributes. Relevant data can be exported in formats such as CSV or IFC or accessed programmatically via APIs. Once the data is extracted, relationships between elements must be identified (Ismail et al., 2018). Spatial dependencies can be determined using clash detection tools or spatial queries to identify adjacent or intersecting elements. Logical relationships, such as parametric constraints, are derived from the model's predefined rules, such as alignment or material specifications. Automation through scripts, such as those created in Dynamo for Revit or Python, can streamline this process, ensuring consistent data extraction and relationship identification.

The next step involves defining dependency rules that classify and quantify relationships between elements. Spatial dependencies, for instance, can be identified by setting thresholds for proximity or adjacency, such as detecting walls within a specific distance from a duct. Functional dependencies involve analyzing how interconnected systems—like pipes linked to HVAC equipment—interact with one another. Logical constraints capture rule-based relationships, such as the connection of doors or windows to their host elements Additionally, cross-disciplinary dependencies must be considered, including how MEP systems integrate with structural elements or how lighting systems interact with architectural features. These rules ensure that dependencies reflect both the physical and functional interrelationships in the model (Xiao et al., 2019).

Once the dependencies are defined, the information is organized into a node-edge model. In this structure, each element in the BIM model is represented as a node with attributes such as ID, category, or location, while relationships between elements are represented as edges, labeled with the type of dependency, such as spatial or functional. Nodes and edges are further enriched with attributes. For efficient storage and querying, this node-edge structure can be stored in a relational database like PostgreSQL or a graph database such as Neo4j. This enables dynamic interaction with the data, facilitating updates and analysis (Ismail et al., 2018).

Visualization is a crucial step in creating an actionable dependency graph. Tools like Gephi, Neo4j, or Python libraries such as NetworkX and Plotly can be used to create an interactive graph (Bastian et al., 2009). Alternatively, visualization plugins integrated into BIM tools, like Autodesk Forge, allow seamless visualization within the BIM environment. The graph should use color coding to distinguish disciplines (e.g., structural, architectural, MEP) and dependency types (e.g., spatial, analytical). Node sizes can reflect criticality, and filtering options can help stakeholders focus on specific aspects of the graph. These visualizations allow teams to quickly identify dependencies, conflicts, and areas requiring attention, enhancing their decision-making capabilities (Ismail et al., 2018).

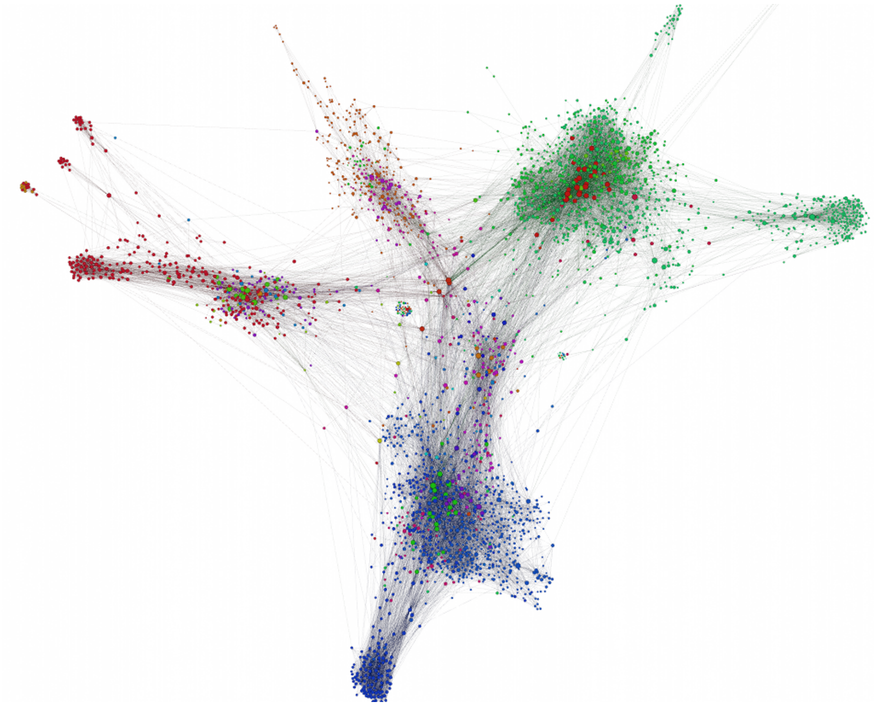


Figure 4.18: Gephi dependency graph

Automation is critical for maintaining the accuracy of the dependency graph as the BIM model evolves. Using APIs like Revit API or Autodesk Forge API, real-time updates can be synchronized between the graph and the model. Changes in the BIM model trigger automated updates in the dependency graph, ensuring it reflects the latest design state. Version control systems can track changes to the graph over time, enabling teams to analyze how dependencies evolve and to maintain a history of design adjustments (Pilehchian et al., 2015). These methods aim to automate change propagation, improve coordination, and reduce manual effort in BIM collaboration, aligning with existing standards like ISO 19650 (Esser et al., 2022).

In a multidisciplinary design team scenario, the dependency graph becomes a shared resource that fosters collaboration. Hosting the graph on a cloud-based platform, such as Autodesk BIM 360, ensures accessibility for all team members. During coordination meetings, the dependency graph can serve as a visual aid to identify and resolve interdisciplinary conflicts. For example, it might highlight a clash between a structural beam and an MEP duct, prompting discussions on whether to reroute the duct or adjust the beam placement (Ismail et al., 2018). This collaborative use ensures that teams are aware of interdependencies and can make informed decisions collectively.

In summary, creating a dependency graph in a BIM environment involves extracting and analyzing data, defining clear dependency rules, organizing relationships into a structured format, and visualizing the graph to support collaboration. Automation ensures the graph remains up-to-date, and hosting it on shared platforms promotes interdisciplinary communication. This approach enables teams to manage complexity, resolve conflicts proactively, and deliver more coordinated and efficient designs.

Chapter 5

Demonstration analysis

5.1 Introduction

In this chapter, the prototype developed in the previous chapter is demonstrated in a workshop setting for the sponsoring company, W+B. The workshop involved 15 experts from the AEC disciplines, including structural engineers, architects, and MEP specialists. The prototype was presented through a practical demonstration, followed by a feedback session where participants completed a canvas document. This canvas aimed to gather feedback on methods and BIM tools related to managing design changes.

The primary goal of this demonstration was to improve communication between AEC disciplines by integrating element dependencies to assess design changes within a BIM environment. Participants answered questions regarding their current use of BIM, potential trends, the advantages and disadvantages of MBSE approaches for tracking design changes, and obstacles—both technical and organizational—for implementation. Lastly, they were asked to consider future solutions for overcoming these obstacles.

This chapter begins by explaining the goals of the prototype and the demonstration. The methodology of the workshop and canvas approach is detailed, followed by an explanation of the canvas questions and their objectives. Finally, the results of the workshop are presented, followed by an analysis of the key points from the data.

Figure 5.1: Demonstration at W+B on the 15th of October

5.2 The Canvas

The canvas serves as a feedback tool to collect insights on how design changes are managed and how the prototype could address communication gaps across AEC disciplines. The goal of the prototype is to enhance communication in BIM environments by using element dependencies to track design changes effectively.

Questions and Goals

1. **Current Situation**
    - **Question:** How do you currently use BIM to manage design changes?
        - **Goal:** To evaluate current practices and
2. **Developments**
    - **Question:** Do you see changes/trends in how design changes are managed in practice?
        - **Goal:** To explore new trends and technological developments that could influence design processes and improve the management of design changes.
3. **Implementing Element Dependencies in BIM**
    - **Advantages:** What advantages do you see in implementing element dependency data in BIM?
        - **Goal:** To investigate the potential benefits of integrating element dependency data and the reasons to adopt this approach.
    - **Disadvantages:** What disadvantages do you see in implementing element dependency data in BIM?
        - **Goal:** To identify potential downsides of implementing element dependency data and weigh them against the benefits.
4. **Obstacles to Implementation**
    - **Technological Obstacles:** What technological obstacles are there in implementing dependency data in BIM?
        - **Goal:** To identify technological challenges that could hinder implementation.
    - **Organizational Obstacles:** What organizational obstacles could arise when implementing dependency data in projects?
        - **Goal:** To foresee organizational challenges and consider how they might be addressed.
5. **Future Vision**
    - **Question:** How can we overcome these obstacles?
        - **Goal:** To build on the identified benefits, challenges, and obstacles and suggest practical improvements for collaboration and conflict management in future projects.

5.3 Demonstration Results

In this section, the responses and feedback from the workshop participants are presented, and organized by the questions posed during the canvas feedback session.

Participants represented various disciplines, including architecture, installations, construction, and project management. Experience with BIM ranged from 0 to 18 years, with most having limited to moderate experience. This variability suggests differing familiarity with BIM tools and their integration, which impacts the effectiveness of interdisciplinary collaboration and the prototype's usability across disciplines.

Most participants relied on Revit and other tools like ACC and Bimcollab for issue tracking and coordination. However, traditional communication methods like verbal updates and in-person meetings were still in use by some participants (e.g., participants 3, 9, 10). There were noted issues with managing cross-disciplinary communication, with several participants (e.g., participant 10) highlighting gaps in design change communication. The need for improved documentation, standardization, and information sharing was a common theme, emphasizing the importance of robust communication mechanisms within the prototype. The participants are listed as follows:

#	Role	BIM Experience (Years)
1	Architectural engineer 1	10
2	Architectural engineer 2	0
3	Architectural engineer 3	5
4	Architectural engineer 4	2
5	Architectural engineer 5	2
6	Architectural engineer 6	18
7	Architectural engineer / project manager	1
8	Architectural engineer / BIM coordinator	7
9	Construction manager	4
10	MEP engineer 1	1
11	MEP engineer 2	0
12	MEP engineer / BIM coordinator	5
13	Structural engineer 1	2
14	Structural engineer 2	1
15	Structural engineer 3	0

Table 5.1: BIM Experience Table

For a comprehensive overview of the references addressing each topic and challenges discussed in this document, please refer to the Appendix. The appendix provides a detailed list of sources, organized by question and category, offering precise citations that support the analysis. This resource serves as a guide for further exploration of the literature and enhances the credibility and depth of the insights presented.

5.3.1 Prototype validation

This section assesses whether the prototype meets key requirements for using MBSE methods to trace dependencies between building elements, aiming to improve change management in BIM environments. Participant feedback highlighted strengths in visualization and early error detection but pointed out limitations in dependency categorization, change tracking, automated notifications, and integration with existing BIM tools. These findings suggest that while the prototype offers basic support for dependency tracking, further refinement is needed to fully support interdisciplinary collaboration and effective change management.

Interdisciplinary dependency mapping

While participants praised BIM for visualization and early error detection, only some (e.g., participants 3, 13, 15) noted the ability to assess dependencies effectively. The lack of standardized dependency categorization was a concern, and the feedback suggests the prototype lacks tools to categorize dependencies comprehensively (e.g., spatial, functional). The prototype supports basic visualization of dependencies but may need enhanced categorization features to fully support interdisciplinary dependency mapping.

Change tracking and version control

Participants raised issues related to compatibility, the need for frequent updates, and difficulty tracking changes effectively (e.g., participant 10). The prototype appears to lack robust change tracking and version control, limiting the ability to manage dependencies over time and hindering effective change management.

Real-time impact analysis

There were indications that the prototype supports some level of real-time impact analysis. Several participants highlighted the enhanced visualization capabilities of BIM tools, which assist in identifying potential issues early and assessing the impact of design changes on stability and functionality (e.g., participants 1, 4, 8). However, while some visualization of impacts is present, the feedback did not confirm whether all dependencies and affected areas are consistently highlighted across disciplines. The prototype provides a degree of real-time visualization for design changes, helping to prevent conflicts by displaying impacted areas. However, to fully meet the requirement, further refinement may be necessary to ensure consistent, comprehensive real-time impact analysis across all components and disciplines.

Automated alerts and notifications

Although some participants mentioned notifications of changes, they raised concerns about limited interoperability and accessibility, indicating that the notification system may not reach all relevant teams effectively. The prototype has a notification feature, but it may not be fully automated or integrated. Further development is necessary to ensure automated, cross-disciplinary notifications.

Integration with existing BIM tools

Compatibility issues, such as difficulties integrating with legacy systems and aligning workflows, were highlighted by participants (e.g., participant 6, participant 11). While the prototype shows some integration with Revit, it does not fully address interoperability challenges across platforms. The prototype has basic integration capabilities but needs further refinement to improve compatibility with existing BIM tools and reduce workflow disruptions.

5.3.2 Canvas answers analysis

Advantages of the prototype

The prototype demonstrated several notable advantages that contributed to its value in the design and construction process:

- **Enhances visualization and accuracy:** The prototype was praised for its visualization capabilities, helping users identify potential issues early (e.g., participants 1, 4, 8, 13). This leads to better error control, cost management, and change impact assessment, addressing some of the core benefits of BIM.
- **Improved collaboration:** Digital tools like Revit and ACC enhance interdisciplinary collaboration by enabling dependency assessments and coordinated efforts across teams, as highlighted by participants 3, 13, and 15.

Key challenges and concerns

Despite the advantages, several challenges were identified during the evaluation:

- **Learning curve and time investment:** The learning curve for BIM tools was a challenge, especially for participants with limited experience (e.g., participants 9, 14). Many called for additional training (e.g., participants 1, 5, 8) to make the prototype more accessible.
- **Standardization issues:** Participants (e.g., participants 2, 12) expressed concerns about the lack of standardization, which creates inefficiencies and complicates workflows. Without clear protocols, the full potential of BIM tools is harder to achieve.
- **Organizational and technical integration:** There was a strong need for better organizational support, with challenges in integrating tools into existing workflows (e.g., participant 6) and ensuring technology access for all team members (e.g., participant 11, 12). Participants also cited the complexity of managing multiple software systems as an obstacle.

In conclusion, while the prototype demonstrated significant advantages, particularly in enhancing visualization, accuracy, and collaboration, there are notable challenges that need to be addressed. The learning curve, standardization issues, and integration into existing workflows were recurring concerns. Future iterations of the prototype could benefit from addressing these concerns through additional training, clearer standards, and improved organizational support to maximize its potential for users across diverse teams.

5.4 Demonstration discussion analysis

The discussion section reflects on the key findings from the data analysis, examining how the feedback from the participants during the demonstration aligns with the goals of the prototype and what improvements can be made. It highlights the successes of the prototype in meeting user needs while also identifying areas where performance fell short or where the design could be optimized. Challenges encountered during development and deployment are explored, with a focus on both technical and operational issues. Additionally, opportunities for future work are presented, including potential refinements to the prototype and the integration of new features or technologies. Finally, the discussion considers potential solutions for overcoming obstacles to implementation, ensuring that future iterations can better address user requirements and lead to more widespread adoption.

5.4.1 Advantages of the prototype

Finding the impact of changes

Participants highlighted a key advantage of the BIM tool: its ability to instantly assess the impact of design changes on the entire project. This real-time adaptability allowed them to visualize adjustments in costs, timelines, and project elements as modifications were made, which not only supported better decision-making but also mitigated risks associated with last-minute changes. This aligns with Azhar (2011) identification of BIM's role in facilitating decision-making and risk management through interconnected models. Similarly, Borrmann et al. (2018) emphasizes BIM's foundational capabilities in tracking design changes, enhancing collaboration, and enabling a dynamic response to evolving project requirements. Cha and Kim (2020) also affirm BIM's strengths in real-time performance measurement, and Liu et al. (2014) highlight BIM's role in comprehensive change management across stakeholder groups. Finally, Langroodi and Staub-French (2012) recognize the utility of BIM in managing changes across multidisciplinary teams, reducing project disruptions from last-minute issues.

Cost estimates for specifications

The BIM tool's support for detailed cost estimation was another advantage that was spotted. Participants reported that the tool's possible capability to generate cost projections for specific components could enable them to make informed, budget-conscious decisions while maintaining the quality and functionality of designs. Azhar (2011) acknowledges BIM's precision in cost estimation, while Borrmann et al. (2018) underscores BIM's role in providing accurate, component-specific cost information. Additionally, Liu et al. (2014) emphasizes the value of financial projections tied to specific design components, helping teams stay aligned with budgetary constraints.

Simulating different design choices

The ability of the BIM tool prototype to simulate alternative design choices was praised for allowing participants to explore multiple options before committing to a final design. This functionality supported the visualization of diverse approaches and facilitated the evaluation of their feasibility, performance, and aesthetic value, fostering creative problem-solving and design optimization. Azhar (2011) emphasizes BIM's utility in supporting design exploration, while Cha and Kim (2020) similarly affirms that BIM enables project teams to evaluate multiple design alternatives. Pilehchian et al. (2015) discuss how simulations within BIM allow for flexible exploration of design solutions, and Segovia and Garcia-Alfaro (2022) stress the importance of DT and BIM simulations in examining different project scenarios effectively.

Analysis of relationships

A major benefit of the BIM tool prototype was its capacity to map interdependencies between project components, such as structural, mechanical, and architectural systems, ensuring harmonious integration. Participants noted that this perspective enabled them to identify potential conflicts early, thereby facilitating better workflow coordination, collaboration, and reducing risks of rework. This capability reflects Azhar

(2011) focus on BIM's ability to analyze project relationships. Borrmann et al. (2018) also discusses BIM's role in visualizing interconnected systems. Bahill and Dean (1996) identified these benefits in SE, including smooth integration, early risk identification, and alignment with stakeholder objectives.

Quality checks and assessments

Automated quality checks were another valuable feature, ensuring that models adhered to specific design standards and criteria. Participants appreciated this feature for its ability to conduct regular assessments that identified errors or inconsistencies, ultimately improving project quality, reducing rework, and ensuring compliance with regulatory standards. Azhar (2011) and Borrmann et al. (2018) both highlight BIM's contributions to quality control through automated assessments, while Cha and Kim (2020) and Liu et al. (2014) affirm that these checks help uphold project standards and minimize the risk of inconsistencies. Mangialardi et al. (2017) also supports the role of BIM in maintaining high-quality project delivery through consistent, regulation-compliant modeling.

5.4.2 Disadvantages of the prototype

Accuracy of parameters

Participants of the demonstration noted that the effectiveness of modeling relies on the accuracy of its input data, with inaccurate parameters leading to unreliable simulations and suboptimal decisions. Participants pointed out that when parameter precision is compromised, the model's ability to simulate real-world scenarios is diminished, increasing the risk of flawed outcomes. This aligns with Eppinger and Browning (2012) findings on the importance of accurate data in complex systems and the risks of decision-making based on erroneous information. Similarly, Madni and Sievers (2018) highlight the challenges in maintaining data precision in MBSE, while Wang et al. (2022) and Z. Sun et al. (2016) emphasize the complexities in data integration and standardization. Senescu et al. (2012) further argues that inaccuracies in input data can lead to misalignment in dependency mapping, raising project risks.

Model interpretation variability

Another drawback noted by participants was the variability in interpreting models across different stakeholders. Diverse modeling methods can lead to different conclusions from the same data, complicating the decision-making process and requiring stakeholders to evaluate which model aligns best with project objectives. Eppinger and Browning (2012) discuss the issue of differing interpretations in engineering decisions, while Parnell et al. (2021) address the complexities of trade-off analysis when models prioritize distinct project aspects. Madni and Sievers (2018) also note that variations in SE methodologies challenge integration across disciplines, and Zou et al. (2020) highlights the need for consensus in model interpretation for cross-disciplinary MBSE workflows.

Increased data management burden

Managing the extensive data required for BIM models can significantly increase project workload, diverting resources from other critical tasks. Participants observed that maintaining, updating, and processing large volumes of data is resource-intensive, posing a strain on team time and capacity. Chen and Whyte (2020) discuss the data management demands in DT, while Eppinger and Browning (2012) address the complexities of data handling in large-scale projects. Madni and Sievers (2018) similarly highlight the substantial workload associated with data-intensive MBSE, with Senescu et al. (2012) noting that dependency modeling requires significant resources, impacting overall project focus.

Reduced creative freedom

Some participants expressed concerns about data-driven modeling potentially restricting creative flexibility. They noted that adhering to model recommendations might constrain designers' ability to explore innovative or unconventional solutions. This was not mentioned in the literature. The literature generally emphasizes the benefits of data-driven models, such as improved accuracy, risk reduction, and streamlined project coordination. However, the concern that such models could disturb architectural creativity had not been previously addressed. This suggests a potential oversight in current MBSE and BIM research, which tends to focus on technical efficiency rather than exploring the balance between automation and creative freedom. The insight from participants underscores a need for future research to consider how MBSE and BIM tools can provide structure without overly constraining the designer's ability to think outside conventional boundaries, especially in fields where innovation and creative exploration are essential.

Models as a support tool, not a solution

Participants acknowledged that while BIM models identify potential issues, they don't provide comprehensive solutions, instead serving as a supportive tool. The models can highlight risks but leave the specific responses up to project managers. This perspective aligns with Eppinger and Browning (2012), who describe DSM as a tool for identifying areas requiring attention rather than offering solutions. Chen and Whyte (2020) also highlight that DTs and DSM require expert interpretation for actionable responses, and Senescu et al. (2012) emphasize that models indicate dependencies but rely on human intervention for problem-solving. Bahill and Dean (1996) similarly describe SE as a supportive rather than directive function.

Challenges with architectural specifications

Participants noted that translating abstract architectural specifications into the model's data-driven framework can be difficult. Due to the qualitative nature of these specifications, BIM models may struggle to interpret or quantify them accurately, potentially impacting the reliability of the generated insights. This insight represents a new finding, as it was not identified in the existing literature. Research on MBSE and BIM tools has largely focused on their technical capabilities, emphasizing their strengths in coordination, efficiency, and accuracy (Madni & Sievers, 2018)(Eppinger & Browning, 2012). However, the challenge of integrating abstract, qualitative design aspects has received little attention. This gap points to a need for future studies to explore how BIM and MBSE tools can better accommodate the subjective and interpretive aspects of architectural design. Addressing this issue could enhance the usability and effectiveness of these tools, ensuring they support both the technical and conceptual dimensions of the design process.

Return on investment (ROI)

While the BIM tool prototype provides valuable insights, its ROI was questioned by participants who weighed the benefits against the costs of software, training, and data upkeep. The findings underscore the need to assess whether the improvements in project efficiency or cost savings justify these investments. Azhar (2011) emphasizes the importance of cost-benefit analysis, and Madni and Sievers (2018) discuss evaluating MBSE for long-term gains. The ROI issue offers a critical perspective for comparing the tool's advantages against its associated costs. This should be explored in more detail.

5.4.3 Technological obstacles

Time constraints

Implementing and maintaining modeling technologies can significantly extend project timelines or necessitate additional resources to stay on track. For project teams operating with strict deadlines, these time-intensive processes can create bottlenecks that delay other essential phases of the project. Integrating modeling technology requires careful balancing of time allocation and resource availability, which can be challenging in high-stakes projects where efficiency is paramount. Zou et al. (2020) note the socio-technical challenges involved, especially in cross-disciplinary workflows where substantial coordination and resources are necessary.Madni and Sievers (2018) highlight the time and resource demands associated with technology adoption. This makes the time to be spent on technical advancements within a project critical to consider before implementation.

Technical feasibility and requirements

Advanced modeling tools often require specialized expertise and access to MBSE technology, creating obstacles for teams that lack the necessary technical skills or tools. Without this expertise, project teams may become reliant on skilled personnel and complex software, which can be impractical for smaller projects or organizations. Ensuring technical feasibility often involves substantial investments in training, hiring, and acquiring sophisticated modeling tools to meet the needs of complex projects. As discussed with the focus group, this type of expertise is still lacking within the company. This need for technical specialism is a new consideration that was not highlighted in the literature. Thus how to incorporate SE experts into complex project teams needs to be researched further in the future.

Predictive design limitations

Predictive models are typically based on real-time data, which might not capture unforeseen changes or deviations that could arise during the design process. The accuracy of these predictions depends heavily on the scope and quality of the data, making it difficult to account for unexpected variables or dynamic factors in a project. This limitation can hinder a model's ability to provide reliable guidance for decision-making, particularly in complex environments where variables may shift without warning. Although Madni and Sievers (2018) discusses how models are constrained by the scope of type data, it does not provide a solution of how to handle unexpected factors. This also needs further research to explore methods such as machine learning algorithms, scenario planning, or hybrid approaches. Addressing these limitations could significantly enhance the reliability and practicality of predictive design tools in multidisciplinary projects.

Transparency issues with AI "black box" models

AI-driven models, often described as "black boxes," present challenges due to the opaque nature of their internal workings, making it difficult for end-users to understand the logic behind certain outputs. This lack of transparency can lead to trust issues, as users may be skeptical of the model's validity and accuracy without insight into the underlying processes. Transparency is essential for user confidence, particularly in decision-critical contexts where trust in the model directly influences project outcomes. Madni and Sievers (2018) discuss transparency challenges in MBSE, while Chen and Whyte (2020) highlight the importance of transparency in DTs and DSM for fostering trust and informed decision-making. Chown and Blyler (2018) emphasize the need for clarity in model operations throughout the design life-cycle to ensure consistent application among interdisciplinary teams. It is important to keep the mechanics of the dependency analysis as transparent as possible so that designers can trace the attached information. Further research on how to deal with black boxes and keeping transparency is needed for optimal implementation of MBSE methods.

5.4.4 Organizational obstacles

Cross-functional collaboration challenges

The demonstration concluded that effective communication across different engineering and design functions is essential but often challenging. Engineers working primarily with other engineers may encounter barriers when interacting with non-technical departments, resulting in a communication gap that can slow down decision-making, hinder problem-solving, and create silos within the organization. This disconnection can lead to a fragmented approach instead of an integrated project workflow, impacting overall project efficiency. Au and Ravindranath (2020) and Eftekhari et al. (2022) emphasize the importance of the project manager's role in bridging gaps and preventing siloed working, highlighting communication skills as a critical factor. Chen and Whyte (2020) suggest that effective data and information exchange is vital to prevent disjointed project management, while Madni and Sievers (2018) advocate for SE processes that integrate technical and non-technical teams. Though the prototype aims to enhance this obstacle, it is also an obstacle to the integration of MBSE methods. Further research on how to get different disciplines on the same level in terms of systematic thinking is required.

Data exchange and accuracy

Inconsistent or delayed data exchange between departments or external stakeholders can lead to inaccuracies and significant issues in project delivery. Misaligned data may require revalidation and adjustments, which consume valuable time and resources. Streamlined and accurate data sharing across departments is crucial to ensure each team operates with reliable information, reducing the risk of rework and misunderstandings that can derail project timelines. Borrmann et al. (2018) discusses the importance of data exchange in project success, while Liu et al. (2014) points out that poor change management in BIM can lead to inaccurate data. Oloufa et al. (2004) note that inefficient information flow results in miscommunication if not structured well, and Pilehchian et al. (2015) highlights the difficulty of tracking design changes in a multidisciplinary environment. Senescu et al. (2012) emphasize the need for automated tracking to prevent outdated data issues.

Phase transition and workflow continuity

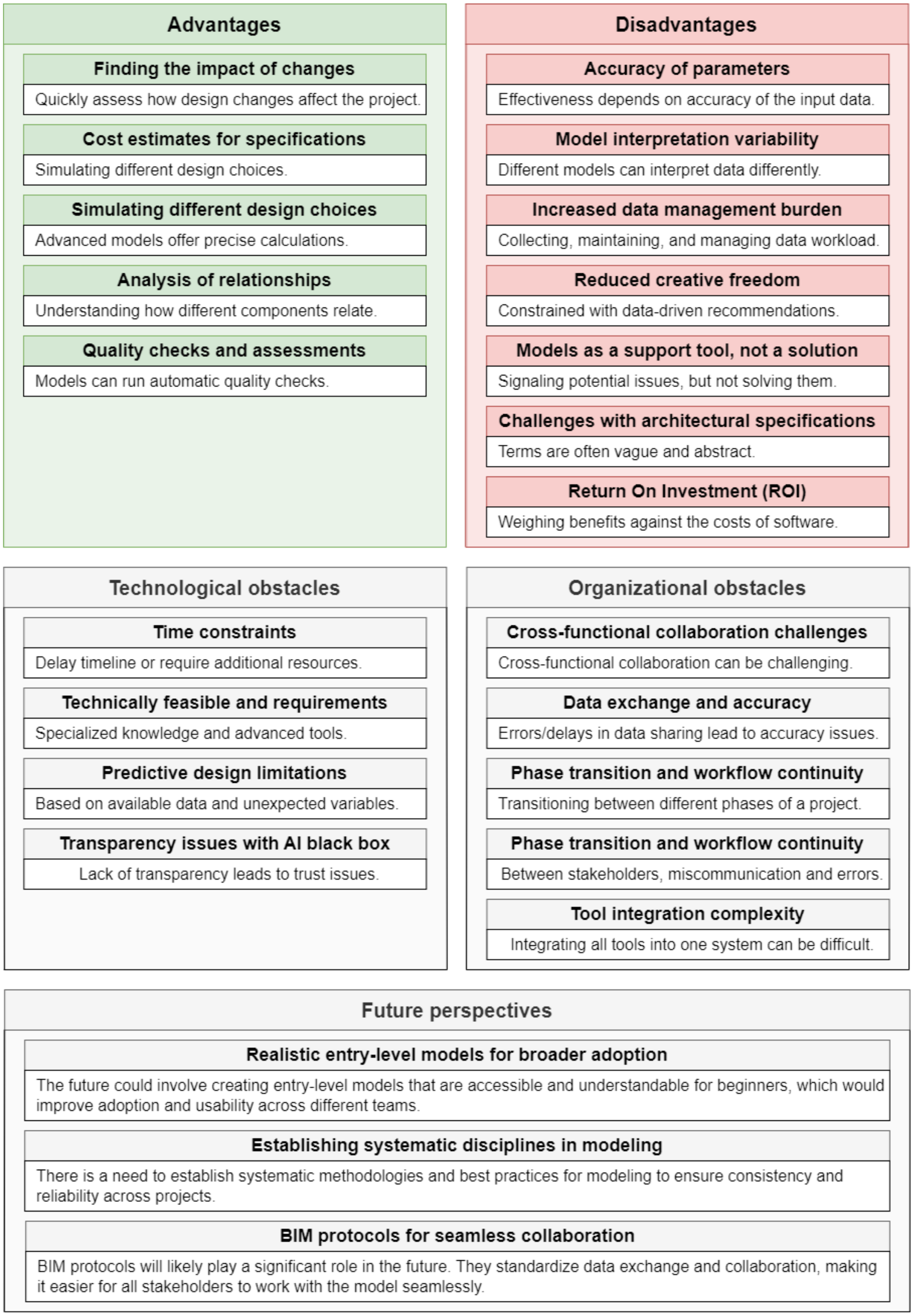
Moving from one project phase to another can introduce errors and inefficiencies if teams are not aligned on goals, data needs, and timelines. Ensuring a smooth transition between phases is critical, especially in complex engineering projects, where maintaining workflow continuity and careful planning is necessary to sustain momentum without sacrificing accuracy or quality. Liu et al. (2014) discuss challenges related to phase transitions and the need for change management when moving between phases. Oloufa et al. (2004) focus on information flow throughout each project phase, while Eppinger and Browning (2012) highlights DSM as a tool for managing dependencies between phases. The DTH theory of Reefman (2022) also mentions the use of DTHs for linking configurations of different phases within the project. These theories help to indicate the complexity of how configurations of project phases align.

Stakeholder coordination

Involving multiple stakeholders in a project often creates coordination challenges, especially if there are no clear information flow channels. Miscommunication or errors can arise when stakeholders have differing expectations or lack access to the same information, leading to potential delays and increased costs. Strong coordination efforts and consistent communication channels are essential to prevent misunderstandings and ensure a cohesive approach among stakeholders. Borrmann et al. (2018) discusses the importance of centralizing data to enhance coordination, while Oloufa et al. (2004) highlights the value of DSM in improving information flow between stakeholders. Pilehchian et al. (2015) emphasize clear communication and data sharing to track design changes effectively, which aids in aligning all parties involved.

Tool integration complexity

Engineering projects often rely on various specialized tools across disciplines, and integrating them into a unified system can be challenging. When there are too many tools, fragmented workflows and data incompatibility can hinder collaboration, making information access challenging. An integrated system that supports multiple tools simplifies operations and fosters smoother collaboration, though achieving this integration is not easy. Borrmann et al. (2018) points out that BIM can integrate multiple tools and systems, but without proper integration, fragmented workflows can impede execution. Liu et al. (2014) note that incompatible tools complicate data sharing and affect consistency and accuracy, while Wang et al. (2022) discuss the diversity of tools across disciplines. Madni and Sievers (2018) warn that the lack of seamless integration leads to fragmented workflows and hinders collaboration. Yassine (2004) suggests using DSM to model and integrate various tools across disciplines for a more cohesive project management environment.



Advantages

Finding the impact of changes
Quickly assess how design changes affect the project.

Cost estimates for specifications
Simulating different design choices.

Simulating different design choices
Advanced models offer precise calculations.

Analysis of relationships
Understanding how different components relate.

Quality checks and assessments
Models can run automatic quality checks.

Disadvantages

Accuracy of parameters
Effectiveness depends on accuracy of the input data.

Model interpretation variability
Different models can interpret data differently.

Increased data management burden
Collecting, maintaining, and managing data workload.

Reduced creative freedom
Constrained with data-driven recommendations.

Models as a support tool, not a solution
Signaling potential issues, but not solving them.

Challenges with architectural specifications
Terms are often vague and abstract.

Return On Investment (ROI)
Weighing benefits against the costs of software.

Technological obstacles

Time constraints
Delay timeline or require additional resources.

Technically feasible and requirements
Specialized knowledge and advanced tools.

Predictive design limitations
Based on available data and unexpected variables.

Transparency issues with AI black box
Lack of transparency leads to trust issues.

Organizational obstacles

Cross-functional collaboration challenges
Cross-functional collaboration can be challenging.

Data exchange and accuracy
Errors/delays in data sharing lead to accuracy issues.

Phase transition and workflow continuity
Transitioning between different phases of a project.

Phase transition and workflow continuity
Between stakeholders, miscommunication and errors.

Tool integration complexity
Integrating all tools into one system can be difficult.

Future perspectives

Realistic entry-level models for broader adoption
The future could involve creating entry-level models that are accessible and understandable for beginners, which would improve adoption and usability across different teams.

Establishing systematic disciplines in modeling
There is a need to establish systematic methodologies and best practices for modeling to ensure consistency and reliability across projects.

BIM protocols for seamless collaboration
BIM protocols will likely play a significant role in the future. They standardize data exchange and collaboration, making it easier for all stakeholders to work with the model seamlessly.

Figure 5.2: Discussion during the workshop session

5.4.5 Future perspectives

Realistic entry-level models for broader adoption

Future BIM-tool initiatives may focus on creating accessible and intuitive entry-level tools to encourage adoption across interdisciplinary teams. Simplified initial interactions will make it easier for individuals less familiar with advanced tools to integrate MBSE methods, providing better usability and confidence in adopting new technology.

These models should focus on essential functionalities, such as dependency mapping, basic change tracking, and straightforward visualization features while omitting highly specialized or complex options that might discourage new users. By streamlining these initial interactions, these tools can improve usability, reduce resistance to adoption, and build user confidence over time. Additionally, intuitive interfaces, guided tutorials, and interactive help systems can support seamless integration, ensuring broader accessibility.

Moreover, these entry-level models should be designed to grow with the user, offering modular additions or upgrades that introduce advanced features as users become more comfortable with the technology. This scalability ensures that the tools remain relevant as professionals advance their expertise. Ultimately, creating realistic and user-friendly entry-level BIM tools can democratize access to advanced CM practices, making it easier for interdisciplinary teams to embrace innovative methodologies while maintaining high levels of collaboration and efficiency.

Establishing systematic disciplines in modeling

Systematic methodologies and best practices in modeling are crucial for ensuring consistency, reliability, and collaboration across complex projects. By adopting a unified framework, interdisciplinary teams can standardize their approaches to data creation, management, and interpretation. This reduces the likelihood of errors, miscommunication, and inefficiencies that often arise from inconsistent modeling practices. A systematic approach not only promotes clear alignment among teams but also provides a foundation for scalable and adaptable workflows.

For instance, methodologies like DSM, as supported by Eppinger and Browning (2012), offer a systematic way to manage interdependencies in complex engineering projects, providing clarity on how components interact and evolve. MBSE methodologies, discussed by Madni and Sievers (2018) and Wymore (2018), advocate for a unified modeling framework that enhances coordination across disciplines. These methodologies emphasize the importance of standardized practices, enabling teams to integrate diverse design inputs while maintaining consistency and accuracy. Implementing such frameworks encourages a culture of discipline in modeling, where adherence to standardized protocols becomes the norm.

BIM protocols for seamless collaboration

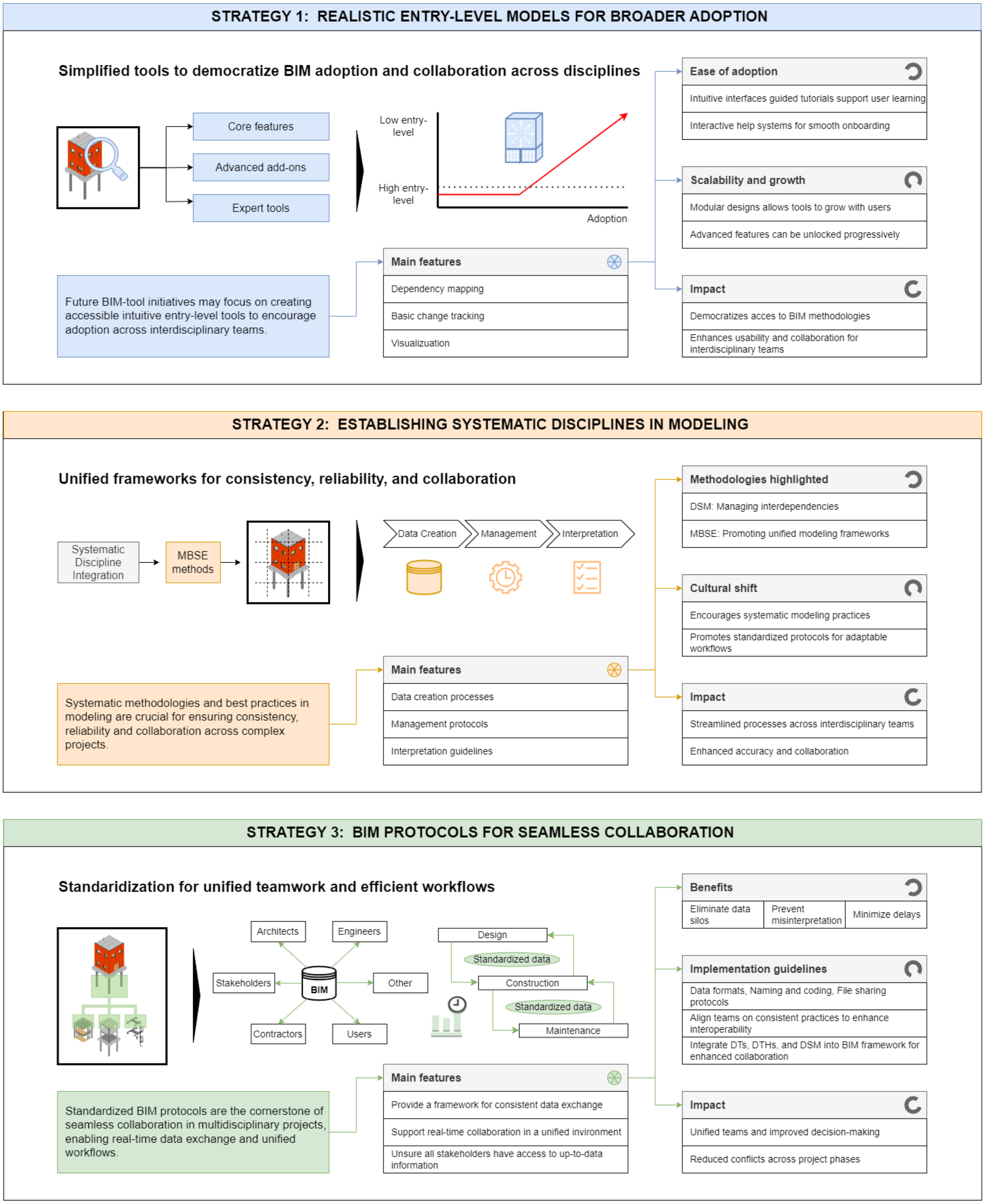
Standardized BIM protocols are a cornerstone for achieving seamless collaboration in multidisciplinary projects. They provide a framework for consistent data exchange, enabling stakeholders to work within a unified environment that supports real-time collaboration. By adopting standardized practices, BIM models can serve as a central hub of accessible and up-to-date information throughout the project life cycle. This reduces barriers to effective communication, prevents data silos, and minimizes delays caused by inconsistent or incomplete information sharing.

The benefits of standardized BIM protocols are well-supported in the literature. Azhar (2011) highlights how standardized data exchange fosters better integration among stakeholders, creating a more cohesive project workflow. Similarly, Liu et al. (2014) underscores the advantages of data consistency, noting that uniform data formats and practices eliminate redundancies and reduce the risk of misinterpretation. Further, Cha and Kim (2020) discusses how standardized BIM methodologies streamline workflows by facilitating smoother data transfer and enhancing communication between teams. This supports improved decision-making processes and reduces conflicts across project phases. Finally, Mangialardi et al. (2017) emphasizes BIM's capacity to enable continuous information sharing, ensuring that stakeholders have access to reliable and relevant data at all times, which is critical for maintaining project momentum.

In practice, implementing standardized BIM protocols involves defining clear guidelines for data formats, naming conventions, and file-sharing practices. These guidelines help ensure that all contributors to a project are aligned on the same standards, reducing miscommunication and enhancing interoperability across diverse platforms and tools. Moreover, standardized protocols support the integration of DTs, DTHs, and DSM, into the BIM framework, ensuring that these MBSE tools are seamlessly incorporated into CM practices.

Strategies

Figure 5.3 illustrates the future perspectives discussed in this chapter, highlighting three strategic approaches for advancing BIM tools and practices: developing realistic entry-level models to foster broader adoption, establishing systematic disciplines in modeling for consistency and reliability, and implementing standardized BIM protocols to enable seamless collaboration. These strategies aim to improve usability, encourage interdisciplinary integration, and promote efficient workflows in complex projects, reflecting the evolving needs of the industry and the potential of BIM to transform multidisciplinary collaboration.



STRATEGY 1: REALISTIC ENTRY-LEVEL MODELS FOR BROADER ADOPTION

Simplified tools to democratize BIM adoption and collaboration across disciplines

Future BIM-tool initiatives may focus on creating accessible intuitive entry-level tools to encourage adoption across interdisciplinary teams.

Main features
- Dependency mapping
- Basic change tracking
- Visualizuation

Ease of adoption
- Intuitive interfaces guided tutorials support user learning
- Interactive help systems for smooth onboarding

Scalability and growth
- Modular designs allows tools to grow with users
- Advanced features can be unlocked progressively

Impact
- Democratizes acces to BIM methodologies
- Enhances usability and collaboration for interdisciplinary teams

STRATEGY 2: ESTABLISHING SYSTEMATIC DISCIPLINES IN MODELING

Unified frameworks for consistency, reliability, and collaboration

Systematic methodologies and best practices in modeling are crucial for ensuring consistency, reliability and collaboration across complex projects.

Main features
- Data creation processes
- Management protocols
- Interpretation guidelines

Methodologies highlighted
- DSM: Managing interdependencies
- MBSE: Promoting unified modeling frameworks

Cultural shift
- Encourages systematic modeling practices
- Promotes standardized protocols for adaptable workflows

Impact
- Streamlined processes across interdisciplinary teams
- Enhanced accuracy and collaboration

STRATEGY 3: BIM PROTOCOLS FOR SEAMLESS COLLABORATION

Standaridization for unified teamwork and efficient workflows

Standardized BIM protocols are the cornerstone of seamless collaboration in multidisciplinary projects, enabling real-time data exchange and unified workflows.

Main features
- Provide a framework for consistent data exchange
- Support real-time collaboration in a unified invironment
- Unsure all stakeholders have access to up-to-data information

Benefits
- Eliminate data silos
- Prevent misinterpretation
- Minimize delays

Implementation guidelines
- Data formats, Naming and coding, File sharing protocols
- Align teams on consistent practices to enhance interoperability
- Integrate DTs, DTHs, and DSM into BIM framework for enhanced collaboration

Impact
- Unified teams and improved decision-making
- Reduced conflicts across project phases

Figure 5.3: Future perspectives strategies

Chapter 6

Discussion

This chapter includes a discussion based on the results from the demonstration and the literature from the state of the art measured against the theoretical framework of the introduction and the research gap. The discussion section aims to synthesize the research findings, examine their implications, and situate them within the broader context of the field. This chapter discusses how the findings contribute to both theory and practice, how they align with or challenge previous research, and their practical implications for the AEC industry. Finally, the limitations of the study are outlined to provide a comprehensive evaluation of the research outcomes.

6.1 Research findings

In the introduction, several critical research gaps were highlighted regarding CM within multidisciplinary construction projects. These gaps include the fragmentation of CM across disciplines, the under-utilization of DTs and DTHs, the limited application of DSM, and the organizational barriers hindering the adoption of these MBSE methods. The overarching aim of this research was to implement MBSE methods into CM practices, enhancing the configuration and management of design changes in complex construction projects.

The main findings were derived by addressing the research questions introduced in the study. Each SQ was explored in detail within separate chapters, leading up to new insights that contribute to the broader objective.

What are the current methods of configuration within MBSE?

The first SQ focused on defining the state-of-the-art in MBSE methods and their relevance to CM. MBSE, a modern approach to SE, centralizes system-related information into a unified configuration model. This approach offers numerous benefits, including improved communication among multidisciplinary teams, enhanced visualization of complex structures, and the ability to capture decision-making processes effectively. However, challenges such as the risk of inaccurate models, inconsistencies due to a lack of standardization, and insufficient V&V mechanisms were also identified.

The results indicate that the DT, DTH, and DSM, as key components of MBSE, play a pivotal role in addressing these challenges and improving CM for AEC projects. Each method contributes uniquely to an integrated MBSE framework:

1. **Digital Twin:** The DT provides a continuously updated virtual representation of physical assets, allowing real-time tracking of changes and simulation of potential scenarios. By acting as a centralized configuration model, the DT ensures that all stakeholders have access to accurate, up-to-date project data, supporting collaboration and reducing errors. It enables data-driven decision-making and improves project efficiency.
2. **Digital Thread:** The DTH connects configurations across all disciplines, ensuring real-time traceability and consistency of design changes. This connectivity ensures that updates in one discipline

are automatically reflected in others, reducing the risk of inconsistencies. The results indicate that DTH enhances alignment with evolving requirements, thereby minimizing delays and improving overall project performance.

3. **Design Structure Matrix:** DSM maps dependencies and interdependencies across system components, offering visual and analytical tools to understand the cascading effects of design changes. By clarifying these relationships, DSM supports task prioritization, conflict anticipation, and effective management of project complexities. The results highlight DSM's capability to enhance communication and coordination across tightly integrated systems.

Together, the findings show that DT, DTH, and DSM form a cohesive MBSE framework that supports real-time data sharing, effective change management, and efficient collaboration across AEC disciplines. This integration optimizes workflows, minimizes rework, and ensures consistency throughout the project life-cycle. The results indicate that adopting this framework not only addresses current CM challenges but also aligns with the industry's transition toward more interconnected and data-driven practices.

How can MBSE methods be used in the context of BIM?

The second research question aimed to develop and test a systematic design approach integrating MBSE methods to improve CM in multi-disciplinary construction projects. This was achieved by creating a mock-up prototype and accompanying practical guidelines, with the requirement list serving as a benchmark to ensure the prototype met the identified needs effectively.

To make sure that the prototype mock-up successfully translates the theoretical concepts into a functional tool, key requirements from the problem statement and the MBSE framework were listed. The requirement list outlines the MBSE functionalities and is further used in the research to verify and validate the prototype. The chapter highlights how the prototype fulfills these requirements:

1. **Interdisciplinary dependency mapping:** The prototype enables clear visualization and categorization of dependencies across various disciplines, such as structural, architectural, and MEP systems. This feature resembles the DSM and supports better coordination by clarifying relationships between components and reducing miscommunication.

2. **Change tracking and version control:** A systematic approach to logging design changes and their impacts was incorporated into the prototype with the use of DTHs. This capability ensures a transparent record of modifications, enhancing traceability and facilitating efficient management of updates.

3. **Real-time analysis:** With the integration of DTs the prototype provides real-time visualization of design changes, allowing teams to understand their potential impacts on interdependencies. This capability helps teams anticipate and address conflicts before they escalate into more significant issues.

4. **Automated alerts and notifications:** An integrated notification system ensures that relevant stakeholders are informed of changes affecting their disciplines. This BIM feature uses visual indicators to highlight impacted areas. This helps with improving communication and enabling quicker, coordinated responses.

5. **Integration with existing BIM tools:** The mock-up prototype was tested on Revit as a BIM tool example. Compatibility with widely used BIM platforms ensures the prototype aligns with existing workflows. This integration supports continuity across project phases by enabling the import, update, and export of data while maintaining consistency with established practices.

The prototype was developed to support a structured approach to managing design changes in multi-disciplinary construction projects. A guideline for its use was created, outlining the following steps:

1. **Tracking successive changes:** The prototype enables detailed mapping of interdependencies, allowing teams to trace the effects of specific modifications. For example, changes to one system can be assessed for their impacts on connected components, ensuring design integrity.

2. **Communicating changes across disciplines:** The prototype's interdisciplinary framework ensures changes are communicated clearly and quickly across relevant teams. Real-time alerts and visual cues enhance understanding of the extent of changes and their implications.
3. **Assessing design change impacts:** The visualization capabilities allow users to evaluate potential conflicts and experiment with alternative solutions, helping to identify the most viable option while ensuring alignment across all disciplines.

The results indicate that the prototype verifies the outlined requirements, serving as a practical tool to address CM challenges in multidisciplinary construction projects. By integrating MBSE methods, it facilitates better communication, real-time analysis, and improved coordination across disciplines. The structured approach provided by the prototype and its guidelines supports efficient change management, enhancing both the design process and overall project outcomes.

How can MBSE be used in the real-world engineering context?

The third research question aimed to assess how MBSE methods, particularly through the use of the prototype developed in the previous research question, could be applied to estimate the impact of design changes across various disciplines in a real-world setting. To address this question, the prototype was demonstrated in a workshop at W+B, The goal of this demonstration was to validate the prototype's effectiveness in improving CM between AEC disciplines by integrating MBSE methods within a BIM environment. The results from this validation provided valuable insights into the prototype's strengths and limitations in assessing the impact of design changes. The demonstration validates the requirements stated in the previous chapter as follows:

1. **Interdisciplinary dependency mapping:** The prototype visualizes dependencies between building elements, aiding early error detection. However, its dependency categorization is basic and lacks advanced systems (e.g., spatial, functional) needed for complex, multidisciplinary projects.
2. **Change tracking and version control:** While the prototype tracks dependencies and changes, it lacks robust version control, making it difficult to manage evolving design elements across project phases.
3. **Real-time impact analysis:** The prototype can visualize real-time design changes and their impacts but lacks consistency in highlighting all dependencies and affected areas, suggesting room for improvement.
4. **Automated alerts and notifications:** The notification system is not fully automated or universally accessible, limiting its effectiveness in notifying relevant teams of design changes.
5. **Integration with existing BIM tools:** While the prototype shows basic integration with BIM tools like Revit, challenges remain with other systems, limiting its seamless functionality across various tools and workflows.

The prototype demonstrated several promising features for managing design changes within a BIM environment. However, its limitations in dependency categorization, change tracking, real-time impact analysis, and integration with BIM tools suggest that further development is required. These issues highlight key technological challenges in applying MBSE methods to complex multidisciplinary projects, including the need for more advanced tools for categorizing dependencies, ensuring comprehensive real-time impact analysis, and improving integration across platforms.

The discussion of the prototype's performance revealed several valuable strengths, including its ability to assist in the quick assessment of design changes, provide cost estimations, facilitate design simulations, and map interdependencies for early conflict detection. These features align with prior findings on the role of BIM in enhancing collaboration and managing changes across complex projects.

However, several limitations were also identified:

1. **Accuracy of parameters:** The prototype's reliance on precise input data raised concerns about its reliability. If parameters are inaccurate, the prototype's outputs may be compromised.

2. **Model interpretation variability:** Differences in how stakeholders interpret the model may lead to inconsistencies, highlighting the need for clearer modeling standards.

3. **Data management burden:** The prototype's data management demands were recognized as obstacles, diverting resources from other critical tasks.

4. **Reduced creative freedom:** The reliance on data-driven approaches may limit innovation by encouraging conventional solutions, thus restricting creative freedom.

5. **Challenges with architectural specifications:** Translating qualitative architectural aspects into quantitative models presented challenges that need further attention.

6. **Return on Investments:** Participants expressed concerns about the ROI, considering the costs associated with the software, training, and ongoing maintenance.

These findings underscore the balance required between automation and creativity, and between ease of use and technical complexity, to ensure the prototype is both practical and effective in real-world scenarios.

The feedback identified several technical challenges that hindered the prototype's effectiveness. Time constraints were a major issue, as implementing and maintaining modeling technologies demanded significant time, which could delay projects, particularly in high-pressure environments. The advanced tools required specialized expertise, making it difficult for organizations with limited resources to integrate the necessary technical knowledge. Predictive design models also struggled to accommodate unforeseen changes, especially in dynamic and complex environments, suggesting a need for more adaptable approaches, such as machine learning or hybrid models. Transparency in AI-driven models was another concern, as their opacity reduced trust in decision-making processes, highlighting the need for improved transparency to build confidence in critical decisions. Additionally, the complexity of integrating specialized tools across disciplines created challenges, emphasizing the need for unified systems that support seamless collaboration and minimize disruptions.

On the organizational side, cross-functional collaboration faced significant barriers. Communication gaps between technical and non-technical teams often led to inefficiencies, underlining the importance of effective project management strategies to encourage collaboration across disciplines. Data exchange and accuracy were also problematic, as delays or inconsistencies in data sharing between departments led to errors and inefficiencies. Ensuring streamlined, accurate data exchange is crucial for project success. Phase transitions between project stages were another challenge, with disruptions causing delays.

To address these obstacles, the following future directions are suggested by the participants of the demonstration:

1. **Realistic entry-level models:** Developing accessible and intuitive entry-level BIM tools with essential functionalities like dependency mapping and change tracking can encourage broader adoption across interdisciplinary teams. These tools should grow with user expertise, incorporating advanced features as teams develop their capabilities.

2. **Establishing systematic disciplines in modeling:** Standardizing methodologies can improve consistency and reliability across projects. An organizational shift toward adhering to these protocols will ensure long-term collaboration and project success.

3. **BIM protocols for seamless collaboration:** Standardized BIM protocols for data exchange can foster real-time collaboration and reduce data silos.

6.2 Interpretations from the research

In line with the expectations, the research findings reveal that integrating MBSE methods into CM practices significantly enhances coordination, communication, and efficiency across multidisciplinary teams. These methods align with the research aim of addressing fragmentation in CM and improving the configuration and management of design changes in complex construction projects.

The study's findings highlight key correlations between MBSE methods and their ability to address the challenges identified in the literature, such as under-utilization of advanced tools like DTs and DTHs, as well as organizational barriers to adopting these methods. The DT provides real-time tracking of changes, allowing stakeholders to maintain up-to-date and accurate project data. This addresses the challenge of fragmented communication and promotes a more data-driven, collaborative approach. Likewise, the DTH ensures that updates in one discipline are reflected across all others, effectively minimizing discrepancies and improving overall project alignment.

Furthermore, DSM's ability to map interdependencies across system components plays a critical role in helping teams anticipate conflicts and manage the complexities inherent in multidisciplinary projects. By visualizing relationships between building elements, DSM facilitates better decision-making and helps prioritize tasks, which is critical for managing design changes efficiently.

The prototype tested as part of the research demonstrates how MBSE methods can be applied within a BIM environment to improve CM. The findings confirm that the prototype meets several key requirements, including interdisciplinary dependency mapping, change tracking, and real-time impact analysis. These features align with the expectations outlined in the study and demonstrate how MBSE methods can streamline workflows, enhance coordination, and facilitate better communication across disciplines.

However, while the results meet many of the expectations, some technical limitations were identified. For example, the prototype's dependency categorization was deemed basic, and its change tracking and version control mechanisms lacked the robustness required for complex projects. These issues point to the need for further development in both the prototype's functionality and its integration with existing BIM tools. Additionally, concerns regarding model interpretation variability and the burden of data management highlight challenges in the practical application of MBSE methods, suggesting that more standardized approaches are needed to improve consistency and reduce the potential for errors.

The feedback from the workshop further revealed organizational challenges, including communication gaps between technical and non-technical teams, issues with data exchange and accuracy, and difficulties with phase transitions. These findings reinforce the need for better cross-functional collaboration and the implementation of standardized BIM protocols to reduce data silos and improve workflow continuity. Moreover, the concerns raised regarding the time and expertise required to implement and maintain advanced modeling technologies underscore the importance of developing realistic, entry-level tools that can scale as teams gain expertise.

6.3 Implementations

This research makes contributions to both theory and practice in the field of CM and SE, particularly in the context of multidisciplinary projects. The integration of MBSE methods, including DTs, DTH, and DSM, within a BIM environment offers insights into the management of design changes and the configuration of complex systems.

Contributions to theory

The experiment provides a new insight into the relationship between MBSE methods and construction project management, particularly how digital and system-based approaches can streamline workflows and improve communication across disciplines. While prior research has explored the potential of these methods individually, this study demonstrates their integration into a cohesive framework that enhances collaboration, decision-making, and conflict resolution in construction projects. The findings support existing theories on the role of BIM in managing change and enhancing collaboration but extend these theories by incorporating advanced MBSE methods that provide a deeper, systems-level perspective on project coordination.

Moreover, the study confirms the theoretical benefits of DTs, DTHs, and DSMs in addressing challenges such as data fragmentation, lack of standardization, and the need for real-time traceability in multidisciplinary environments. This integration not only aligns with but also enhances existing models in SE and CM literature. The research's emphasis on real-time data sharing and seamless updates across disciplines challenges the conventional view of CM as a fragmented, static process, suggesting instead a more interconnected, dynamic model driven by continuous data flow.

However, the study also identifies some limitations of existing theoretical models. The basic categorization of dependencies and the lack of robust version control mechanisms in the prototype demonstrate that existing frameworks may need to be further refined to handle the complexity and scale of real-world construction projects. This highlights the need for further theoretical development in tools for managing design change impacts, real-time communication, and integration across systems.

Contributions to practice

In practical terms, the research introduces a functional prototype that integrates MBSE methods into a BIM environment, providing a mock-up of a practical tool for managing design changes in multidisciplinary projects. The prototype's ability to map dependencies, track changes, and analyze real-time impacts represents a significant advancement in CM practice. By aligning with existing BIM tools, such as Revit, the prototype mock-up allows for smoother integration into current workflows, enhancing its potential for real-world application.

The findings also point to several practical implications for the industry. The integration of DTs, DTHs, and DSMs into the CM process can lead to more accurate project planning, reduced errors, and enhanced collaboration. The real-time analysis capabilities of the prototype can help anticipate and address conflicts before they escalate, thus improving project efficiency and reducing costs. Moreover, the automated alerts and notifications feature supports more timely responses to design changes, facilitating better coordination across teams and disciplines.

Furthermore, the research emphasizes the importance of developing user-friendly, entry-level tools that can facilitate the adoption of these advanced methods. This insight is especially valuable for smaller firms or teams with limited resources or technical expertise. The practical recommendation to design scalable BIM tools that grow with user expertise ensures broader access to these advanced practices and stimulates a culture of continuous improvement within the construction industry.

Alignment with previous research

The findings of this research generally agree with prior studies that highlight the importance of collaboration, data-sharing, and change management in construction projects. Previous research has consistently pointed to the benefits of BIM in managing complex design changes and improving communication between disciplines. This study builds on these findings by demonstrating how the integration of MBSE methods can further enhance these processes, making them more data-driven and interconnected.

However, the study also offers a nuanced contribution by addressing gaps identified in previous research, particularly the under-utilization of advanced tools like DTs and DTHs in CM. While prior studies have explored their potential, few have demonstrated how these technologies can be practically implemented and integrated into existing workflows. This research provides evidence that the combination of DTs, DTHs, and DSMs not only supports better decision-making but also offers a more systematic approach to managing design changes and improving overall project performance.

Practical implications and challenges

Despite the promising findings, the research also identifies several practical challenges that need to be addressed to fully realize the potential of MBSE methods in CM. The reliance on accurate input data, issues with model interpretation variability, and the complexities of tool integration across disciplines highlight the need for improved standardization and training. These findings suggest that while the theoretical advantages of MBSE are clear, their successful implementation in practice requires careful consideration of organizational barriers, technical challenges, and the development of more robust, user-friendly tools.

The study also raises concerns regarding the costs and resources required to implement these advanced technologies, such as DTs and DSMs, and their potential impact on ROI. This suggests that companies must weigh the benefits of these tools against the investment needed for software, training, and maintenance. Therefore, it is important for future research to explore strategies for making these tools more accessible, cost-effective, and scalable, particularly for small and medium-sized enterprises.

In conclusion, the research contributes both theoretically and practically by demonstrating how MBSE methods can be integrated into BIM to improve CM practices. The results generally align with previous studies on the role of BIM in enhancing collaboration and managing change but also extend existing theories by introducing advanced system-based methods to improve efficiency and coordination. The practical implications of the findings emphasize the need for better tool integration, user-friendly interfaces, and scalable solutions to overcome existing barriers to adoption. The study thus lays the groundwork for future research and development in this area, highlighting the potential for MBSE methods to revolutionize CM practices.

6.4 Limitations of the research

While this research has made valuable contributions to the integration of MBSE methods within CM and BIM, there are several limitations that should be acknowledged.

Research design and methodological limitations

One of the key limitations of this study is related to the scope of the research design. The study focused on a specific set of MBSE methods, namely DTs, DTH, and DSM, and their integration with BIM tools in a mock-up prototype. While this provided valuable insights into the potential of these technologies, it is beyond the scope of this study to address the full range of MBSE methods that could also contribute to CM. Future research could expand on this by exploring other MBSE techniques and their relevance to the construction industry.

Additionally, the prototype tested in the study, while functional and promising, is limited in its current form. It primarily serves as a proof of concept, and its effectiveness in large-scale, real-world projects remains untested. This study focused on a controlled demonstration setting, and the results may not fully reflect the challenges of implementing such a system in complex, dynamic project environments. The prototype's limitations, such as its basic categorization of dependencies and lack of robust version control, suggest that further development is needed to make it suitable for practical, industry-wide application.

Sample size and data limitations

The study also relied on a relatively small sample size, particularly during the validation phase, where the prototype was tested in a workshop setting at W+B. While the workshop provided useful feedback, it is important to note that the findings are based on a limited number of participants and may not be fully representative of the broader industry. The feedback gathered may be influenced by the specific context of the workshop and the particular expertise of the participants. A larger, more diverse sample of professionals across different sectors of the construction industry would provide more comprehensive insights.

Furthermore, while the study examined the theoretical aspects of MBSE and BIM integration, it did not account for the full range of practical variables that can impact the success of such integration, such as organizational culture, team dynamics, and the availability of resources. These factors could significantly influence the feasibility and effectiveness of implementing MBSE methods in CM, and future studies should explore these dimensions more deeply.

Unanticipated obstacles and technological limitations

During the course of the research, several unanticipated obstacles were encountered, particularly with the integration of the prototype into existing BIM platforms. Although the prototype was designed to be compatible with Revit, challenges with integration across other BIM tools were identified. The prototype's functionality with other systems was not explored in this research, suggesting that further work is needed to develop more flexible, interoperable tools that can integrate with a variety of platforms used across the construction industry.

Additionally, the study encountered technical limitations related to the accuracy and reliability of the data used in the prototype. The prototype's reliance on precise input data meant that inaccuracies in the data could compromise the results. Moreover, the complexity of managing vast amounts of data in a real-time, collaborative environment posed significant challenges in terms of system performance and user experience. These issues underscore the need for more robust data management strategies and more advanced tools to handle complex, multi-disciplinary projects.

Chapter 7

Conclusion and recommendations

7.1 Conclusion

In this chapter, the findings from the SQs and the main RQ are summarized, addressing the overall objective of this study: how MBSE methodologies can be effectively integrated within the construction industry to visualize interdependencies, manage design changes, and enhance multidisciplinary collaboration in BIM environments. These findings contribute to a structured framework for improving decision-making and project efficiency in complex engineering contexts, offering both theoretical and practical advancements.

SQ 1: MBSE Methods for CM within BIM

SE is an interdisciplinary approach designed to manage the complexity of system development throughout its life-cycle. A system is a structured set of components that interact to achieve a common goal, ranging in complexity from simple systems, like bicycles, to adaptive systems, such as ecosystems. SE applies scientific principles and processes, including V&V, to ensure systems meet stakeholder requirements. It emphasizes collaboration across disciplines, balancing constraints like performance, cost, and reliability to create integrated, functional systems that fulfill their intended purposes.

MBSE extends the principles of SE by emphasizing models as the core medium for system development. Unlike document-centric approaches, MBSE leverages digital models as a consistent and authoritative source of information. One of the primary benefits of MBSE is its ability to improve communication and knowledge transfer across diverse teams. By using a common framework and visualizing complex interactions, MBSE provides clarity, ensuring better decision-making and a more seamless transfer of design knowledge. However, it can also present challenges. A major risk is inaccurate models; if the model doesn't correctly represent the system or its environment, decisions based on it could be flawed, leading to costly mistakes. Additionally, an over-reliance on models without real-world validation can lead to unexpected risks during implementation. Rigorous standardization and continuous V&V are critical to overcoming these potential pitfalls.

In the BIM environment, MBSE provides a structured approach to managing the technical and functional dependencies of complex construction systems. BIM traditionally focuses on the physical design and geometry of projects, while MBSE incorporates the functional and systemic aspects. By integrating MBSE methods construction projects can use tools to visualize interdependencies, simulate the impact of design changes, and improve alignment across disciplines. This integration ensures that BIM workflows extend beyond physical modeling to include dynamic, system-level insights, bridging the gap between design and operational requirements.

A unified configuration integrates all discipline-specific models, aligning diverse stakeholder inputs into a single, consistent system. This approach minimizes inefficiencies associated with multiple, isolated configurations, reducing errors and fostering collaboration. By adopting a unified configuration model, like CM2, organizations can synchronize data across design, engineering, and construction processes. This ensures that changes in one domain are automatically reflected across all disciplines, enabling seamless change management and enhanced communication. Theoretically, a unified configuration transforms the fragmented workflows of traditional systems into a coordinated process, promoting efficiency and innovation in complex projects.

The current configuration methods within MBSE revolve around three key methodologies: DT, DTH, and DSM. Each of these methods offers distinct but complementary tools for managing the complex configurations needed in multidisciplinary projects in the AEC industry.

DT provides a virtual model that reflects real-time data from the physical asset, allowing stakeholders to track changes, simulate scenarios, and ensure configuration alignment across project stages. As a centralized configuration model, DT offers consistent and up-to-date project data, facilitating collaboration and minimizing errors through data-driven decision-making.

DTH links data across all phases of the project, maintaining traceability and ensuring design modifications are accurately propagated across configurations. This approach supports alignment among project disciplines, reduces the risk of inconsistencies, and enhances communication among stakeholders, improving decision-making and minimizing costly delays.

DSM maps dependencies and interdependencies among project components, allowing teams to visualize the impact of design changes on other configurations. DSM aids in identifying and managing complex relationships, prioritizing tasks, and resolving potential conflicts in tightly integrated systems, enhancing project planning and coordination.

Together these methods create an MBSE framework that contributes real-time data sharing, effective change management, and collaboration across AEC disciplines. By integrating these methods, project teams can streamline workflows, reduce rework, and achieve consistency from design to construction, supporting a shift towards a more interconnected and data-driven approach in the industry.

SQ 2: Practical implementation of MBSE methods for CM within BIM

To address the second research question, which aimed to develop and test a systematic design approach with the integration of MBSE methods for improved CM, a mock-up prototype was created. This prototype served as a functional tool to prove theoretical concepts within practice, guided by a requirement list derived from the problem statement and the MBSE framework. These requirements were used as benchmarks to ensure that the prototype met the project's objectives effectively. The following requirements were included to the prototype's design, with the development process ensuring their realization:

1. **Interdisciplinary dependency mapping:** Mainly using the DSM to identify the type of dependency and type of change.
2. **Change tracking and version control:** By using the DTH, configurations across various disciplines within the project are linked.
3. **Real-time analysis:** Making use of the DT as a real-time visualization tool of design changes and their impacts.
4. **Automated alerts and notifications:** This extra feature uses visual indicators to inform stakeholders of changes impacting their disciplines.
5. **Integration with existing tools:** The mock-up prototype was tested with Revit, demonstrating compatibility with widely used BIM platforms.

The practical guideline developed in this research offers a structured approach to managing design changes in multidisciplinary construction projects by integrating insights from MBSE methods. The guideline consists of three steps:

1. **Tracking successive changes:** The prototype enables detailed mapping of interdependencies, allowing teams to trace the effects of specific modifications. For example, changes to one system can be assessed for their impacts on connected components, ensuring design integrity.
2. **Communicating changes across disciplines:** The prototype's interdisciplinary framework ensures changes are communicated clearly and quickly across relevant teams. Real-time alerts and visual cues enhance understanding of the extent of changes and their implications.

3. **Assessing design change impacts:** The visualization capabilities allow users to evaluate potential conflicts and experiment with alternative solutions, helping to identify the most viable option while ensuring alignment across all disciplines.

By following the steps, teams are equipped to manage interdependencies more effectively. The mock-up prototype serves as a proof of concept, translating theoretical concepts into practical tools that enhance communication, collaboration, and decision-making. It facilitates proactive identification of potential conflicts, supports cross-disciplinary coordination, and allows for iterative testing of alternative solutions.

SQ 3: MBSE methods in the real-world engineering context

The research explored how MBSE methods, integrated with BIM environments, can estimate the impact of design changes in real-world multidisciplinary construction projects. Validation of the developed prototype provided insights into its practical application, strengths, and areas for improvement.

MBSE demonstrated significant potential for managing dependencies, improving collaboration, and anticipating the ripple effects of design changes. The prototype's ability to visualize interdisciplinary dependencies allowed for early error detection and more coordinated workflows. Additionally, MBSE enabled real-time impact analysis of design modifications, helping teams address potential conflicts proactively. By integrating dependency mapping and structured communication pathways, the prototype improved the clarity and accuracy of information flow between disciplines, offering tangible benefits in dynamic project environments.

Despite these strengths, several challenges were identified. Effective implementation of MBSE methods requires precise input data, consistent modeling standards, and significant data management resources, all of which can pose barriers for organizations with limited technical or financial capacity. Integration with existing BIM tools, while achievable, was hindered by compatibility issues and workflow mismatches, limiting the seamless adoption of MBSE practices. Furthermore, reliance on structured, data-driven approaches raised concerns about reduced creative freedom, as such systems may inadvertently favor conventional solutions over innovative designs. Questions about ROI, particularly in terms of training, maintenance, and software costs, further highlighted the need for a balanced approach to MBSE integration.

From an organizational perspective, successful adoption of MBSE depends on overcoming communication gaps between technical and non-technical teams. Establishing standardized modeling protocols and fostering real-time data exchange across disciplines is critical to reducing inefficiencies and improving collaboration. Additionally, tools must address the challenge of phase transitions in projects, ensuring that disruptions between stages are minimized to maintain timelines and project quality.

To enhance the use of MBSE in the practical field, several recommendations emerge. Scalable tools that begin with entry-level functionalities can encourage broader adoption while making space for the integration of new tools. Standardized protocols for modeling and BIM workflows can ensure consistency and reliability, enhancing collaboration between teams. Moreover, developing adaptive and transparent systems, potentially incorporating machine learning or hybrid approaches, can address unforeseen changes while building trust through clear decision-making processes.

RQ: How can engineers in a BIM environment use MBSE to visualize interdependencies between configurations and analyze the impact of design changes?

Based on the research findings from the SQs, MBSE methods can significantly enhance the visualization of configurations and contribute to impact analysis within a BIM environment. These will be summarized in this section. Visualization of interdependencies is made possible with the integration of interdisciplinary dependency mapping, real-time interconnectivity, and enhanced decision support. MBSE methods allow engineers to map relationships between building elements and system components. This mapping enables early detection of potential conflicts and inefficiencies. Furthermore can tools like DTs and DTHs synchronize updates across disciplines, ensuring that changes in one domain are reflected universally. This prevents fragmented configurations and improves overall project alignment. Finally, DSM visualizations facilitate a better understanding of system interrelations, helping engineers to identify the type of interdependency.

Providing impact analysis of design changes is possible due to the support of MBSE methods by real-time analysis of how changes in one configuration affect elements from other disciplines. The use of DSM provides a systematic way to anticipate the domino effect on system structures from design changes. It also provides more efficient cost and risk estimation. The integration of BIM with MBSE enables automated simulations and cost analysis, helping teams estimate the implications of changes more accurately, The mock-up prototype demonstrated the ability to simulate design modifications, offering insights into potential outcomes and risks before implementation of the change.

The research further aimed to find solutions for real-world applications, identifying the strengths of MBSE in practice, as well as finding challenges and limitations. These obstacles can then be used to find routes for further implementation strategies in the future. Starting with the strengths of MBSE in practice, the following points were identified in the Discussion section; conflict mitigation, collaboration across disciplines, and error reduction. By visualizing interdependencies, MBSE aids in identifying and resolving conflicts early in the design process. Real-time updates and shared data streams help improve communications and teamwork among diverse engineering teams. And lastly, Ultimately reducing the likelihood of errors stemming from fragmented communication or misaligned system components.

Although the strengths are significant, several challenges and limitations were identified during the demonstration and further in the Discussion section. The challenges were technical barriers, integration with existing tools, scalability and accessibility, and organizational motivation. The complexity of MBSE tools requires training and expertise, which may be a constraint for smaller organizations. Furthermore, the integration with multiple BIM platforms other than Revit is challenging since it was not tested in this research. Scalability and accessibility should be provided by entry-level tools to encourage broader adoption. The final challenge involves non-technical barriers, such as communication gaps and resistance to change.

The following section will conclude the implementation strategies to answer the question of how engineers can use MBSE methods within CM in a BIM environment. In short, these are the standardization of processes, incremental adoption, cross-disciplinary training, and enhanced tools and features. Starting with the standardization of processes, by establishing consistent modeling protocols and methodologies the variability in tool interpretation can be reduced. this will improve the accuracy of the models. The next strategy involves incremental adoption for all AEC disciplines. Developing scalable, user-friendly tools with logical functionalities can lower the entry barrier for MBSE integration. Furthermore, cross-disciplinary training should be exercised to encourage knowledge sharing between technical and non-technical teams. So they can create a work ethic of collaboration and improve model interpretation. The final strategy involves enhanced tools and features. Future developments should focus on dependency categorization, automated alerts, comprehensive change tracking, and real-time analysis capabilities.

Engineers in a BIM environment can leverage MBSE to bridge the gap between configuration management and real-time decision-making. While MBSE offers transformative potential for improving efficiency, collaboration, and error detection, its full adoption in the real world requires addressing technical and organizational challenges. By combining BIM and MBSE methodologies, teams can enhance project outcomes, paving the way for smarter, more integrated construction management practices.

7.2 Recommendations & further research

Recommendations for practical application

Based on the findings, implementations, and limitations of this research, the following practical steps are proposed to guide future research integrating MBSE within BIM environments to improve CM.

- **Guidelines for MBSE integration:** Companies should establish clear guidelines on how MBSE methods such as DTs, DTH, and DSM can be integrated into BIM workflows. This will ensure project managers and teams have a structured approach to applying these advanced techniques.
- **Data management and version control:** It is recommended that companies invest in tools that enable real-time data synchronization and robust version control across disciplines. This can help minimize errors caused by fragmented or outdated data. Special attention should be given to ensuring the accuracy and reliability of input data to optimize the performance of MBSE-enabled BIM systems.
- **Training and capacity building:** Project teams should receive training on the use of MBSE and BIM tools to ensure seamless adoption and effective application. Workshops should focus on bridging gaps between disciplines, improving understanding of system interdependencies, and fostering collaboration.
- **Invest in tools:** It is advisable to prioritize the use of open standards (e.g., IFC) to improve interoperability between different BIM and MBSE platforms. Companies should adopt scalable tools that can accommodate the varying needs of small-scale and large-scale projects alike.
- **Pilot and validate tools in real projects:** Pilot testing of MBSE-integrated BIM tools in real-world construction projects is recommended to validate their effectiveness and identify practical challenges. Companies should track performance metrics such as cost savings, conflict resolution time, and project efficiency to assess the ROI of implementing these tools.

Recommendations for further research

While this research provided valuable insights into MBSE and BIM integration, several opportunities for future studies remain:

- **Explore alternative MBSE techniques:** Further research is required to establish the applicability of other MBSE techniques, such as model-based simulations and system dynamics, to enhance CM practices in construction. To better understand the implications of these results, future studies could investigate how these methods interact with BIM in dynamic, multi-stakeholder environments.
- **Address scalability:** Future studies should validate the scalability of MBSE methods in large, complex construction projects. This could include testing the prototype with larger data sets and more diverse project teams. Long-term studies could provide insights into the long-term benefits of MBSE-BIM integration on project outcomes.
- **Investigate organizational factors:** Future research could explore how organizational culture, team dynamics, and resistance to change impact the adoption of MBSE methods in construction management. Studies could also identify strategies to address these barriers and promote a collaborative, systems-oriented approach within organizations.
- **Investigate data management:** As this research was limited by data accuracy and compatibility, future research should focus on developing advanced data validation techniques and interoperable systems. Studies could explore how emerging technologies, such as blockchain or artificial intelligence, can improve data reliability and system integration.
- **Develop industry-specific adaptations:** Future research could investigate how MBSE tools can be tailored to specific sectors within the construction industry, such as residential, commercial, or infrastructure projects. Studies could also focus on adapting MBSE-enabled BIM tools for smaller firms with limited resources.

References

Au, J., & Ravindranath, R. (2020). Bridging the Gap Between Architects, Engineers and Other Stakeholders in Complex and Multidisciplinary Systems – a Holistic, Inclusive and Interactive Design Approach. *INCOSE International Symposium*, *30*(1), 153–167. https://doi.org/10.1002/j.2334-5837.2020.00714.x

Azhar, S. (2011). Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. *Leadership and Management in Engineering*, *11*(3), 241–252. https://doi.org/10.1061/(asce)lm.1943-5630.0000127

Baccarini, D. (1996). The concept of project complexity—a review. *International journal of project management*, *14*(4), 201–204. https://doi.org/10.1016/0263-7863(95)00093-3

Bahill, A. T., & Dean, F. F. (1996). WHAT IS SYSTEMS ENGINEERING? a CONSENSUS OF SENIOR SYSTEMS ENGINEERS1. *INCOSE International Symposium*, *6*(1), 500–505. https://doi.org/10.1002/j.2334-5837.1996.tb02045.x

Bano, M., Imtiaz, S., Ikram, N., Niazi, M., & Usman, M. (2012). Causes of requirement change - a systematic literature review. *EASE 2012*. https://doi.org/10.1049/ic.2012.0003

Bastian, M., Heymann, S., & Jacomy, M. (2009). Gephi: An Open Source Software for Exploring and Manipulating Networks. *Proceedings of the International AAAI Conference on Web and Social Media*, *3*(1), 361–362. https://doi.org/10.1609/icwsm.v3i1.13937

Borrmann, A., König, M., Koch, C., & Beetz, J. (2018, January). *Building Information modeling: why? what? how?* https://doi.org/10.1007/978-3-319-92862-3\{_}1

Bosch-Rekveldt, M., Bakker, H., Hertogh, M., & Mooi, H. (2014, October). *Drivers of Complexity in Engineering Projects*. https://doi.org/10.1007/978-3-319-05915-0\{_}18

Buede, D. M. (2024, January). *The Engineering Design of Systems : Models and Methods*. https://ci.nii.ac.jp/ncid/BA45532436

Carayannis, E. G., Samara, E. T., & Bakouros, Y. L. (2014, September). *Innovation systems*. https://doi.org/10.1007/978-3-319-11242-8\{_}5

Cha, H., & Kim, J. (2020). A study on 3D/BIM-based on-site performance measurement system for building construction. *Journal of Asian architecture and building engineering*, *19*(6), 574–585. https://doi.org/10.1080/13467581.2020.1763364

Chen, L., & Whyte, J. (2020). Analysing Interdependencies of Complex Engineering Systems Using a Digital Twin-Driven Design Structure Matrix. *Construction Research Congress 2020*. https://doi.org/10.1061/9780784482865.045

Chown, B., & Blyler, J. (2018). Increasing the productivity of an MBSE development team throughout the system design lifecycle. *2018 Annual IEEE International Systems Conference (SysCon)*, 1–3. https://doi.org/10.1109/syscon.2018.8369587

Clark, J. O. (2009). System of Systems Engineering and Family of Systems Engineering from a standards, V-Model, and Dual-V Model perspective. *IEEE*. https://doi.org/10.1109/systems.2009.4815831

Clauset, A., Moore, C., & Newman, M. E. J. (2008). Hierarchical structure and the prediction of missing links in networks. *Nature*, *453*(7191), 98–101. https://doi.org/10.1038/nature06830

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2008, March). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*. http://ci.nii.ac.jp/ncid/BA87578739

Eftekhari, N. A., Mani, S., Bakhshi, J., & Mani, S. (2022). Project Manager Competencies for Dealing with Socio-Technical Complexity: A Grounded Theory Construction. *Systems*, *10*(5), 161. https://doi.org/10.3390/systems10050161

Eppinger, S. D., & Browning, T. R. (2012, January). *Design Structure Matrix Methods and Applications*. https://doi.org/10.7551/mitpress/8896.001.0001

Esser, S., Vilgertshofer, S., & Borrmann, A. (2022). Graph-based version control for asynchronous BIM collaboration. *Advanced Engineering Informatics*, *53*, 101664. https://doi.org/10.1016/j.aei.2022.101664

Fayez, M., Axelsson, P., Oloufa, A. A., & Hosni, Y. (2003). DSM Versus CPM: Issues for Planning Design amp; Construction Activities. https://doi.org/10.1061/40671(2003)22

Freddi, A., & Salmon, M. (2018, July). *Requirements and Specifications*. https://doi.org/10.1007/978-3-319-95342-7\{_}3

Gilb, T., & Maier, M. W. (2005). 11.4.2 Managing Priorities: A Key to Systematic Decision-Making. *INCOSE International Symposium*, *15*(1), 1687–1705. https://doi.org/10.1002/j.2334-5837.2005.tb00782.x

Graignic, P., Vosgien, T., Jankovic, M., Tuloup, V., Berquet, J., & Troussier, N. (2013). Complex System Simulation: Proposition of a MBSE Framework for Design-Analysis Integration. *Procedia Computer Science*, *16*, 59–68. https://doi.org/10.1016/j.procs.2013.01.007

Grieves, M. W. (2019, January). *Virtually Intelligent Product Systems: Digital and Physical Twins*. https://doi.org/10.2514/5.9781624105654.0175.0200

Guess, V. C. (2021, February). *Vincent C. Guess*. Dorrance Publishing.

Ismail, A., Strug, B., & Ślusarczyk, G. (2018, January). *Building Knowledge Extraction from BIM/IFC Data for Analysis in Graph Databases*. https://doi.org/10.1007/978-3-319-91262-2\{_}57

Jensen, P., Olofsson, T., & Johnsson, H. (2012). Configuration through the parameterization of building components. *Automation in construction*, *23*, 1–8. https://doi.org/10.1016/j.autcon.2011.11.016

Langroodi, B. P., & Staub-French, S. (2012). Change Management with Building Information Models: A Case Study. *Construction Research Congress 2012*, 1182–1191. https://doi.org/10.14288/1.0050914

Lindkvist, C., Stasis, A., & Whyte, J. (2013). Configuration management in complex engineering projects. *Procedia CIRP*, *11*, 173–176. https://doi.org/10.1016/j.procir.2013.07.046

Liu, F., Jallow, A. K., Anumba, C. J., & Wu, D. (2014). A Framework for Integrating Change Management with Building Information Modeling. *Computing in Civil and Building Engineering (2014)*. https://doi.org/10.1061/9780784413616.055

Madni, A. M., & Sievers, M. (2018). Model-based systems engineering: Motivation, current status, and research opportunities. *Systems Engineering*, *21*(3), 172–190. https://doi.org/10.1002/sys.21438

Mangialardi, G., Di Biccari, C., Pascarelli, C., & Lazoi, M. (2017, January). *BIM and PLM Associations in Current Literature*. https://doi.org/10.1007/978-3-319-72905-3\{_}31

McKay, A., Rice, H. P., Chau, H. H., & De Pennington, A. (2021). MAINTAINING CONSISTENCY ACROSS DESIGN DESCRIPTIONS IN ENGINEERING PRODUCT DEVELOPMENT. *Proceedings of the Design Society*, *1*, 1987–1996. https://doi.org/10.1017/pds.2021.460

Mitchell, M., & Newman, M. (2002). Complex systems theory and evolution. https://works.bepress.com/melanie_mitchell/18/

Mokhtar, A., Bédard, C., & Fazio, P. (1998). Information Model for Managing Design Changes in a Collaborative Environment. *Journal of computing in civil engineering*, *12*(2), 82–92. https://doi.org/10.1061/(asce)0887-3801(1998)12:2(82

Oloufa, A. A., Hosni, Y. A., Fayez, M., & Axelsson, P. (2004). Using DSM for modeling information flow in construction design projects. *Civil Engineering and Environmental Systems*, *21*(2), 105–125. https://doi.org/10.1080/10286600310001638474

Parnell, G. S., Kenley, C. R., Whitcomb, C. A., & Palanikumar, K. (2021). System design and engineering trade-off analytics: State of the published practice. *Systems Engineering*, *24*(3), 125–143. https://doi.org/10.1002/sys.21571

Pavalkis, S. (2016). Towards Industrial Integration of MBSE into PLM for Mission-Critical Systems. *INCOSE International Symposium*, *26*(1), 2462–2477. https://doi.org/10.1002/j.2334-5837.2016.00306.x

Piccirillo, I. N., De Almeida, L. F. M., De Araújo, L. Q., & Da Silva, S. L. (2017). Design Structure Matrix and Project Management: bibliometric analysis. *Product Management Development*, *15*(2), 86–91. https://doi.org/10.4322/pmd.2017.008

Pilehchian, B., Staub-French, S., & Nepal, M. P. (2015). A conceptual approach to track design changes within a multi-disciplinary building information modeling environment. *Canadian Journal of Civil Engineering*, *42*(2), 139–152. https://doi.org/10.1139/cjce-2014-0078

Reefman, R. (2022, September). *Configiratiemanagement* (1st ed.). Maj Publishing.

Sandars, J., & Goh, P.-S. (2020). Design thinking in medical education: The key features and practical application. *Journal of Medical Education and Curricular Development*, *7*, 2382120520926518.

Segovia, M., & Garcia-Alfaro, J. (2022). Design, Modeling and Implementation of Digital Twins. *Sensors*, *22*(14), 5396. https://doi.org/10.3390/s22145396

Senescu, R. R., Head, A. W., Steinert, M., & Fischer, M. A. (2012, September). *GENERATING a NETWORK OF INFORMATION DEPENDENCIES AUTOMATICALLY*. https://doi.org/10.3139/9783446434127.012

Sun, M., Fleming, A., Senaratne, S., Motawa, I., & Yeoh, M. L. (2006). A Change Management Toolkit for Construction Projects. *Architectural Engineering and Design Management*, *2*(4), 261–271. https://doi.org/10.1080/17452007.2006.9684621

Sun, Z., Lorscheid, I., Millington, J. D., Lauf, S., Magliocca, N. R., Groeneveld, J., Balbi, S., Nolzen, H., Müller, B., Schulze, J., et al. (2016). Simple or complicated agent-based models? a complicated issue. *Environmental Modelling & Software*, *86*, 56–67.

Tiwari, S., & Franklin, H. (1994). Automated configuration management in concurrent engineering projects. *Concurrent Engineering*, *2*(3), 149–161. https://doi.org/10.1177/1063293x9400200302

Wang, K., Guo, F., Zhang, C., & Schaefer, D. (2022). From Industry 4.0 to Construction 4.0: barriers to the digital transformation of engineering and construction sectors. *Engineering Construction Architectural Management*, *31*(1), 136–158. https://doi.org/10.1108/ecam-05-2022-0383

Wood, H., & Ashton, P. (2009). Factors of complexity in construction projects [Proceedings 25th annual ARCOM conference ; Conference date: 07-09-2009]. *Proceedings 25th annual ARCOM conference*, *2*, 857–866.

Wymore, A. W. (2018, May). *Model-Based Systems Engineering*. https://doi.org/10.1201/9780203746936

Xiao, Y.-Q., Li, S.-W., & Hu, Z.-Z. (2019). Automatically Generating a MEP Logic Chain from Building Information Models with Identification Rules. *Applied Sciences*, *9*(11), 2204. https://doi.org/10.3390/app9112204

Yassine, A. (2004). An introduction to modeling and analyzing complex product development processes using the design structure matrix (dsm) method. *Urbana*, *51*(9), 1–17.

Zou, M., Vogel-Heuser, B., Sollfrank, M., & Fischer, J. (2020). A Cross-disciplinary Model-Based Systems Engineering Workflow of Automated Production Systems Leveraging Socio-technical Aspects. https://doi.org/10.1109/ieem45057.2020.9309803

Appendix A

Phase I

A.1 Keywords

Theme	Keywords	Reference
Complex projects	Complex construction projects - project complexity - Complicated vs complex - Dimensions of complexity	Sandars & Goh, 2020; Z. Sun et al., 2016; Baccarini, 1996; Bosch-Rekveldt et al., 2014
Complex projects & MBSE	Model-Based Systems Engineering - Complex projects - Configuration - Digitalization	Cha & Kim, 2020; Eftekhari et al., 2022; Reefman, 2022; Bano et al., 2012; Wood & Ashton, 2009
Configuration	Configuration - Configuration Management	Jensen et al., 2012; Reefman, 2022
BIM & configuration	Configuration - Configuration & BIM - Configuration construction sector - Change management - BIM - Design changes construction sector	Azhar, 2011; Borrmann et al., 2018; Langroodi & Staub-French, 2012; Pilehchian et al., 2015; Reefman, 2022; Mangialardi et al., 2017; Liu et al., 2014; Z. Sun et al., 2016
BIM configuration methods	BIM - Configuration methods - MBSE	Madni & Sievers, 2018; Reefman, 2022; Graignic et al., 2013
DT & DTH in MBSE	Digital Twin - Digital Thread - MBSE - Construction sector	Segovia & Garcia-Alfaro, 2022; Grieves, 2019; Reefman, 2022; Madni & Sievers, 2018; Chow & Blyder, 2018
DSM to visualize DTH	Design Structure Matrix - Digital Thread - Project Management	Eppinger & Browning, 2012; Piccirillo et al., 2017; Yassine, 2004
Integration obstacles	MBSE integration - Industrial integration - Construction digitalization - Digital transformation	Chen & Whyte, 2020; Pavalkis, 2016; Zou et al., 2020; Wang et al., 2022; Senescu et al., 2012

Table A.1: Themes, Keywords, and References for the introduction

Theme	**Keywords**	**Reference**
Fragmentation of CM across disciplines	Fragmentation construction industry - Construction sector disciplines - Configuration - MBSE - DT	Eppinger & Browning, 2012; Reefman, 2022; Mokhtar et al., 1998; Pilehcian et al., 2015; Madni & Sievers, 2018; Grieves, 2019
Underutilization of DT and DTH	DT - DTH	Reefman, 2022; Segovia & Garcia-Alfaro, 2022
Limited application of DSM	DSM - CM - System requirements - DSM application - DSM practice	Eppinger & Browning, 2012; Freddi & Salmon, 2018; Oloufa et al., 2004; Chen & Whyte, 2020
Organizational barriers	MBSE - DSM - DT - DTH - Change management - Implementation - Organizational barriers	M. Sun et al., 2006
Potential contributions	–	Eppinger & Browning, 2012; Madni & Sievers, 2018; Reefman, 2022; Segovia & Garcia-Alfaro, 2022; Freddi & Salmon, 2018; Chen & Whyte, 2020; M. Sun et al., 2006

Table A.2: Themes, Keywords, and References for the research gap

Theme	Keywords	Reference
What is SE	Systems Engineering - Complex Systems	Carayannis et al., 2014
Systems	–	Mitchell & Newman, 2002; Clauset et al., 2008; Carayannis et al., 2014
Definition SE	Systems Engineering - Construction industry - MBSE	Buede, 2024; Wymore, 2018; Bahil & Dean, 1996
V&V	V&V - Construction projects - Configuration Management - Systems of systems	Madni & Sievers, 2018; Reefman, 2022; Clark, 2009
Challenges in SE	Systems Engineering - MBSE - Trade-offs - Challenges - Benefits - Pitfalls - SE & AEC	Eppinger & Browning, 2012; Madni & Sievers, 2018; Parnell et al., 2021; Gilb & Maier, 2005; Au & Ravindranath, 2020
Benefits of SE	–	Bahil & Dean, 1996
MBSE	MBSE - Configurations - Construction industry	Madni & Sievers, 2018; Reefman, 2022
Characteristics of MBSE	–	Madni & Sievers, 2018
Benefits of MBSE	–	Madni & Sievers, 2018
Pitfalls of MBSE	–	Madni & Sievers, 2018
What is BIM	Building Information Modeling - Trends - Benefits - Challenges	Wood & Ashton, 2009; Azhar, 2011; Reefman, 2022
Difference MBSE & BIM	MBSE - BIM - MBSE & BIM difference	Madni & Sievers, 2018; Azhar, 2011
Implementing MBSE in BIM	–	Guess, 2021
One configuration	Configurations in construction - Configuration Management	Jensen et al., 2012; Madni & Sievers, 2018; Freddi & Salmon, 2018; Reefman, 2022; Guess, 2021
DT	Digital Twin - MBSE - Automated Digital Twin	Segovia & Garcia-Alfaro, 2022; Reefman, 2022; Tiwari & Franklin, 1994
MBSE and DT integration	–	Madni & Sievers, 2018
Application of DT	–	Grieves, 2019; Reefman, 2022
DTH	Digital Thread - Configurations - Consistent configurations - MBSE - Change Management - Digital link	Reefman, 2022
Linking configurations	–	McKay et al., 2021; Reefman, 2022; Madni & Sievers, 2018
Digital link	–	Madni & Sievers, 2018
Following DTH	–	Langroodi & Staub-French, 2012
DSM	Design Structure Matrix - Digital link - System interdependencies - Configuration management	Eppinger & Browning, 2012; Yassine, 2004; Chen & Whyte, 2020
Using DSM to link dependencies	–	Chen & Whyte, 2020; Eppinger & Browning, 2012; Yassine, 2004; Fayez et al., 2003; Lindkvit et al., 2013

Table A.3: Themes, Keywords, and References

Appendix B

Phase II

B.1 Mock-up prototype

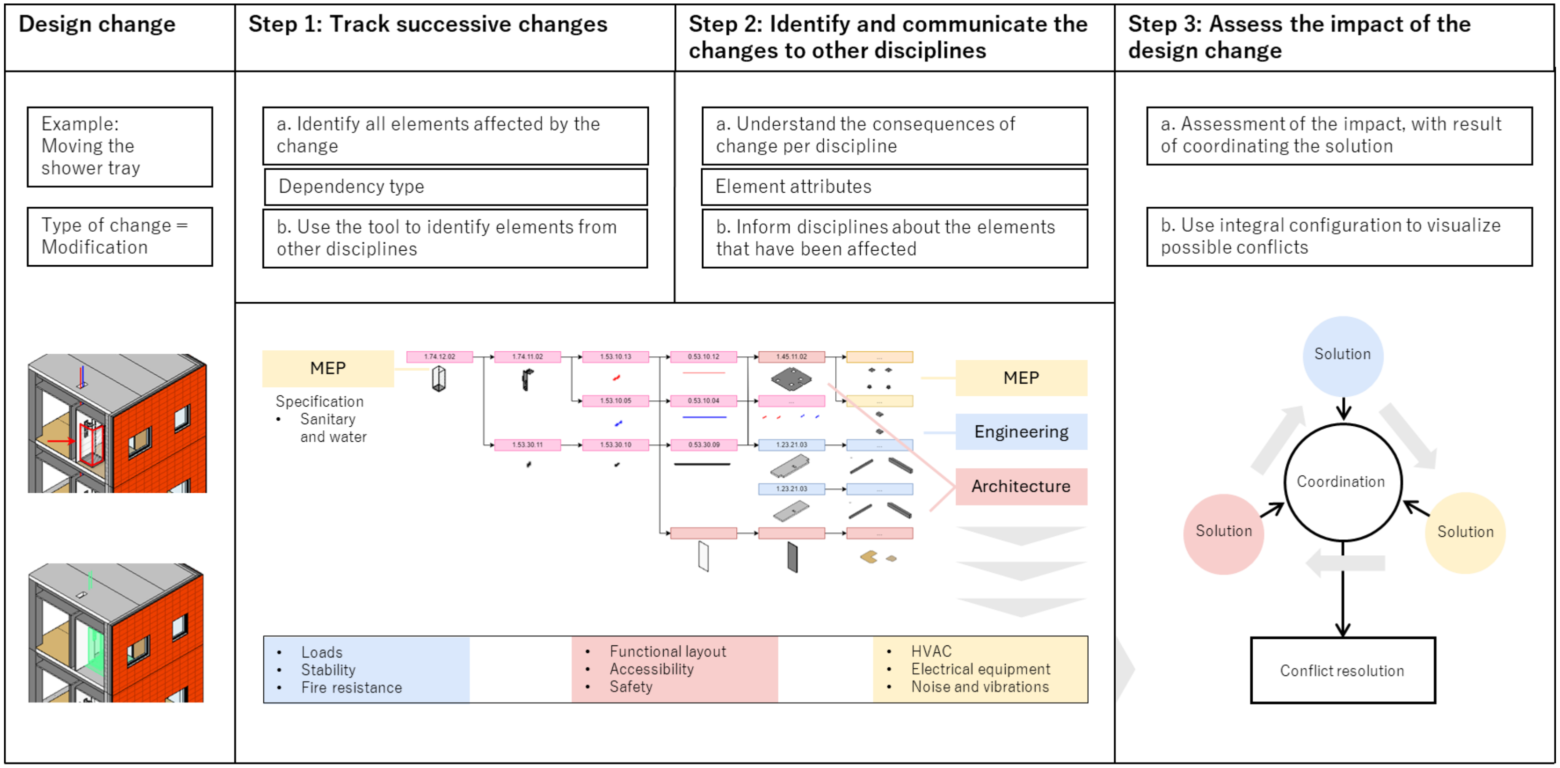
Table B.1: Elements of the prototype and their references with integration details

Prototype element	**References**	**Integration description**
Configuration	Jensen et al. (2012)	Configurations define how elements from various disciplines (structural, architectural, MEP) are organized. Each discipline's elements are arranged to meet specific functional and design objectives, ensuring effective interdisciplinary collaboration.
Design changes	Langroodi and Staub-French (2012), Pilehchian et al. (2015)	The prototype allows for additions, modifications, and deletions of elements, reflecting changes in design. These changes are tracked and managed to maintain consistency across the entire model, influencing the configuration and dependencies of elements.
Element attributes (geometry, position, specification)	Langroodi and Staub-French (2012)	Elements have key attributes—geometry (physical shape), position (location within the system), and specification (functional and performance details). These attributes ensure that each element is correctly placed and meets the project's requirements, and they interact with other components.
Dependency types (spatial and analytical)	Langroodi and Staub-French (2012)	Dependencies define the relationships between elements, including spatial (e.g., Connected To, Supported By) and analytical (e.g., Structural Integrity, Mechanical Interaction). These relationships are essential for maintaining the structural and functional integrity of the model.
Inter-element dependencies	Reefman (2022), Mangialardi et al. (2017)	Dependencies between elements ensure that any changes in one component are accurately reflected across related components. These dependencies are critical for a cohesive design process, ensuring that changes propagate smoothly and maintain the integrity of the entire system.

Table B.2: Integration of MBSE methods in the mock-up prototype

MBSE Method	Integration into the mock-up Ppototype	References
Digital Twin (DT)	The DT provides a virtual representation of physical structures, integrating discipline-specific configurations (Structural, Architectural, MEP). Each discipline is displayed with its elements in three distinct views: Exterior, Interior, and Section, ensuring real-time updates of the building's structure and functionality.	(Segovia & Garcia-Alfaro, 2022), (Reefman, 2022)
Digital Threads (DTH)	DTH links elements across different disciplines (Structural, Architectural, MEP), ensuring that any modification in one configuration is reflected in others. These threads connect dependencies between elements, enabling seamless data flow and change propagation across disciplines.	(Reefman, 2022), (McKay et al., 2021)
Design Structure Matrix (DSM)	The DSM visualizes interdependencies between elements across different disciplines. It helps track how changes in one element affect others, aiding in interdisciplinary coordination and managing design modifications. The DSM is structured as a matrix, organized by discipline, showing both intra- and inter-disciplinary dependencies.	(Eppinger & Browning, 2012), (Madni & Sievers, 2018)

B.2 Practical guideline



Design change

Example: Moving the shower tray

Type of change = Modification

Step 1: Track successive changes

a. Identify all elements affected by the change

Dependency type

b. Use the tool to identify elements from other disciplines

Step 2: Identify and communicate the changes to other disciplines

a. Understand the consequences of change per discipline

Element attributes

b. Inform disciplines about the elements that have been affected

Step 3: Assess the impact of the design change

a. Assessment of the impact, with result of coordinating the solution

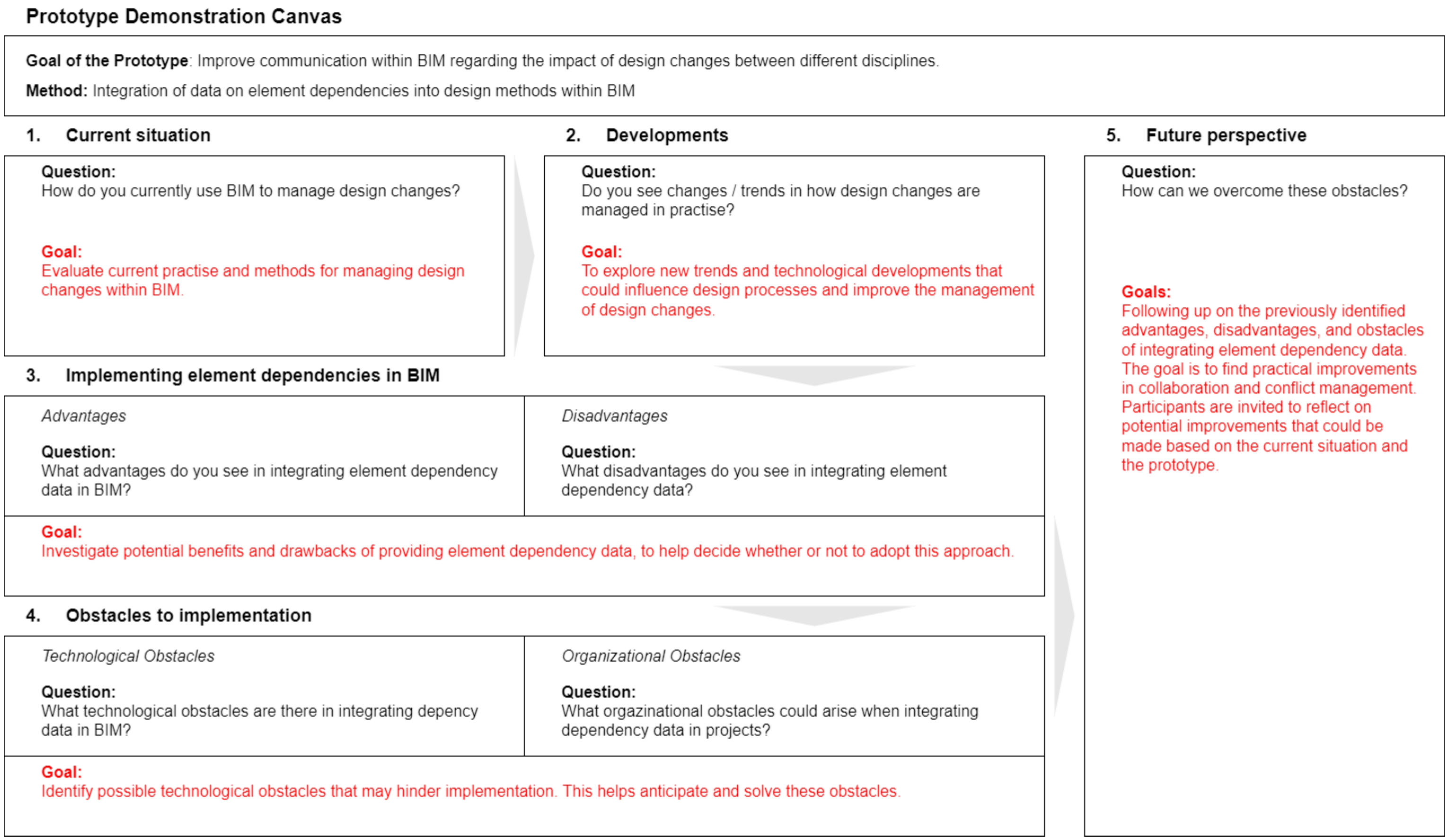
b. Use integral configuration to visualize possible conflicts

Figure B.1: Guideline for implementation

Appendix C

Phase III

C.1 The canvas



Prototype Demonstration Canvas

Goal of the Prototype: Improve communication within BIM regarding the impact of design changes between different disciplines.

Method: Integration of data on element dependencies into design methods within BIM

1. Current situation

Question:
How do you currently use BIM to manage design changes?

Goal:
Evaluate current practise and methods for managing design changes within BIM.

2. Developments

Question:
Do you see changes / trends in how design changes are managed in practise?

Goal:
To explore new trends and technological developments that could influence design processes and improve the management of design changes.

3. Implementing element dependencies in BIM

Advantages

Question:
What advantages do you see in integrating element dependency data in BIM?

Disadvantages

Question:
What disadvantages do you see in integrating element dependency data?

Goal:
Investigate potential benefits and drawbacks of providing element dependency data, to help decide whether or not to adopt this approach.

4. Obstacles to implementation

Technological Obstacles

Question:
What technological obstacles are there in integrating depency data in BIM?

Organizational Obstacles

Question:
What orgazinational obstacles could arise when integrating dependency data in projects?

Goal:
Identify possible technological obstacles that may hinder implementation. This helps anticipate and solve these obstacles.

5. Future perspective

Question:
How can we overcome these obstacles?

Goals:
Following up on the previously identified advantages, disadvantages, and obstacles of integrating element dependency data. The goal is to find practical improvements in collaboration and conflict management. Participants are invited to reflect on potential improvements that could be made based on the current situation and the prototype.

Figure C.1: The Canvas for the demonstration

Question 1: Describe how you use BIM tools currently

Participant	Response
1	Utilizing visual tools in Revit and managing issues through ACC.
2	Primarily focused on issue management using ACC or Bimcollab.
3	Not currently using BIM tools but familiar with issue management features.
4	Using BIM for documentation and coordination but interested in expanding to scheduling.
5	Only minimally engaged with BIM, usually through shared documents from other teams.
6	Uses BIM to check models and resolve clashes in design coordination.
7	Primarily uses BIM for clash detection and visualization in Navisworks.
8	Applies BIM for project visualization and initial design reviews.
9	Uses BIM for managing data and documentation workflows.
10	Involved in BIM for quality control and design validation.
11	Employs BIM for construction planning and site coordination.
12	Uses BIM models for spatial analysis and project reviews.
13	Primarily uses BIM for project documentation and sharing updates.
14	Engages with BIM tools for interdisciplinary coordination meetings.
15	Involved with BIM for structural analysis and compliance checks.

Question 2: Is there a trend toward more digital documentation?

Participant	Response
1	Yes, the use of 3D modeling is increasing, with less reliance on paper documentation.
2	Yes, there is an increasing emphasis on documentation.
3	No, some teams still rely heavily on traditional methods.
4	Yes, but the shift is slow and inconsistent across projects.
5	Yes, but with reservations about accessibility and training.
6	Yes, digital documentation is becoming more common in all projects.
7	Yes, paper documents are gradually being replaced by digital models.
8	Yes, digital documentation is more frequently required by clients.
9	Yes, a strong trend toward fully digital records.
10	Yes, but implementation varies depending on project needs.
11	Yes, though the change is gradual in some regions.
12	Yes, moving toward digital, although some paper is still used.
13	Yes, digital documentation is a growing requirement.
14	Yes, and digital standards are evolving accordingly.
15	Yes, digital documentation is becoming more prevalent.

Question 3: List the pros and cons of current BIM tools

Participant	Aspect	Response
1	Pro	Enhanced ability to visualize connections and quickly identify potential issues.
	Con	Requires a more time-intensive setup process for effective implementation.
2	Pro	Provides timely notifications about changes and updates.
	Con	Need to establish standardization protocols for implementation.
3	Pro	Improves collaboration and document control across teams.
	Con	Limited by software compatibility issues across platforms.
4	Pro	Increases coordination and reduces errors in documentation.
	Con	Steep learning curve, particularly for less tech-savvy team members.
5	Pro	Streamlines communication and data sharing among project stakeholders.
	Con	Requires significant investment in training and technology upgrades.
6	Pro	Enhances accuracy and consistency in documentation.
	Con	Some users find the tools difficult to navigate.
7	Pro	Improves conflict detection and minimizes rework.
	Con	Higher upfront costs and complexity in adoption.
8	Pro	Facilitates better design visualization.
	Con	Technical issues can disrupt workflows.
9	Pro	Encourages a collaborative working environment.
	Con	Dependence on reliable network and software stability.
10	Pro	Supports comprehensive project data management.
	Con	Requires frequent software updates.
11	Pro	Enables early identification of design errors.
	Con	Needs extensive training for full utilization.
12	Pro	Improves clarity and consistency across project stages.
	Con	High hardware requirements and costs.
13	Pro	Aids in real-time project monitoring and control.
	Con	Compatibility issues with legacy systems.
14	Pro	Supports standardization and compliance efforts.
	Con	Limited interoperability with some platforms.
15	Pro	Enhances design quality and reduces revisions.
	Con	Can be overwhelming for new users.

Question 4: What are the technical and organizational challenges of BIM tools?

Participant	Aspect	Response
1	Tech.	Additional software licenses may be necessary for optimal functionality.
	Org.	Introducing another tool may increase administrative overhead.
2	Tech.	Clarifying how this approach integrates with current workflows is essential.
	Org.	Concerns around standardization and collaboration with external parties/library sharing.
3	Tech.	Requires high-performance hardware and regular updates.
	Org.	Resistance from some teams who are accustomed to traditional methods.
4	Tech.	Interoperability issues between different BIM software can slow down processes.
	Org.	Getting buy-in from senior management who may not see immediate value.
5	Tech.	Difficulty integrating with existing legacy systems in the company.
	Org.	Lack of skilled personnel and comprehensive training programs.
6	Tech.	Limited compatibility with older software versions.
	Org.	Difficulty in aligning teams on consistent usage practices.
7	Tech.	High data storage and backup requirements.
	Org.	Limited BIM experience among some project members.
8	Tech.	Network connectivity issues can disrupt usage.
	Org.	Challenges in adapting workflows to digital processes.
9	Tech.	Need for advanced hardware for optimal performance.
	Org.	Resistance to adopting new digital tools.
10	Tech.	Complex integration with existing digital systems.
	Org.	Initial skepticism from traditional teams.
11	Tech.	Difficulties in synchronizing updates across systems.
	Org.	Communication issues between teams with different BIM familiarity.
12	Tech.	Software maintenance and upgrade demands.
	Org.	Training requirements for successful adoption.
13	Tech.	Compatibility challenges with various formats.
	Org.	Lack of a unified strategy for implementation.
14	Tech.	Risk of data loss with insufficient backups.
	Org.	Difficulties in securing necessary budget for resources.
15	Tech.	Regular software updates needed to avoid bugs.
	Org.	Resistance to change among senior personnel.

Question 5: What further support or resources are needed to use BIM tools effectively?

Participant	Response
1	Additional training sessions on advanced BIM functionalities would be beneficial.
2	Access to more online resources and a dedicated support team for technical issues.
3	A clearer guide on how BIM integrates into our existing workflow is needed.
4	More hands-on workshops focusing on real-world project scenarios.
5	More in-depth tutorials and access to consultants for complex issues.
6	Enhanced user guides and step-by-step documentation for specific tasks.
7	Regular refresher courses on new updates and features in BIM software.
8	Improved access to case studies showcasing successful BIM implementations.
9	Dedicated IT support for troubleshooting BIM-related technical problems.
10	Financial support for upgrading outdated hardware to meet BIM requirements.
11	Regular training sessions on new functionalities and features of the tools.
12	Access to a centralized database of BIM standards and best practices.
13	More training focused on collaboration and sharing features within BIM.
14	Budget for software updates and the hiring of specialized BIM coordinators.
15	Improved online knowledge base and quick-access tutorials for common tasks.

C.2 Prototype validation

Table C.1: Validation of requirements based on participant feedback

Requirement	Validated by Participants	Feedback Summary	References
Interdisciplinary dependency mapping	Partially validated	Participants praised basic visualization of dependencies but noted a lack of standardized dependency categorization (e.g., spatial, functional).	(Reefman, 2022), (McKay et al., 2021), (Chen & Whyte, 2020)
Change tracking and version control	Not validated	Issues with compatibility and difficulty tracking changes effectively were raised. Prototype lacks robust change tracking and version control tools.	(Madni & Sievers, 2018)
Real-time impact analysis	Partially validated	Enhanced visualization of impacts was noted, but some participants questioned if all affected areas were consistently identified across disciplines. Further refinement needed.	(Tiwari & Franklin, 1994)
Automated alerts and notifications	Not fully validated	Some notification features were present but concerns about limited interoperability and accessibility were raised. Further automation and integration needed.	(Langroodi & Staub-French, 2012), (Segovia & Garcia-Alfaro, 2022)
Integration with existing BIM tools	Partially validated	Basic integration with Revit was noted, but compatibility issues with legacy systems and workflows were highlighted. Further improvements needed for better interoperability.	(Grieves, 2019)

C.3 Discussion VS literature

Table C.2: Advantages of the prototype and alignment with literature

Advantage	**Description**	**Resembles literature?**	**References**
Finding the impact of changes	Assesses the impact of design changes on costs, timelines, and elements in real time, aiding decision-making and risk mitigation.	Yes	Azhar (2011), Borrmann et al. (2018), Cha and Kim (2020), Liu et al. (2014), Langroodi and Staub-French (2012)
Cost estimates for specifications	Generates cost projections for components, supporting budget-conscious decisions without compromising quality.	Yes	Azhar (2011), Borrmann et al. (2018), Liu et al. (2014)
Simulating different design choices	Explores and evaluates multiple design options for feasibility, performance, and aesthetics.	Yes	Azhar (2011), Cha and Kim (2020), Pilehchian et al. (2015), Segovia and Garcia-Alfaro (2022)
Analysis of relationships	Maps interdependencies between components, identifies conflicts early, and reduces rework risks.	Yes	Azhar (2011), Borrmann et al. (2018), Bahill and Dean (1996)
Quality checks and assessments	Performs automated checks to ensure regulatory compliance, reduce errors, and improve project quality.	Yes	Azhar (2011), Borrmann et al. (2018), Cha and Kim (2020), Liu et al. (2014), Mangialardi et al. (2017)

Table C.3: Disadvantages of the prototype and alignment with literature

Disadvantage	**Description**	**Resembles literature?**	**References**
Accuracy of parameters	The effectiveness of modeling depends on accurate input data. Inaccurate parameters lead to unreliable simulations and poor decision-making.	Yes	Eppinger and Browning (2012), Madni and Sievers (2018), Wang et al. (2022), Z. Sun et al. (2016), Senescu et al. (2012)
Model interpretation variability	Different stakeholders may interpret models differently, complicating decision-making and requiring consensus.	Yes	Eppinger and Browning (2012), Parnell et al. (2021), Madni and Sievers (2018), Zou et al. (2020)
Increased data management burden	Managing large amounts of data for BIM models can be resource-intensive and divert focus from other critical tasks.	Yes	Chen and Whyte (2020), Eppinger and Browning (2012), Madni and Sievers (2018), Senescu et al. (2012)
Reduced creative freedom	Data-driven modeling may restrict creative flexibility, as it might constrain designers from exploring unconventional solutions.	No	N/A
Models as a support tool, not a solution	BIM models identify issues but don't provide comprehensive solutions; they are a support tool requiring human intervention.	Yes	Eppinger and Browning (2012), Chen and Whyte (2020), Senescu et al. (2012), Bahill and Dean (1996)
Challenges with architectural specifications	Translating abstract architectural specifications into a data-driven framework can be challenging for BIM tools, affecting the accuracy of generated insights.	No	N/A
Return on investment (ROI)	The ROI of BIM tools is questioned, weighing the costs of software, training, and data upkeep against the benefits.	Yes	Azhar (2011), Madni and Sievers (2018)

Table C.4: Technological obstacles and alignment with literature

Obstacle	**Description**	**Resembles literature?**	**References**
Time constraints	Implementing and maintaining modeling technologies can extend project timelines and require additional resources, creating bottlenecks.	Yes	Zou et al. (2020), Madni and Sievers (2018)
Technical feasibility and requirements	Advanced modeling tools require specialized expertise and resources, creating obstacles for teams lacking these resources.	No	N/A
Predictive design limitations	Predictive models rely on real-time data but cannot capture unforeseen changes, limiting their reliability.	Yes	Madni and Sievers (2018)
Transparency issues with AI "black box" models	AI models can be opaque, leading to trust issues as users struggle to understand the logic behind outputs.	Yes	Madni and Sievers (2018), Chen and Whyte (2020), Chown and Blyler (2018)

Table C.5: Organizational obstacles and alignment with literature

Obstacle	**Description**	**Resembles Literature?**	**References**
Cross-functional collaboration challenges	Effective communication across engineering and design functions is often challenging, leading to silos and reduced efficiency.	Yes	Au and Ravindranath (2020), Eftekhari et al. (2022), Chen and Whyte (2020), Madni and Sievers (2018)
Data exchange and accuracy	Inconsistent or delayed data exchange can lead to inaccuracies, requiring revalidation and adjustments.	Yes	Borrmann et al. (2018), Liu et al. (2014), Oloufa et al. (2004), Pilehchian et al. (2015), Senescu et al. (2012)
Phase transition and workflow continuity	Poor phase transitions can introduce errors and inefficiencies if teams are not aligned on goals, data, and timelines.	Yes	Liu et al. (2014), Oloufa et al. (2004), Eppinger and Browning (2012), Reefman (2022)
Stakeholder coordination	Miscommunication and errors arise when stakeholders have differing expectations or lack access to the same information.	Yes	Borrmann et al. (2018), Oloufa et al. (2004), Pilehchian et al. (2015)
Tool integration complexity	Integrating multiple tools across disciplines can create fragmented workflows and data incompatibility.	Yes	Borrmann et al. (2018), Liu et al. (2014), Wang et al. (2022), Madni and Sievers (2018), Yassine (2004)

Table C.6: Future perspectives on modeling tools and BIM protocols

Perspective	**Description**	**Resembles literature?**	**References**
Realistic entry-level models for broader adoption	Future BIM-tool initiatives may focus on creating accessible and intuitive entry-level tools to encourage adoption across interdisciplinary teams, with simplified initial interactions to improve usability and reduce resistance to adoption.	Yes	Azhar (2011), Liu et al. (2014), Madni and Sievers (2018)
Establishing systematic disciplines in modeling	Systematic methodologies and best practices in modeling are essential for ensuring consistency and collaboration. By adopting unified frameworks like DSM and MBSE, teams can standardize data creation and management, ensuring reliable workflows.	Yes	Eppinger and Browning (2012), Madni and Sievers (2018), Wymore (2018)
BIM protocols for seamless collaboration	Standardized BIM protocols enable consistent data exchange, fostering collaboration across multidisciplinary teams. Clear data formats and guidelines reduce miscommunication and ensure seamless information flow.	Yes	Azhar (2011), Cha and Kim (2020), Liu et al. (2014), Mangialardi et al. (2017)

C.4 Problems from practice and solutions from theory

Table C.7: Disadvantages of the prototype and proposed solutions

Problem	**Description**	**Solution**	**References**
Accuracy of parameters	Inaccurate input data can lead to unreliable simulations and suboptimal decisions, diminishing the model's ability to simulate real-world scenarios.	Improve data accuracy and integration, using standardized frameworks to ensure data quality and consistency.	Eppinger and Browning (2012), Madni and Sievers (2018), Wang et al. (2022), Z. Sun et al. (2016), Senescu et al. (2012)
Model interpretation variability	Different stakeholders may interpret models in varied ways, complicating decision-making and requiring consensus on model alignment.	Standardize interpretation methods and foster cross-disciplinary consensus-building to ensure consistent model understanding.	Eppinger and Browning (2012), Parnell et al. (2021), Madni and Sievers (2018), Zou et al. (2020)
Increased data management burden	Managing large volumes of data for BIM models can divert resources from other tasks and strain team capacity.	Implement more automated data management tools and integrate real-time data handling to reduce manual workload.	Chen and Whyte (2020), Eppinger and Browning (2012), Madni and Sievers (2018), Senescu et al. (2012)
Reduced creative freedom	Data-driven modeling can limit designers' creativity by imposing constraints, potentially stifling innovation.	Balance structure with creative flexibility by designing tools that support, rather than restrict, innovative exploration.	Not addressed in literature, identified as a gap in current research.
Models as a support tool, not a solution	Models highlight potential issues but do not provide comprehensive solutions; human intervention is needed to address these risks.	Emphasize the supportive role of models, focusing on expert interpretation for actionable responses.	Eppinger and Browning (2012), Chen and Whyte (2020), Senescu et al. (2012), Bahill and Dean (1996)
Challenges with architectural specifications	Translating abstract architectural specifications into the model's data framework can be difficult, impacting model reliability.	Develop tools to better handle qualitative, abstract design elements, bridging the gap between technical and conceptual design.	Not identified in existing literature, suggesting a need for future research.
Return on investment (ROI)	The ROI of the BIM prototype is questioned, considering software, training, and data upkeep costs.	Conduct a thorough cost-benefit analysis to assess whether the benefits of the tool outweigh its costs.	Azhar (2011), Madni and Sievers (2018)

Table C.8: Technological and organizational obstacles and proposed solutions

Problem	**Description**	**Solution**	**References**
Time constraints	Implementing modeling technologies can extend project timelines or require additional resources, creating bottlenecks.	Careful time allocation and resource balancing; avoid overburdening projects with unnecessary modeling tasks.	Zou et al. (2020), Madni and Sievers (2018)
Technical feasibility and requirements	Advanced modeling tools require specialized expertise and access to technology, which may not be feasible for smaller teams or projects.	Invest in training, hire skilled personnel, or provide access to necessary technology for complex projects.	Not highlighted in literature, identified as a new consideration.
Predictive design limitations	Predictive models may not capture unforeseen changes, affecting decision-making in dynamic environments.	Explore methods such as machine learning, scenario planning, or hybrid approaches to handle unexpected factors.	Madni and Sievers (2018) (limited solution).
Transparency issues with AI "black box" models	AI-driven models are opaque, making it difficult for users to trust and understand the model's outputs.	Improve model transparency and ensure that users can trace decisions, fostering confidence in AI-driven tools.	Madni and Sievers (2018), Chen and Whyte (2020), Chown and Blyler (2018)
Cross-functional collaboration challenges	Communication barriers between technical and non-technical teams can slow decision-making and create silos.	Foster collaboration through project managers with strong communication skills and systematic thinking.	Au and Ravindranath (2020), Eftekhari et al. (2022), Chen and Whyte (2020), Madni and Sievers (2018)
Data exchange and accuracy	Inaccurate or delayed data exchange leads to rework, inefficiencies, and project delays.	Streamline and automate data exchange processes to ensure real-time, accurate information sharing across teams.	Borrmann et al. (2018), Liu et al. (2014), Oloufa et al. (2004), Senescu et al. (2012)
Phase transition and workflow continuity	Errors and inefficiencies may arise when transitioning between project phases without proper alignment.	Use tools like DSM and DTH to manage dependencies and ensure smooth transitions between phases.	Liu et al. (2014), Oloufa et al. (2004), Eppinger and Browning (2012), Reefman (2022)
Stakeholder coordination	Miscommunication or errors among stakeholders can cause delays and increased costs.	Establish clear communication channels and centralized data access to align stakeholders and prevent misunderstandings.	Borrmann et al. (2018), Oloufa et al. (2004), Pilehchian et al. (2015)
Tool integration complexity	Integrating various specialized tools into a unified system can lead to fragmented workflows and data incompatibility.	Use DSM to model and integrate tools, fostering seamless tool interaction and improving project cohesion.	Borrmann et al. (2018), Liu et al. (2014), Wang et al. (2022), Madni and Sievers (2018), Yassine (2004)