Towards Model-Based Systems Engineering in the Construction Industry

Adopting Model-Based Systems Engineering to improve efficiency of Systems Engineering processes for a contractor

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Abstract

As construction projects become more complex, the amount of information is expanding. Contractors have adopted Systems Engineering (SE) to effectively capture this information of a system and ensure complex projects are realised on time and meet the high-quality needs of clients. However, the traditional use of documents and dispersion of information across digital systems leads to time-consuming and error-prone processes.

To address this problem, this research explores how Model-Based Systems Engineering (MBSE) can be adopted to enhance SE processes of a contractor. MBSE is a modelling approach using a centralised system model consisting of interconnected sub-models. As MBSE has been adopted successfully in other industries, the construction industry continues to rely on the traditional document-centric SE approach. Therefore, the main research question of this research is: "How can Model-Based Systems Engineering be adopted to improve efficiency of Systems Engineering processes for a contractor?".

This question is answered by first analysing existing literature on SE and MBSE. Continued by conducting interviews and an industry analysis to determine requirements for MBSE adoption, resulting in a selection of MBSE methods, tools, and languages suitable for contractors. In this way, an adoption proposal is created, including the change in digital landscape and information management. The tool Capella is used to model a case study project using MBSE principles. Finally, an expert session validates the benefits of the created MBSE models.

Key findings highlight MBSE's potential to address some of the limitations of the current SE approach used by contractors. Furthermore, adopting MBSE requires careful consideration of implementing a MBSE tool and determining the single source of truth for each information element in the digital landscape. To realise the full potential of MBSE, information must be stored in models instead of documents. The added value of MBSE is validated by modelling a case study in the Capella tool and conducting an expert session. The main benefit of integrating a MBSE tool for contractors is a faster and higher quality design for disciplines using functional system behaviour. The modelling approach enables easier understanding of the system, more complete interface identification, faster impact analyses, and potential to enhance efficiency in the testing phase.

Challenges of this modelling approach consist of human resistance, integration with current system, expectation variations per discipline, management and responsibility of models, and additional design effort. Finally, the PARiHS framework provides input for the establishment of four maturity levels, which organisations can apply stepwise to effectively adopt MBSE.

Keywords: Systems Engineering (SE), Model-Based Systems Engineering (MBSE), Construction Industry, Digital Information Management (DIM), MBSE Methods, MBSE Tools, MBSE Languages, Digital Landscape, Information Swimming Lane, Capella MBSE Tool.

Acknowledgements

This document presents the master's thesis titled "Towards Model-Based Systems Engineering in the Construction Industry". With the completion of this thesis, the final stage of the master Construction Management and Engineering at TU Delft has been completed. This master's journey started by searching for a topic connected to my interests and previous experiences. With a background in Technology, Policy, and Management and a student job in Systems Engineering, I marked systems and models as interesting thesis topics. This resulted in applying for an open graduation position at BAM. Renée Verboven responded enthusiastically to this application with a topic about Model-Based Systems Engineering, which started an inspiring journey.

I am enormously grateful for the opportunities and lessons this journey provided me, which inspired me about the MBSE potential at contractors. Over the past few months, Renée Verboven and Floris Bunnik excellently introduced me to the company BAM, helped me guiding my research, and helped to contact many passionate colleagues. These colleagues shared valuable insights about projects and practical applications, inspiring me to continue the research. Furthermore, a research group for adopting MBSE was set up at BAM, which brought the topic to life within the organisation and therefore motivated me even more.

After developing a thesis proposal, I began to form a thesis committee. Sander van Nederveen introduced me to Pieter van Langen and Hans Wamelink. With their invaluable knowledge about systems, construction industry, Systems Engineering, and Model-Based Systems Engineering, a thesis committee full of experts was created. During my thesis journey, I sincerely appreciate all committee members for the conversations, constructive feedback, and extensive support.

At last, I would like to use this opportunity to thank my girlfriend, family, and friends for serving as a foundation of support to execute this research.

Sander Kraaijeveld

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Executive summary

Introduction

The construction industry faces several challenges as project are complex due to involvement of multiple stakeholders across lifecycle phases, technological advancements, and changing strategic business goals. This results in an increasing amount of information elements and its interactions. Systems Engineering (SE) is an interdisciplinary approach adopted by the construction industry to ensure these complex projects can be delivered on time and to the wishes from clients. In combination with the upcoming digitalisation, the amount of information can effectively be captured and managed in digital systems to derive solutions based on the requirements determined by clients. However, the interoperability between these digital systems is low, resulting in time intensive processes and risks of inconsistencies and errors.

In other industries, Model-Based Systems Engineering (MBSE) has presented opportunities to effectively address such challenges. MBSE is an extended approach of SE and supports SE processes but replaces the traditional document-based approach with model-centric practices. It emphasises digital models as the primary communication channel, leading to an overarching system model comprised of these digital sub-models. As Relatics is adopted by Dutch contractors and described as MBSE tool, it lacks interoperability functionalities to offer MBSE advantages.

Research goal

Due to MBSE's potential to improve efficiency of SE processes and mitigate multidisciplinary challenges of SE, this study addresses the effective adoption of MBSE into contractors' SE processes. This goal is captured in the main research question:

How can Model-Based Systems Engineering (MBSE) be adopted to improve efficiency of the Systems Engineering (SE) processes for a contractor?

To address this question, first understanding is established of the SE processes at a contractor and the limitations these processes face. Subsequently, this research focuses on the definition of MBSE for the construction industry, including the MBSE benefits and challenges revealed in other industries. Furthermore, values and derived requirements enable the success factors for MBSE adoption within a contractor. MBSE presents three adoptions components, named methods, languages, and tools, to successfully adopt MBSE. It is crucial to address which of these components can be applied to contractor organisations, based on the formed requirements. By additionally generating insights into the current Digital Information Management structure, a MBSE adoption proposal can be presented. Finally, the proposal must be validated to demonstrate its added value and effective implementation. This enables practical insights and recommendations, which can be incorporated into an effective roadmap.

Research methodology

The methodology of this research is organised across five phases, each addressing a distinct research sub-question. The first phase investigates the current application of SE to contractors. A literature review explores the principles of SE, application to the construction industry, and the associated limitations. Conducting a secondary literature review is part of the second phase, exploring the MBSE concept. It examines the literature on the definition, potential benefits, and challenges related to MBSE.

The subsequent phase answers part of the research question about values and requirements of the MBSE adoption. Through a comparative industry analysis and semi-structured interviews, key insights and recommendation for MBSE adoption are presented. The fourth phase explores the literature referenced MBSE methods, languages, and tools by conducting another literature review. Additionally, this phase includes a document analysis to assess the internal digital landscape of contactors for the creation of a MBSE proposal. Finally, a case study evaluates the proposed MBSE adoption by integrating previous project data. The integration and use of a MBSE tool is tested by an expert session, providing input for several maturity levels for organisations, leading to a roadmap.

Results

Contractors' Systems Engineering (SE) processes cover requirements analysis, functional analysis and allocation, design synthesis, design realisation, verification and validation, and supporting processes. SE has been applied by the Dutch construction industry based on the ISO 15288 standard and the Guideline SE standard. Although many advantages of SE are mentioned, it encounters several challenges, such as error-prone and inefficient processes. This is the result of the document-based nature of SE, the vast amount of project information, dispersion of information across systems, and limited interoperability of the systems.

MBSE has the potential to mitigate these interdisciplinary challenges with a complete and interconnected system, consisting of several sub-models. However, MBSE also faces challenges, like human resistance, steep learning curve, integration with existing systems, standardisation level of the system, over-reliance on models, managerial support, adoption strategy selection, and a financial upfront investment.

Furthermore, requirements are established for MBSE adoption at a contactor. Organisational requirements include a standardised MBSE framework, reliable tool adoption, user-friendly MBSE approach, minimal expansion, pilot-based adoption, MBSE maturity level framework, success communication, and management commitment. Technically, seamless system integration, flexible standardisation of system, open standard compliance, one single source of truth, traceability of decisions, and early-stage model analysis are MBSE adoption requirements.

Regarding MBSE methods, OOSEM, SYSMOD, and ARCADIA are well-suited for construction industry application, as they align well with SE standards and are widely adopted or user-friendly. The modelling language SysML is preferred because it is the standard MBSE language. Tools, like Cameo and Enterprise Architect are recommended due to their support of SysML and extended capabilities. The tool Capella is favoured as well with the advantages of an open-source type and easy to learn.

Current digital landscape of contractors lacks functionalities to adopt MBSE. An additional MBSE tool, with its associated method and language, must be integrated. Furthermore, a federated single source of truth across several tools must be established. An information swimming lane diagram illustrates the authoritative source of each information type and the flow of information between tools.

Modelling of the construction project Spooldersluis in the Capella MBSE tool primarily reveals that most added value emerges for disciplines extensively using functional system behaviour, such as the technical installations discipline. Modelling in Capella results in a more comprehensive overview of interfaces and overview of the impact of modifications. Furthermore, earlier visual understanding of the system, extension of options for the Validation and Verification (V&V) process, and the potential to improve test phase efficiency are highlighted as benefits.

Limitations of this modelling approach consist of additional effort, human resistance, Capella's add-on extensions, variations in expectation per discipline, integration into existing workflows, and time-investment for competence development. However, the initial time-investment for model development facilitates the creation of standardised models, which can be reused to enhance efficiency in future projects.

The last aspect of this study focuses on a roadmap for organisations. The PARiHS implementation framework reveals to implement MBSE for disciplines with the highest added value but also highlights the need for managerial support, progress measurement, competence development, clear workflow, and a core MBSE team. This framework results in four maturity levels, starting with the foundation of a federated single source of truth and continuing to organisational MBSE preparation. Later, a MBSE tool must be integrated and finally a transition must be enabled towards model-centric practices.

Discussion

The benefits and challenges of this MBSE modelling approach are mostly confirmed by the literature. This study complements academic literature by providing unique perspectives of MBSE to the construction industry. Contractors can use the established requirements, the method, tool, and language analysis, the Digital Information Management analysis, the case study findings, and the roadmap for their organisational MBSE adoption.

However, further research will provide a broader and deeper understanding of MBSE. Analysing needs of the broader industry and interfaces between client and contractor, subcontractors and partners enables a more efficient MBSE adoption. By expanding the data with more construction project case studies and MBSE modelling tools, scalability can be tested and diverse outcomes can be achieved. Lastly, the use and effect of a MBSE tool for static projects must be tested. A MBSE tool offers the greatest value in projects involving behavioural systems, but may be less beneficial for static projects, in which its use may be limited or omitted due to low returns.

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List of Abbreviations

SE	Systems Engineering
MBSE	Model-Based Systems Engineering
BIM	Building Information Management
DIM	Digital Information Management
INCOSE	International Council on Systems Engineering
SoI	System of Interest
SoS	System of Systems
V&V	Verification and Validation
SMART	Specific, Measurable, Acceptable, Realistic, Time-bound
SBS	System Breakdown Structure
WBS	Work Breakdown Structure
AI	Artificial Intelligence
OTL	Object Type Library
CDE	Common Data Environment
ES	Exchange Scenario (diagram)
SFCD	System Functional Chain Description (diagram)
SFBD	System Functional Breakdown (diagram)
SDFB	System Data Flow Blank (diagram)
SAB	System Architecture Breakdown (diagram)
LDFB	Logical Data Flow Blank (diagram)
LFBD	Logical Functional Breakdown (diagram)
LCBD	Logical Component Breakdown (diagram)
LAB	Logical Architecture Breakdown (diagram)
PCBD	Physical Component Breakdown (diagram)
PAB	Physical Architecture Breakdown (diagram)

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1. Introduction

This chapter discusses the current situation, need for improvement, research goal, and the methodology of this study. In Section 1.1, the current situation in the construction industry is discussed. Section 1.2 presents need for improvement of this current situation using Model-Based Systems Engineering. The research gap is stated in section 1.3, based on a literature gap of MBSE. Subsequently, the scope of this study is discussed in Section 1.4 to provide clarity on defining the research gap. Section 1.5 explains the main research question and sub-questions. The methods to address the research sub-questions is discussed in Section 1.6. In section 1.7, the expected result of this study are presented, organised per research question. Section 1.8 outlines the venue in which this research is conducted, namely BAM, a contractor active in the Dutch construction industry.

1.1 Current situation

1.1.1 Complex projects and systems

Engineering projects are complex due to several factors, like stakeholder involvement, technological advancements, organisational structures, and strategic business objectives (Prieto, 2017). These factors ensure many components in a project which incorporates the presence of many interactions. The dynamic nature of project components and their interactions often lead to continuous changes, a challenge complexity brings to project management (Cristóbal et al., 2018).

In construction projects, the total project is divided into phases, such as initiation, planning and design, procurement and tendering, construction, handover, and operation. These project phases are coordinated by multiple stakeholders, like clients and contractors. The coordination with phases results in a complex network, consisting of many varied interrelated parts which is characterised by Baccarini (1996) in terms of differentiation and interdependency. Differentiation refers to the number of varied components in a project, like tasks or parts, while interdependency denotes the degree of interactions between these components.

To get insight into these networks and manage them effectively, systems thinking is widely adopted in the construction industry. Systems thinking is a holistic approach that emphasises how systems function over time and in context of larger systems of systems, and how their individual elements interact (Prieto, 2023). In systems thinking, a system is defined as an interconnected set of components that is clearly organised to form a unified whole (Arnold & Wade, 2015). In order to improve decision-making and problem-solving skills, systems thinking seeks to comprehend the interdependencies, feedback loops, and patterns found in complex systems.

1.1.2 Systems Engineering (SE) for contractors

In the construction industry, contractors receive such complex projects from a client who has already conducted preliminary work. The client defines a specific request and a conceptual design. The contractors fulfil this request by creating a final design, execution design, and subsequently conducting the execution. In complex construction projects, a Systems Engineering (SE) approach has widely been adopted by contractors in the construction industry to ensure that projects are delivered on time, within budget and to the requirements specified by the client (Lynghaug et al., 2021).

Systems Engineering (SE), rooted in systems thinking, is an interdisciplinary approach that integrates both technical and management processes to ensure that a complex system can be realised with high-quality and meets the needs and requirements throughout their lifecycle (Buede, 2008). It includes the development and tracking of technical information for decision-making, as well as verification that technical design solutions satisfy client requirements (Walden et al., 2015). Contractors have adopted this approach to effectively capture the information in a successful system to arrive at a solution based on the request of the client, utilising the V-model. The V-model is a graphical representation of the systems development lifecycle, emphasising verification and validation at each stage.

1.1.3 Digitalisation

Historically, project information was documented using paper-based records. However, with advancements in digitalisation, information is currently stored in online documents or even digital tools. The digitalisation has offered many advantages, such as increased productivity, higher quality, and faster response times, ultimately contributing to more efficient project management and execution (Aghimien et al., 2018).

The involvement of a large number of stakeholders and disciplines in projects has made efficient information capture and exchange increasingly challenging. However, advancements in information and communication technologies have played a crucial role to improve efficiency in the construction industry. In the early 2000s, Building Information Modelling (BIM) was introduced as a key technology aimed at enhancing collaboration and improving project efficiency. BIM is widely regarded as a fundamental tool for facilitating higher levels of integration amongst project stakeholders, ultimately contributing to greater productivity, and streamlined project delivery (Allison et al., 2018).

Not only development emerged regarding information modelling, but also advancements on information management. Relatics is such an advancement, designed as a software tool to structure, analyse and integrate project-related information (Relatics, 2025). In this way, Relatics enables the Systems Engineering approach, including requirements management, traceability, and collaboration amongst stakeholders.

1.2 Need for improvement

Due to the increasing digital maturity, construction projects generate and use large amounts of complex data throughout the project lifecycle. For such projects, multiple tools and systems are used to store this large amount of complex data. The different tools do not communicate with each other, which makes valuable information difficult to access and creates a complex system. Current Systems Engineering processes rely on a complex system involving multiple tools to perform tasks such as generating reports and validating requirements. Due to the distribution of information across various systems and tools, these processes become time-consuming and increases the risk of errors, leading to extended project completion times. This challenge in the construction industry highlights the need for improved interoperability in a way that systems and tools can effectively communicate. With high interoperability, workflows get more streamlined and interconnected, improving the efficiency of the Systems Engineering processes.

1.2.1 Model-Based Systems Engineering (MBSE)

Model-Based Systems Engineering (MBSE), originated from the aerospace sector, has the potential to improve interoperability in construction industry, given its successful adoption in other industries (Akundi & Lopez, 2021). MBSE is the systematic application of modelling to help with requirements, design, analysis, verification, and validation for systems which starts with the conceptual phase and proceeds through each lifecycle stage (INCOSE, 2007). MBSE replaces document-centric with model-centric practices to ensure the digital documents are interconnected, resulting in models that can understand the complexity of the systems and can make information easily accessible and traceable (Madni & Sievers, 2018). MBSE is an approach that creates domain models as the primary way for information exchange (Kievit et al., 2023). As MBSE extends principles of SE by emphasising digital models as the primary medium, MBSE is a powerful potential solution to the multidisciplinary challenges posed by construction projects.

Relatics describes itself as a tool that supports MBSE, and Relatics has already been adopted by multiple contractors (Relatics, 2025). Relatics is a system that helps to control complex project information by using a central environment for requirements management, streamlining communications, and providing and maintaining visibility into project structures and changes.

However, there remains a need for a more advanced approach or system that facilitates a higher degree of information exchange and interoperability. Currently, Relatics does not, for example, seamlessly integrate with BIM software. For instance, if requirements change in Relatics, the design in a BIM model will not automatically adjust. Relatics can also not analyse and interpret any of its data. MBSE with a higher degree of interoperability would have such features. While Relatics serves as a valuable tool in supporting the Systems Engineering (SE) processes, further advancements are required to achieve a complete interconnected system of digital models for the construction sector.

As discussed, MBSE is a broad term which can be adopted using several maturity levels, implying its level of organisational process improvement. In order to prevent miscommunication about the broad term MBSE, the name 'MBSE' is used to imply the needed completely interconnected system of digital models, which will improve the efficiency of the current SE processes. The MBSE of Relatics is referred to as 'Relatics MBSE', having a much lower maturity level than 'MBSE', as it is just a tool that documents and controls project information.

Due to its adoption in various sectors and its potential, MBSE has been widely explored in academic literature. De Saqui-Sannes et al. (2022) investigated the available tools, methods, and languages of the MBSE approach in order to give practitioners the keys for a selection of MBSE methods, tools, and languages. One of the languages designed for MBSE is the Systems Modelling Language (SysML) which includes diverse types of diagrams for dynamic behaviour and static structure that help in modelling various aspects of a system. Van de Brug (2024) already showed how MBSE can enhance configuration management within BIM by using Digital Twins or Digital Threads. The research concludes that a broader adoption of MBSE in the construction industry brings many advantages, but companies must prioritise establishment of clear guidelines for MBSE integration and investigate organisational factors influencing adoption.

1.3 Research gap

According to previous section about MBSE, there is still a need on how the MBSE approach can be broadly and effectively adopted in the current SE processes of contractors. Due to the time-consuming SE processes, MBSE has the potential to improve the efficiency of these SE processes.

To answer the question of how to adopt MBSE, it is essential to first establish a detailed understanding of the current state-of-the-art SE processes and its limitations, but also to understand the MBSE concept within the construction industry. It is important to address the benefits of MBSE for the construction industry, as research revealed a still existing question on the added value of MBSE (Henderson et al., 2023). Furthermore, for successful adoption the previous section prioritises to investigate the technical and organisational challenges and strategies of MBSE.

Furthermore, there is a need to explore MBSE methods, languages, and tools that can be used for successful MBSE adoption in the construction industry. The proposed outcome enables a thorough investigation for future MBSE adoption on how it can effectively support and enhance a contractor's project processes.

1.4 Research scope

This study addresses the domains of Model-Based Systems Engineering (MBSE), Digital Information Management (DIM), Systems Engineering (SE), and contractors in the construction industry. These domains define the research scope, which is explained below and visualised in Figure 1.1.

- **MBSE.** The MBSE approach has the potential to create a completely interconnected system of digital models. In this way, models and tools can become more interconnected. There is still a gap on which method, tool, and language, but also which organisational and technical steps are most appropriate for MBSE adoption.

- **SE.** Systems Engineering is the current leading approach for contractors to generate solutions that meet the client's demand but has its limitations. The result of SE are time-consuming processes, which needs improvement.

- **Contractors in the construction industry.** As explained before, contractors play a pivotal role in ensuring that solutions are generated using a SE approach, tailored to meet clients' specific requirements. While MBSE adoption will also affect clients in the construction industry, the primary focus of this research is on contractors. Contractors, in contrast to clients, are responsible for execution of the work and practical application of SE. Clients provide contractors with project information in a specific format, which is the interface between contractor and client. Contractors are dependent on the information of this interface and expect a certain digital format. Although clients might need to make some organisational or technical changes, these can be explored in future research. It is expected that the adoption of MBSE by contractors will lead to widespread MBSE adoption for the sector making it easier for the client to adapt.

- **DIM.** DIM concerns collection, storage, management, and dissemination of digital information within an organisation. It includes using technologies to efficiently manage and leverage information. DIM plays a crucial role in the construction industry as projects generate large amounts of data. An efficient DIM will lead to efficient processes and improved decision-making.

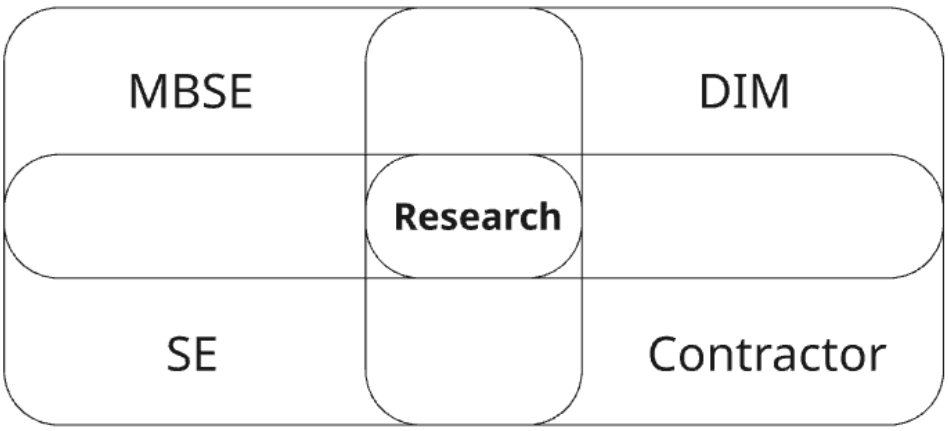

Figure 1.1: Research scope

1.5 Research questions

Based on the research gap, the research questions addresses how MBSE can enhance the current Systems Engineering processes of a contractor. The following main research question will answer this research gap:

How can Model-Based Systems Engineering (MBSE) be adopted to improve efficiency of the Systems Engineering (SE) processes for a contractor?

To answer the main research question, the research is divided into phases with the following sub-questions:

1. *How does Systems Engineering processes at a contractor currently work and what are the limitations?*
    - Develop a description of Systems Engineering and its processes and formulate the limitations of SE.
2. *What is MBSE, and what are its benefits and challenges for a contractor?*
    - Define the definition of MBSE in the context of a contractor and explore the added value and challenges it can bring for a contractor.
3. *What are requirements for successful MBSE adoption at a contractor?*
    - Establish requirements for successful MBSE adoption at a contractor, including requirements the MBSE system must adhere to. This will be the input for the design of the MBSE adoption proposal.
4. *Which methods, languages, and tools can be used to adopt MBSE, and what adaptations are required in Information Management to enable this transition?*
    - Understand the existing methods, modelling languages, and tools of MBSE and develop a description for MBSE adoption with appropriate method, language, and tools. This is based on the requirements of research sub-question 3. Furthermore, investigate the change in digital information management and SE processes for adopting MBSE at a contractor.
5. *How can the proposed MBSE adoption be validated within the context of Systems Engineering processes?*
    - Test the proposed MBSE adoption through a case study, including an expert evaluation, to collect insights on its practical application and effectiveness. Additionally, the needed organisational and technical steps will be determined with a roadmap.

1.6 Methodology

To develop answers for theses research question, an appropriate methodology must be selected and followed. In this paragraph, the research methodology will be outlined as illustrated in Figure 1.2. The study is divided into five phases, each containing its own research sub-question.

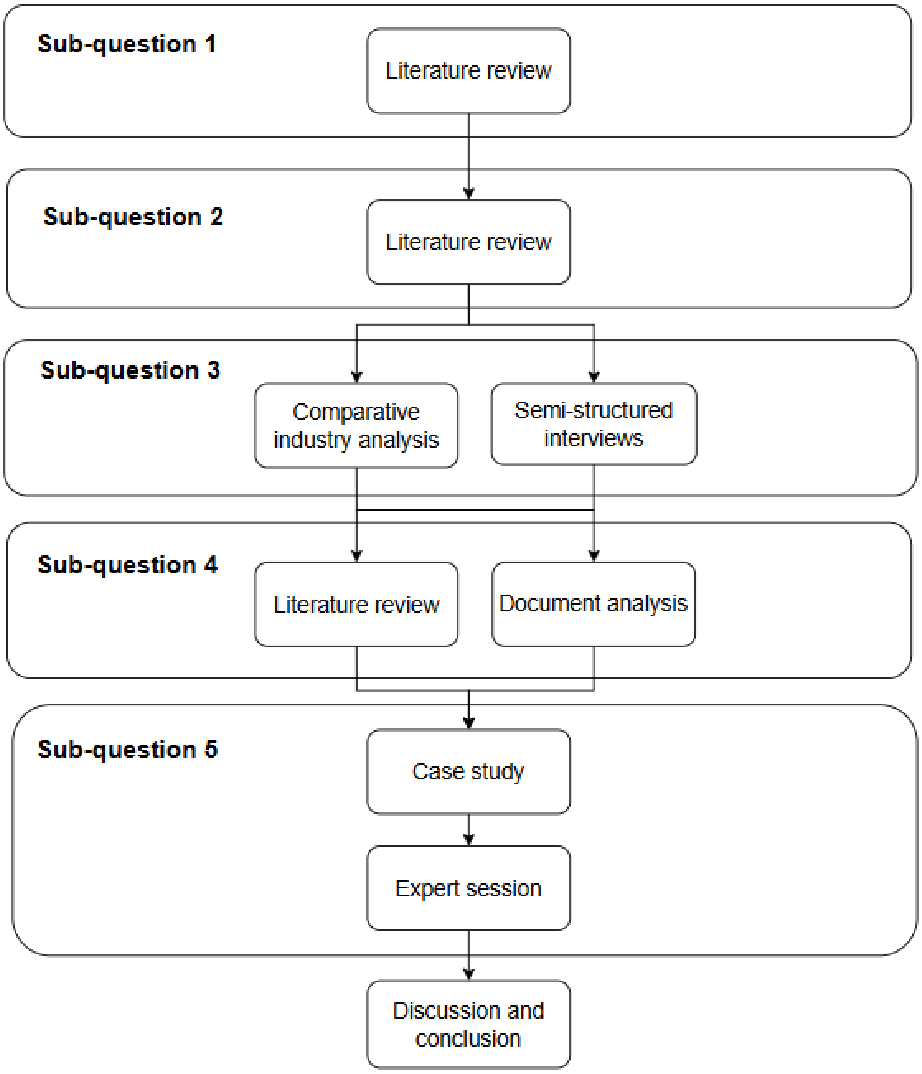

Figure 1.2: Research methodology

Sub-question 1

To answer sub-question 1, it is essential to determine the current state-of-the-art of the use of Systems Engineering for a contractors' processes, which can be obtained by a literature review on Systems Engineering and SE processes. The literature review will also explore the specific application of SE for the construction industry and contractors. Lastly, the limitations of Systems Engineering will be examined with a literature review.

Sub-question 2

Additionally, given the broad scope of MBSE, a secondary literature review will be conducted to address sub-question 2. The literature review will dive into the broad term of MBSE and what it can bring for a contractor. Subsequently, the benefits and challenges of MBSE will be examined by conducting another literature review.

Sub-question 3

Sub-question 3 will be answered by a comparative industry analysis and semi-structured interviews. The comparative industry analysis will analyse MBSE adoptions in various industries to identify the key lessons learned. The interviews will be conducted to gain practical information on requirements for such a digital advancement like MBSE. But also, to identify potential challenges and resources are needed for successful adoption. The semi-structured interviews will also provide similarities with the SE limitations and MBSE benefits from the literature. As well as, to potentially uncover new limitations and benefits, specifically for a contractor in the construction industry.

Sub-question 4

The existing MBSE methods, languages and tools will be explored by the literature review for sub-question 4. Additionally, this sub-question includes a document analysis to get a view on the current situation of the company BAM. The document analysis will uncover the digital landscape of BAM and information flows within this landscape. In this way, the current situation can be analysed to create a MBSE proposal.

Sub-question 5

To answer the last sub-question, the proposed MBSE adoption of sub-question 4 will be evaluated to a case study. For the case study test, data from a previous project conducted by BAM will be integrated into a MBSE tool. These results will be analysed and evaluated by an expert session with BAM employees, being part of the case study project. This approach will facilitate the provision of further insights and recommendations regarding the practical adoption of MBSE, leading to the establishment of a roadmap to adopt MBSE.

1.7 Expected results

The research will primarily focus on the processes and the conceptual phase of system development, rather than developing or coding a new tool. In this paragraph, the results for each research sub-question will be described.

- The first result of this research will be a comprehensive view on the state-of-the-art Systems Engineering and its processes. Sub-question 1 will also identify the limitations of the Systems Engineering approach. Chapter 2 will answer sub-question 1.

- Sub-question 2 will result in a detailed description of MBSE and what this means for a contractor. Furthermore, the added value of MBSE and its challenges will be described, which is based on a literature review. This will be discussed in Chapter 3.

- The result of sub-question 3 will be a list of requirements for successful MBSE adoption, including requirements for MBSE adoption. Chapter 4 will start with a comparative industry analysis and continues with the analysis of the semi-structured interviews. These will introduce values and requirements for adopting MBSE.

- The answer to sub-question 4 will be a proposal of how MBSE can be adopted into the current practice of a contractor, including the appropriate MBSE methods, languages, and tools. Chapter 5 will describe and select the MBSE methods, tools, and languages. Lastly, Chapter 6 will examine the MBSE adoption proposal for contractors by investigating the current situation at BAM and the needed modifications to adopt MBSE effectively.

- For sub-question 5, the MBSE adoption proposal will be evaluated by experts with a case study test, which will generate further insights for effective application. Additionally, a roadmap will be developed to facilitate the effective adoption of MBSE, detailing the necessary organisational and technical steps for MBSE adoption. Chapter 7 will describe this sub-question.

1.8 Research venue

The research will be conducted at the Dutch company BAM, a Dutch leading contractor, who has interest to be a leader in digitalisation. The research activities are scheduled to be conducted at BAM Infraconsult, the engineering consultancy firm of BAM Infra, and specifically at the department of 'Systems Engineering' which is part of the group 'Information management'. BAM Infra has just set up a research group called 'MBSE', which will be joined.

2. Current SE processes and its limitations

2.1 Introduction

This chapter provides an in-depth exploration to answer research sub-question 1 about Systems Engineering (SE), its application in the construction industry, and its limitations. Section 2.2 defines the concept of systems and the principles of SE, highlighting its history, interdisciplinary nature, and structured approach to managing complex projects. Section 2.2 also examines the ISO 15288 standard and the V-model, which are essential frameworks for implementing SE processes. Section 2.3 discusses the application of SE in the construction industry and the specific SE processes used by contractors, including technical and supporting processes. The limitations and challenges of SE are addressed in Section 2.4. Finally, Section 2.5 provides a summary of the chapter.

2.2 Systems Engineering (SE)

Before diving into the SE processes, this section explores the SE concept and its history. As systems and SE are widely used words leading to different interpretations, the definition of both these concepts has to be established. This section closes with an explanation of the standard of SE, ISO 15288, and the V-model.

2.2.1 Systems

The most widely recognised concept of a system originates from von Bertalanffy (1969), perceiving a system as a whole composed of interacting parts. This concept is general and purposeless, which is why the Internation Council on Systems Engineering (INCOSE) draw the following definition for the context of Systems Engineering based on this general view: “A system is a combination of interacting elements organised to achieve one or more stated purposes” (Walden et al., 2015). This definition implies that elements exist which do not belong to the system and are outside of the system boundary. The System of Interest (SoI) is the collection of elements and interconnections that exist within the defined system boundary, illustrated in Figure 2.1.

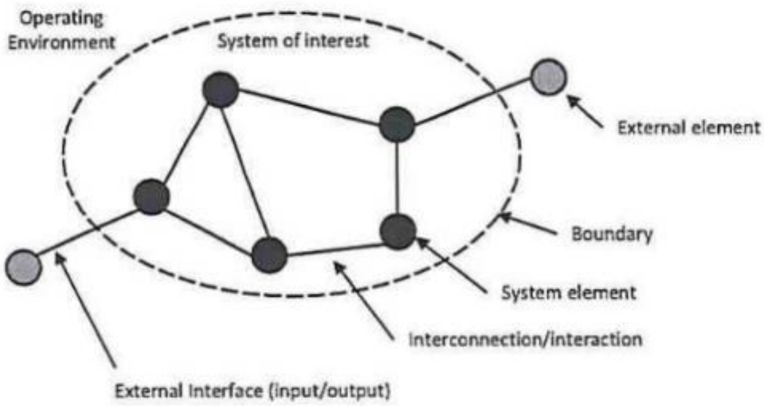

Figure 2.1: SoI with elements, interactions, and boundary (Faulconbridge & Ryan, 2014)

There are diverse ways to classify systems, which are categorised by Faulconbridge & Ryan (2014) into the following four types:

- **Closed/open** refers to the fact if the system is isolated from the environment or if the system accepts input from the operating environment.
- **Physical/conceptual** refers to systems existing in a physical form or to systems that do not have a physical form.
- **Natural/human-made/human-modified** refers to systems that are the result of natural process and contain natural elements or to systems that are made or modified by humans for human purposes.
- **Precedented/unprecedented** refers to systems with elements that have been produced before or to systems with elements that have not been produced before.

Within the context of the construction industry, a system is referred to as an open, physical system that is human-made or human-modified from precedented or unprecedented elements. These systems refer to something that will physically be built new, be replaced, or be renovated. These systems are made by humans or modified by humans as humans are responsible for the realisation. Additionally, the systems are open as they have physical and social interaction with the environment they are built in.

Since a system is defined as a combination of elements that interact, each element can either not further be decomposed or decomposed into further lower-level system elements. This means that a system can have elements that are either atomic or can be viewed as a system itself. At any given level of detail, the elements are grouped into distinct subgroups of elements, underlying to a higher-level system (Walden et al., 2015). This is illustrated in Figure 2.2, which shows hierarchy within a system. This introduces the fact that one person's SoI can be viewed as a system element in another person's SoI.

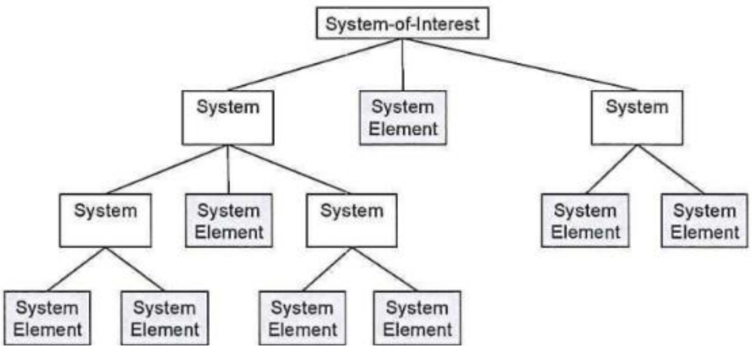

Figure 2.2: Hierarchy of elements in a SoI (Faulconbridge & Ryan, 2014)

A System of System (SoS) is an SoI whose elements are independent subsystems, collaborating to achieve the common goal of the SoI. Each system in the SoS is managerially and operationally independent. Each systems element has its own authorities, lifecycle, requirements, emergent behaviour, and interfaces which creates a SoS that is complex (Walden et al., 2015). It is required to understand these complex systems to ensure that the purpose of the system can be achieved efficiently and effectively.

2.2.2 SE definition

Systems Engineering started at the Bell Telephone Laboratories in the1940s as a paradigm to mitigate complex processes or systems (Fagen, 1975). Since it was founded, SE continued and evolved as a distinct discipline. The defence and aerospace industries were the first that started to adopt SE (Goode et al., 1957). These industries started to emphasise the process involved instead of the holistic principles. Around the 2000s, the construction industry started to gain interest in SE for complex projects, especially for large infrastructural projects (Cusumano et al., 2024). Most construction projects faced time and cost overruns and did not deliver outcomes aligned with the client's demand as complexity of projects rose. Cost, time, and quality performance slightly improved by applying SE to projects (Beste, 2021). Initially, SE was applied on large complex construction projects, due to the complexity and necessity to integrate subsystems into a unified whole. Currently, SE is also applied on smaller projects because of requirements introduced by the supply chain or due to the interest to better and faster designing. SE is often required for contractors by clients in the Netherlands (de Graaf et al., 2017).

As mentioned, the Systems Engineering approach can help to understand complex systems, but a wide range of SE definitions are defined due to its adoption by various industries, institutions, and organisations. Here are some of the widely used definitions of SE from the literature:

> "Systems Engineering is an interdisciplinary approach and means to enable the realisation of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost, schedule, performance, training and support, test, manufacturing, and disposal. Systems engineering integrates all the disciplines and speciality groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs" (Walden et al., 2015).

> "Systems Engineering is an interdisciplinary approach that integrates both technical and management processes to ensure that complex projects meet stakeholder needs and operational requirements throughout their lifecycle" (Buede, 2008).

> "Systems Engineering is an iterative process of top-down synthesis, development, and operation of a real-world system that satisfies, in a near optimal manner, the full range of requirements for the system" (Eisner, 2008).

For this research, the first definition of SE provided by Walden et al. (2015) will be applied, as this is extensively cited in scientific research on SE in the construction industry. This definition is described by the Internation Council on Systems Engineering (INCOSE), the world's largest organisation for SE. The definition covers several principles, which can be reflected with the following key words:

- **Interdisciplinary.** Projects are often segmented based on the specific disciplines involved, such as civil engineering, mechanical installations, and electrical installations. An interdisciplinary approach to system design and realisation prevents issues arising at the interfaces between different disciplines (Bouwend Nederland et al., 2013).
- **Iterative.** Most projects are complex consisting of many objects. An iterative process helps to successfully realise such projects. The SE process will iterate between requirements, functions, and solutions.
- **Lifecycle.** Each system that is or will be built has a lifecycle from concept to development, realisation, operation, and ends with demolition. This implies that the system will be optimised for every phase of its lifecycle.
- **Transparent.** The SE approach is transparent as decisions including reasons will be recorded and saved by verifying the requirements of the stakeholders.
- **Requirements.** SE starts with analysing the requirements set by stakeholders and clients. These requirements serve as input for developing the best solution.

The SE approach is based on systems thinking, a perspective that enhances awareness of wholes and how parts within those wholes connect. Systems thinking is characterised by processes of discovery, learning, diagnosis, and dialogue, facilitating sensing, modelling, and discussing the real world. These activities enhance understanding, definition, and interaction with systems. A systems thinker understands integration of systems into the broader context, understands their behaviour, and possesses the skills to manage them effectively (Sillitto, 2012). As an example, SE tries to gain insights into the relationship between specified requirements. These insights can be gained by understanding the connections of the system elements and their relation to the system.

2.2.3 ISO 15288 and V-model

The most commonly used standard for the application of Systems Engineering is the ISO 15288, established by the International Organisation for Standardisation (ISO) in 2015 (ISO/IEC-IEEE, 2015). This standard has been widely adopted by the construction industry and is required by public client in the Netherlands (de Graaf et al., 2017). The ISO 15288 standard is applicable to project organisations, like contractors in the construction industry. Because of these two facts, the ISO 15288 standard will serve as a basis for this study.

The ISO 15288 states that a system progresses through its lifecycle as the result of actions, performed and managed by people in organisations, using processes for execution of activities. The lifecycle of a system is divided into six general stages: Concept, Development, Production, Utilisation, Support, and Retirement.

A popular lifecycle model that is fundamental for the definition of SE is the V-model, which focuses particularly on the concept, development, and production stage. Like the ISO 15288 standard, the V-model is recognised in the construction industry and will therefore be discussed in this section (Emes et al., 2012). The V-model highlights the need for continuous validation with stakeholders, the need to define verification plans during requirements development, and the importance of continuous risk and opportunity management (Clark, 2009). A key aspect of the V-model and SE is verification and validation. Verification ensures that a system is built correctly by assessing requirement compliance. Validation ensures system goals have been achieved by comparing a system's behaviour to its needed or expected behaviour (Madni & Sievers, 2018).

The V-model, visualised in Figure 2.3, proceeds in time and system maturity from left to right. The left side of the V-model focusses on developing a design from the highest level to the lowest level of detail. The right side of the V ensures that the proposed design from the left will be realised, according to requirements. This structure helps to systematically decompose complex systems into manageable components and subsequently integrates these back into the unified whole (Clark, 2009).

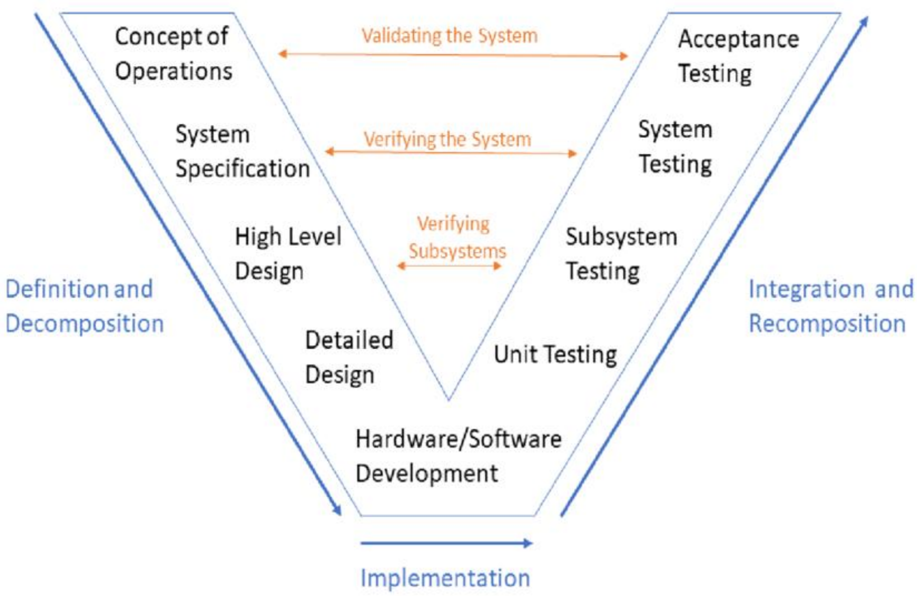

Figure 2.3: V-model (Shamieh, 2011)

2.3 SE at a contractor

After the SE concept is understood, the application of SE by contractors can be examined. This section starts with discussing the different SE processes and the categorisation of these. Additionally, the application of SE processes by contractors in the construction industry is described in 2.3.1. This section closes with an explanation on the sequence of these processes, visualised in a process model in 2.3.2.

2.3.1 SE processes in construction sector

Within the aforementioned lifecycle stages, a variety of processes are executed to meet the client's demand. These system lifecycle processes are categorised into four types: Technical processes, Technical Management processes, Agreement processes, and Organisational Project-Enabling processes (ISO/IEC-IEEE, 2015). The Technical Management, Agreement, and Organisational Project-Enabling processes are in many publications and manuals also collectively referred to as the Supporting processes.

The Technical processes are used to define the system requirements, to convert these requirements into an effective product, to ensure the consistent reproduction of the product, when necessary, to utilise the product to deliver the requisite services, to maintain the provision of these services, and to manage the disposal of the product upon its retirement from service. The Supporting processes are used to establish agreements, provide the needed resources for the project, and to manage the resources and assets. The Supporting processes support the development of the system through its lifecycle and must therefore always be given attention. ISO 15288 divides the Supporting processes into sixteen distinct processes and the Technical processes into fourteen processes, which are visualised in Figure 2.4.

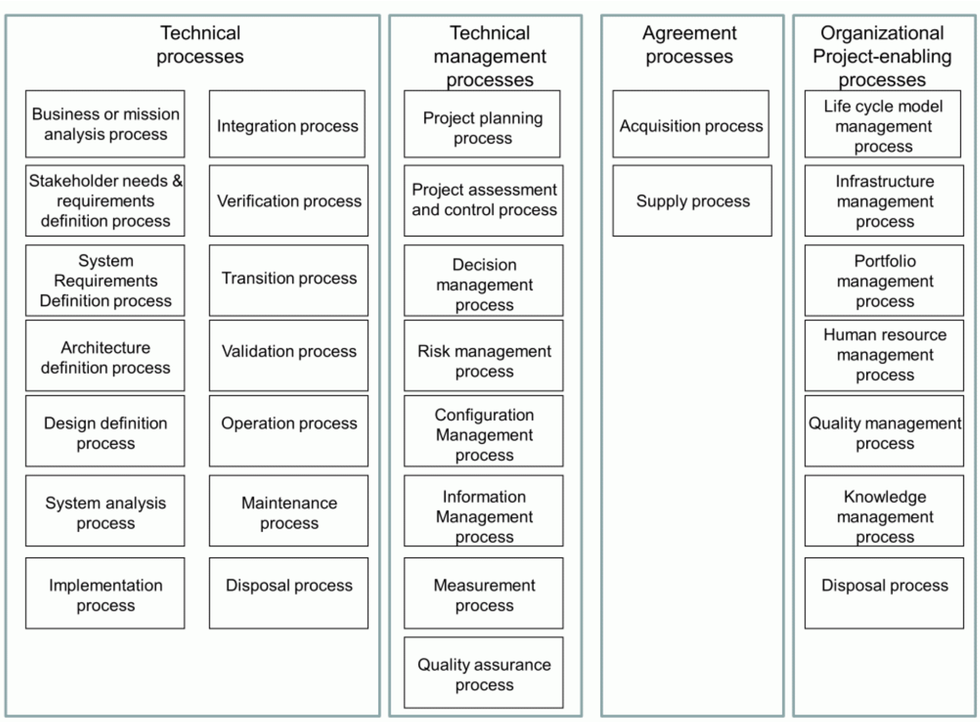

Figure 2.4: Technical and Supporting processes according to ISO 15288 (ISO/IEC-IEEE, 2015)

A Dutch consortium, in the construction industry, and in particular the civil engineering sector, has developed a Guideline Systems Engineering (Bouwend Nederland et al., 2013). This guideline has been created to help organisations practically implement SE in their project processes and has been applied by large contractors and consultancy engineering firms in the civil engineering sector.

The Guideline Systems Engineering transformed these Technical processes to the following ten main processes: Definition process of stakeholder requirements, Requirements analysis process, Architecture design process, Verification process, Validation process, Implementation process, Integration process, Handover process, Maintenance process, and Demolition process (Bouwend Nederland et al., 2013). Because SE covers the entire lifecycle of a system, the Technical processes are also referred to as SE processes in the Guideline Systems Engineering. The Technical SE processes are intended for determining the requirements for a system and realising an efficient system (Bouwend Nederland et al., 2013).

2.3.2 SE process model for contractors

To gai insight into the sequence of processes and its efficiency, processes can be represented visually with, for example, a process model. Berghuis (2018) developed, based on de Graaf et al. (2017), a process model of the Dutch contractors' SE processes in Figure 2.5. De Graaf et al. (2017) also developed a measurement tool which measures the SE performance in construction projects. In the process model of Figure 2.5, some Technical processes of the Guideline SE are combined, like implementation and integration into realisation. Some other processes of the Guideline SE can be found in the model, such as requirements analysis, design, verification, and validation.

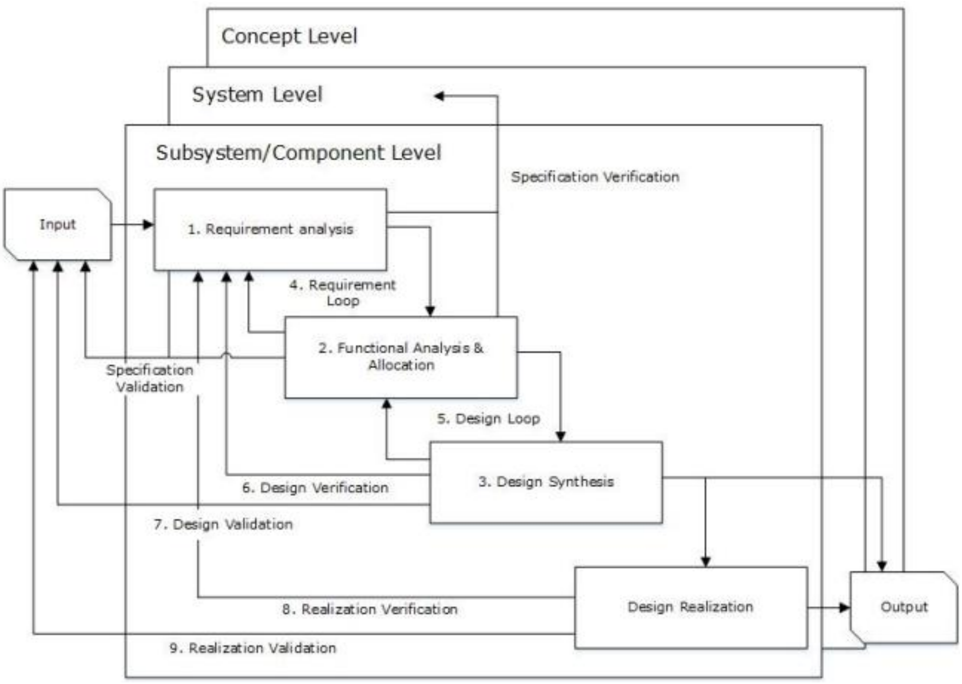

Figure 2.5: SE process model (Berghuis, 2018)

The initial process of SE is the requirements analysis. This analysis is conducted to define the system's functionalities and the performance it must achieve. This phase involves translating the demands and needs of clients and stakeholders, in the model referred to as input, into quantifiable requirements. In many projects, the client or stakeholders collects and releases the information of this input. The outcome of the requirements analysis is a Verification and Validation (V&V) plan, which outlines the methods, timing, and responsible parties for verifying and validating specific requirements. Key considerations in this analysis are to include prioritisation of requirements, formulating them according to the SMART criteria (Specific, Measurable, Acceptable, Realistic, Time-bound), and ensuring the traceability of these requirements.

The subsequent core process in SE is the functional analysis and allocation process, conducted to determine the system's functionality. The functionality of the system defines what the system should realise based on measurable requirements, instead of detailing how it should perform these functions. Subsequently, these functions are coupled to objects, which collectively form the System Breakdown Structure (SBS). Finally, these objects are linked to activities, resulting in the Work Breakdown Structure (WBS). This process could impact the previous process of the requirements analysis. If so, the requirements analysis will have to be redone.

The design synthesis is the third process executed in SE, focused on transitioning the requirements and functions into design solutions. The design solution should align with the requirements and functions from the previous SE processes. Design choices must incorporate the rationale to establish traceability. If it becomes clear that requirements or functions must be adjusted due to insights from the design process, the functional analysis and allocation and even the requirements analysis process must be redone.

Design realisation is another core process to enable actual creation of the design. During realisation, technical work will be executed. The result of this process is a built system and an as-built document, which states how the system is realised. The as-built could deviate from the design document, like drawings, if changes have been made. After the system is realised, it can be handed over to the client, maintained, and finally be demolished at the end of the lifecycle.

Lastly, Verification and Validation (V&V) are core SE processes, occurring regularly during the aforementioned processes. These V&V processes are executed to demonstrate that requirements, functions, design solutions, and eventually the realised system meet the needs of the client and stakeholders. The output of the V&V processes are V&V reports, containing information elements such as the responsible person, moment, method, and outcome of the V&V.

2.4 SE limitations

SE is a widely used approach and has many advantages, like an increase in satisfaction of interest, less redesign of design solutions, and a reduction of failure costs and rework (Berghuis, 2018). This is achieved by understanding the stakeholders' views, a clear focus on requirements, and recognition of key issues, uncertainties, and risks early. Despite these advantages, SE also faces challenges which will be described in this section.

Systems Engineering has traditionally been applied on new systems (Elliot et al., 2012). For construction projects aimed at enhancing infrastructure, the primary objective is to renovate or maintain existing structures. Such projects do not focus on what needs to be built but focus on the short-term interruptions of current systems during their upgrade to current standards. Frequently, information regarding the current state of structures is not completely accessible, complete, or accurate. Consequently, the condition of the existing system remains ambiguous, complicating the completion of the initial tasks in the SE process (de Graaf, 2014). If the primary analyses in SE cannot be conducted due to missing information, subsequent SE tasks are negatively impacted due to the iterative nature of SE. This means SE emphasises pre-work rather than re-work.

Furthermore, an increase of system requirements, due to the rising complexity of systems, results in time-consuming integration and management of the components (Madni & Sievers, 2018). Although digital tools are used for storing information, searching for the correct information still becomes time-consuming due to the increasing amount of project information. Additionally, because SE is a document-based approach, certain information may be hidden in these distinct documents. This increases the risks of missing critical information and interfaces. Requirements, for example, are demonstrated in several separate documents and are reported in certain digital tools. Design choices, which are based on these requirements, are capture in documents or reports. If changes in requirements or design occur frequently, the changes must be recorded, and processes must be redone. In this way, dependencies become difficult to manage or impact analyses become time-intensive as the information is stored in several separate documents. Thus, searching for information and documenting becomes inefficient due to the document-based approach in complex systems (Madni & Sievers, 2018). But also increases the risks on errors due to modifications. The limitation of document-based can significantly impact larger projects but can also affect the subsequent projects of a certain system. If a system has to be changed or renovated and information is stored in documents, the needed information for subsequent projects may also be hidden and time-consuming to retrieve.

The final limitation of SE is closely related to the previous one. Communication and coordination can be challenging due to the involvement of multiple disciplines and stakeholders (Au & Ravindranath, 2020). Currently, each discipline within contractors uses its own sub-models and selection of tools, each with distinct purposes and specific information requirements and outputs. As a result, information may be duplicated across different models and tools, resulting in a lack of integrated overview. This fragmentation is inefficient and prone to errors. Together with the fact that each discipline has a different lead time, integral design becomes a challenge.

2.5 Summary

This section provides a summary of Chapter 2.

A system is often described as a combination of interacting elements organised to achieve one or more goals. Each of these elements may be decomposed into further subordinate system elements, which introduces hierarchy within systems. Each systems element has its own authorities, lifecycle, requirements, emergent behaviour, and interfaces.

Systems Engineering (SE) is a broad term and has been widely described in literature. The key elements of SE can be described as interdisciplinary, iterative, lifecycle, transparent, and requirements. The SE approach is based on Systems Thinking, which enhances understanding, definition, and interaction of systems.

ISO 15288 is a standard for SE which has widely been adopted by the construction industry. The ISO 15288 defines that a system progresses through its lifecycle by executing processes. A widely used lifecycle approach in the construction industry is the V-model, which focuses on concept, development, and realisation. The V-model highlights the need for continuous validation and verification. The V-model first decomposes a system into components and then integrates the several components into a whole.

Several processes occur within the lifecycle of a system to meet the client demand. These processes are categorised into Technical processes and Supporting processes by the standard ISO 15288. For the construction industry the processes are made more explicit in a Guideline SE so it can effectively be used at companies. A process flow model for contractors in this sector has been made by de Graaf et al. (2017). This diagram shows the iterative nature of SE and highlights in what order processes, like requirements analysis and design, are executed. Furthermore, it can be concluded that Verification and Validation (V&V) processes are recurrent.

Despite the advantages of SE, like increased customer satisfaction and reduced failure costs, the SE adoption by contractors faces challenges. SE is fundamentally a document-based approach and due to the substantial volume of project information in the current situation, processes are error-prone and inefficient. This resulted in time-consuming searching for information and documenting in digital tools due to the large amount of information. Finally, there are distinct sub-models for each discipline, each using its own set of tools with minimal interoperability, which makes communication complicated and execution time of processes larger.

3. MBSE and its added value

3.1 Introduction

This chapter delves into the concept of Model-Based Systems Engineering (MBSE), providing an answer on research sub-question 2 about its definition, benefits, and challenges. Section 3.2 start with determining the definition of a model within the context of this study. Next, it introduces the definition of MBSE, explaining the specific definition used, what it entails, and how it operates. Section 3.3 examines the benefits of MBSE, drawing insights from both literature and interviews. Section 3.4 provides an analysis of obstacles and limitations faced when adopting MBSE, as identified in existing literature and through interviews. Section 3.5 concludes the chapter with a summary.

3.2 MBSE

In this section, first the term 'model' will be examined to gain a clear understanding before determining the definition of MBSE. Subsequently, the characteristics of MBSE and its adoption components will be discussed.

3.2.1 Models

Before diving into MBSE, an understanding of a model is necessary. A model is a representation of a selected domain of interest, by capturing the important aspects and simplifying or omitting irrelevant features (Barcelo et al., 2012). Ludewig (2003) described three essential criteria that must be satisfied for a model to be considered valid: representation of an original objects or phenomenon, exclusion of properties of the original object or phenomenon, and establishment of a functional model, meaning it can effectively exchange the original for specific purposes.

A model can be a graphical, mathematical, or physical representation. Graphical models cover breakdown structures, flowcharts, or other types of diagrams. Mathematical models include models using equations. Physical models, such as 3D models, represent physical objects. The goal of a model is to facilitate understanding and decision-making.

This study uses the term 'model' to refer to an abstract description of a System of Interest (SoI). The specific abstraction decisions made within a model are guided by the model's intended purpose. Models can be used during the design phase to describe potential systems that have yet to be realised. These are referred to as descriptive models. In the field of SE, these kinds of models arise in the development and maintenance of a system (Fitzgerald et al., 2015). Specifically, descriptive models of existing system elements can be integrated with design models of elements that have to be constructed. Models can cover various aspects of a system, including its structure, functionality, communication, and behaviour.

3.2.2 MBSE definition

Wymore (1993) first introduced the term MBSE, covering several rigorous mathematical concepts, like the mathematical structure of requirements. The initial applications of MBSE emerged in the defence and aerospace industries in the early 2000s (Barcelo et al., 2012). Later, MBSE has been adopted by the automotive and manufacturing sectors. These industries deal with complex systems containing various subsystems, which MBSE effectively addresses. Today, MBSE is increasingly recognised as a preferred approach to system development, focused on formalising the use of models in requirement extraction, trade studies, analysis, design, and Verification and Validation (V&V) activities during the lifecycle of a system (Madni & Sievers, 2018).

The definition provided by INCOSE Technical Operations (2007) for Model-Based Systems Engineering (MBSE) is used in this study and is formulated as follows: "Model-Based Systems Engineering is the formalised application of modelling to support system requirements, design, analysis, verification, and validation activities, beginning in the conceptual design phase and continuing throughout the development and subsequent lifecycle phases". INCOSE predicts that the future of SE will be model-based, incorporating high-precision static and dynamic models across several levels of abstraction.

As it states in this definition, similar to SE, it supports the lifecycle processes of a system. MBSE can be viewed as an extension of the SE approach, by using one single centralised system model, also referred to as repository or overarching model, rather than separate individual models (Tommasi & Vacca, 2014). The term 'model-based' concerns the application of visual and textual information modelling methods, techniques, and tools to SE activities.

3.2.3 MBSE characteristics

The centralised system model is the single source of truth, reflecting the state of system development (Madni & Sievers, 2018). The MBSE system model comprises a set of interconnected models, each complementing with unique perspectives. This interconnection distinguishes MBSE from traditional engineering with models, in which models are used without consistency and relationships (Madni & Sievers, 2018). The multidimensional system model cannot be viewed in its entirety. Only the individual sub-models can be examined.

MBSE integrated models from various discipline into a unified system that represents the physical system and verifies its behaviour. This integration is illustrated in Figure 3.1. In the construction industry, examples of such representations include the geographical information model, the structural 3D model, and the Object Breakdown Structure. These models provide different perspectives but refer to the same physical system and facilitates the management of interactions between components and disciplines.

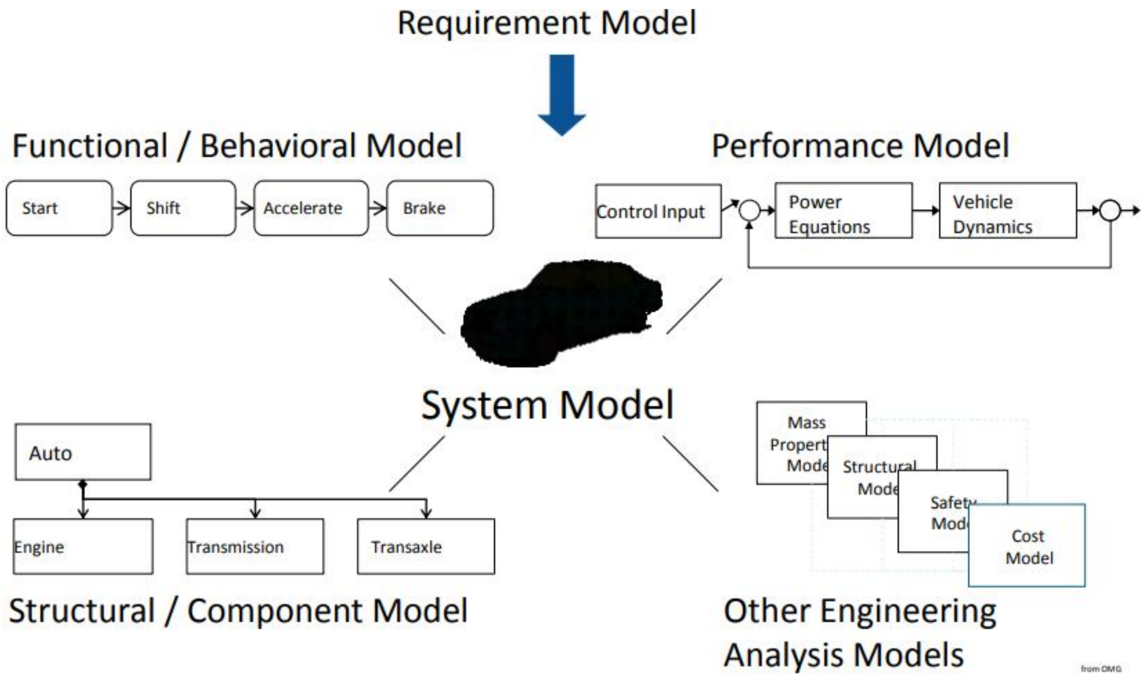

Figure 3.1: Set of models related to the system model in MBSE (Hart, 2015)

According to the previous chapter, the current SE processes in the construction industry are not entirely document-based but can better be described as digital-based. This represents an intermediate step between document-based and model-based approaches, as several digital tools and models are used to store information or documents. One of the digital tools used by contractors in the construction industry is Relatics. Relatics aids in managing complex project information by providing a central environment for requirements management, streamlining communications, and maintaining visibility into project breakdown structures and changes. Although Relatics describes itself as an MBSE tool, it is essentially a relational database in which elements can be linked and information can be stored. It primarily serves as a tool for storing information and generating documents based on the recorded data. This is different from how MBSE has been described earlier, which involves a centralised system model consisting of several interconnected sub-models. As an example, Relatics does not include a 3D constructive model.

The next in developing SE in the construction industry is to adopt a model-based approach. When a set of models is used, the models are interconnected and interdependent, ensuring that changes in one model require updates across the complete set (Acheson et al., 2013). This interdependence amongst models is not present in document-based or digital-based SE. MBSE moves from relying on authoritative documents to managing digital models within a comprehensive system model using extensive data. However, documents remain crucial for system development and client approval and thus should not entirely be eliminated. Consequently, MBSE has the ability of simple automated generation of documents, derived from the models (Wilking et al., 2024). This capability supports engineers by reducing the need for manually created engineering documents.

3.2.4 MBSE adoption components

To effectively adopt MBSE, an organisation must adhere to appropriate practices. There are three pillars considered to effectively adopt MBSE: methods, tools, and languages (de Saqui-Sannes et al., 2022). Each with its own unique features and strengths that make it more suitable for specific practices.

An MBSE modelling method refers to a systematic approach or set of procedures to perform specific tasks. It does not only focus on the creation of models, but users must also consider model governance and model usage. Although the number of MBSE is increasing over time, non are completely mature or compliant with the specific needs of an organisation. Furthermore, it is crucial to recognise that the adoption of MBSE necessitates the use of specific software tools or an integrated framework of tools (Chami et al., 2018). The strength of MBSE is dependent on these tools and current market offers a wide selection of such tools, each with distinct strengths and weaknesses. Consequently, an evaluation of available tools must be conducted before selecting an appropriate tool for MBSE adoption.

The standard MBSE language is SysML, which is a critical pillar for MBSE. However, there are many other languages available supporting the adoption of MSE. A language provides standardised guidelines and structures for expressing system information. It provides no information about the modelling process and must be integrated with a specific method to become entirely applicable. A concept frequently associated with models is the meta-model. This provides a formal definition of the model's properties and in essence defines the abstract syntax used by a modelling language. Furthermore, it serves as a representation of a category of models by sharing common characteristics within this language. A single modelling tool can generate multiple models, consisting of the same meta-model. Its relationship is illustrated in Figure 3.2. An overview of the methods, tools, and languages in provided in Chapter 5.

The discussion of MBSE adoption often centres on the technical details, like language and tools, instead of identifying and understanding the human factor and processes. This is the reason Chami et al. (2018) describes two other crucial components for MBSE adoption: personnel and processes. The personnel component relates to the personnel involved in the MBSE adoption and the effect they have on the adoption. This component should include both technical and management aspects and is often underestimated. MBSE must be aligned to a process to connect disciplines and effectively execute activities.

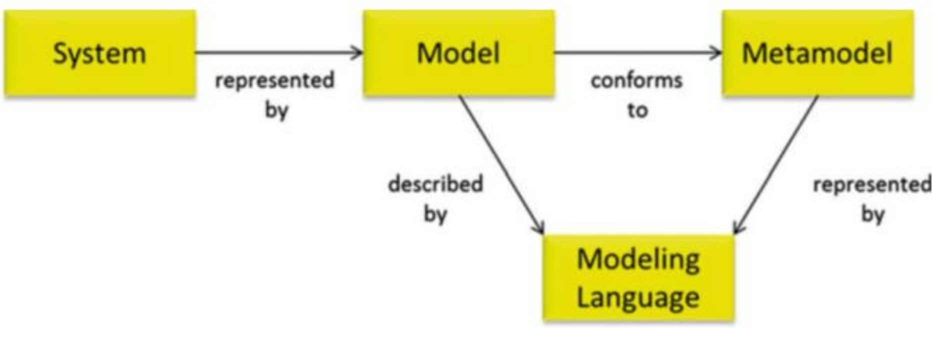

Figure 3.2: System, model, modelling language, and meta-model (Madni & Sievers, 2018)

3.3 Benefits of MBSE

MBSE offers a variety of benefits that has been widely documented in literature. This section provides the key benefits of MBSE. As MBSE replaces the traditional document-centric approach with a centralised system model, it can provide a single source of truth. This model-driven approach ensures that each stakeholder, like engineers or clients, work with consistent, updated, and traceable information throughout the system lifecycle (Walden et al., 2015).

One of the most significant advantages of MBSE is the enhancement of communication and collaboration across multidisciplinary teams. Using a unified model, MNSE helps to align subsystems, disciplines, and stakeholders. This alignment fosters a more unified and integrated approach to system development, which reduces misunderstandings and deviations.

Furthermore, MBSE significantly improves the management of complex systems. It allows systems to be visualised from multiple perspectives including requirements, behaviour, structure, and design. This comprehensive visualisation supports impact analyses and consistency, enabling teams to trace every design element back to its associated requirement and rationale (Walden et al., 2015). The ability to view the system from different perspectives ensures that each aspect is considered, leading to a more robust and transparent design.

The use of formal models also facilitates early validation and simulation, leading to the earlier detection of design errors. Simulating the System of Interest (SoI) allows for behavioural analysis, performance assessments, and trade-off decisions before implementation (Madni & Sievers, 2018). This proactive approach helps identify design errors, non-compliances, or performance issues before they become costly problems. Early validation and simulation catch potential issues in the design phase before the production phase starts.

Early error detection contributes to improved product quality and more efficient development timelines. Fewer defects result in less rework, accelerating the overall process and reducing costs (Carroll & Malins, 2016) (Chodas, 2014). This reduction in rework not only saves time and money but also enhances the reliability and performance of the final product.

Finally, MBSE enables better knowledge capture and reuse. Storing system information in standardised and structured models leads to easier transfer knowledge across projects and teams, leading to shortened development cycles and long-term efficiency benefits (Walden et al., 2015). This structured approach to knowledge management ensures that valuable insights and lessons learned can be captured and used for future project, promoting continuous improvement and innovation.

3.4 MBSE challenges

Although MBSE offers many advantages, its successful adoption depends on overcoming several challenges. Understanding and addressing them is essential to realise the full potential of MBSE in practice. The challenges have been examined in the literature and can be organised into four key dimensions: Human, Technological, Organisational, and Financial.

3.4.1 Human

One of the primary challenges in adopting MBSE is the steep learning curve involved in transitioning to MBSE. Project managers and engineers, used to their traditional document-based methods, may struggle to shift towards a model-based approach, which necessitates a different mindset (Friedenthal et al., 2014). Challenges emerge when end users have diverse levels of MBSE knowledge and are not provided sufficient time for training and development.

According to Hallqvist & Larsson (2016), MBSE is fundamentally a change process that impacts a highly complex system, with humans being the critical system elements. Resistance is common, particularly when employees lack familiarity with new processes and modelling tools. This knowledge enables them to appreciate the value of models and accurately interpret the information derived from the MBSE processes and tools (Carroll & Malins, 2016).

Another challenge is the risk of over-reliance on models. Solely depending on models without cross-validating them with real-world data can lead to overconfidence and trust by humans in the predictions the models generate. This increases the likelihood of overlooked risks or errors during project execution (Madni & Sievers, 2018). However, innovative technologies such as Artificial Intelligence (AI) can help mitigate this. For example, AI can detect large outliers in live performance data of objects. In this way, early risk detection can be supported (Wu et al., 2024).

3.4.2 Technological

Selecting a method, toolset, and modelling language for MBSE is challenging, as these elements are interconnected. One of the biggest shortcomings in the immaturity of MBSE tools and frameworks, which often over-promote their capabilities. No single selection can satisfy every requirement, and integration with other systems, such as simulation, requirements management, or existing IT infrastructure, often demands custom solutions (Chami et al., 2018). Another challenge is the integration of MBSE with existing tools and processes. Many organisations have established workflows that rely on document-based systems, making the integration of MBSE into these workflows a complex and time-consuming process (Heydari, 2023).

Another critical issue is the lack of consistency and standardisation across models. When teams use inconsistent terminology, methods, or assumptions, it can result in confusion and miscommunication, highlighting the need for strict standardised processes in MBSE (Madi & Sievers, 2018). Developing a tailored MBSE method aligned with a predefined purpose and scope is also a challenge (Chami et al., 2018). Setting up the required method and facilitating it with modelling rules, guidelines, and tool modifications can be a challenging task. Although the number of MBSE methods is increasing over time, none are completely ready for use or aligned with specific organisational needs. For adoption to succeed, the chosen method must match the knowledge, experience, and working culture of the people involved. The chosen method must also serve as a clear communication tool towards stakeholders.

The evolution of systems, characterised by an increasing number of components and interactions, has also increased their complexity. This arises due to the high number of model elements and the dependencies amongst these elements and models. Frequently, this level of complexity challenges the boundaries of existing MBSE methods and tools (Chami et al., 2018).

3.4.3 Organisational

In addition to the technical aspects of developing the models, it requires a cultural change which affects the overall organisation structure in terms of adopting new processes in current SE processes. Adopting MBSE effects collaboration, management, and decision-making of teams throughout the project lifecycle. Organisations must establish clear model management processes to ensure MBSE models are properly created, updated, verified, and reused (Carroll & Malins, 2016). Without extensive validation, configuration control, and quality checks, the value of models decreases quickly.

A lack of commitment form management can be a significant barrier for teams attempting to adopt MBSE, as the risk associated with unfamiliarity is only supported by operational stakeholders in such cases (Bonnet et al., 2015). Without strong managerial support, teams may struggle to effectively adopt MBSE.

An organisation can choose between two adoption strategy approaches: off-cycle of on-cycle. Off-cycle refers to flexible adoption that allows for quick adaptation to changing circumstances. On-cycle refers to strict planning, integrating MBSE directly into projects. The first approach is considered ideal, as the second approach is more challenging due to additional costs for ongoing projects (Chami et al., 2018). The on-cycle approach can lead to increased resistance if the change is too substantial, causing engineers to become overwhelmed by the complexity. Suryadevara & Tiwari (2018) concluded that MBSE adoption cannot be achieved in one go. An off-cycle approach, when implemented iteratively, is considered more ideal as it allows for learning and adaptation, drawing valuable lessons during the process.

3.4.4 Financial

Lastly, adopting MBSE requires a substantial upfront investment, particularly if it has not yet been considered. This includes determining an effective investment strategy, accurately estimating costs, and quantifying the return on investment (Chami et al., 2018). Additionally, an organisation must invest in full-scale MBSE tools and institutionalise tool-use procedures to ensure compatibility of tools.

An organisation must also invest in training, coaching, and collaboration. Engineers might get overwhelmed by the complexity of MBSE (Bonnet et al., 2015). Coaching helps engineers to use MBSE correctly and ensures to achieve the benefits. Another important enabler is to build confidence through best practices, examples, and success stories. Lessons learned from earlier applications, shared through sessions, can enhance adoption and avoid common obstacles.

3.5 Summary

This section provides a summary of Chapter 3.

Before applying MBSE, it is essential to first understand it. A model is a crucial part of MBSE and can be described as a simplified, purposeful representation of a system that omits irrelevant details. According to INCOSE (2007), MBSE uses interconnected models to represent different system views, replacing fragmented and document-based approach with a centralised system model, which serves as a single source of truth.

Effective MBSE adoption requires alignment across three pillars, which are method, tool, and language, and requires attention to components like personnel and processes. Methods define how modelling is done, tools enable it, and languages like SysML provide a standard for communication. However, successful adoption also depends on trained engineers and the integration of MBSE into current processes.

MBSE offers numerous benefits, like ensuring consistent and traceable information for each stakeholder by replacing traditional document-centric approach with a centralised system model. Furthermore, MBSE enhances communication and collaboration across multidisciplinary teams, aligning subsystems and stakeholders, thereby reducing misunderstandings. Early validation and simulation facilitated by formal models also help to detect design errors early. Additionally, MBSE enables better knowledge capture and reuse, promoting faster development cycles and long-term efficiency. Every benefit contribute to greater consistency, quality, and efficiency in the engineering process.

MBSE can address some of the issues faced by SE, but it also comes with its own set of limitations and challenges. These challenges can be categorised into four components: Human, Technological, Organisational, and Financial. Human challenges include the steep learning curve for training and resistance to change amongst engineers familiar with the traditional workflow. From a technological perspective, selecting and integrating appropriate tools, methods, and languages can overwhelm existing systems and teams. Other technological challenges relate to the need for standardisation and risk of over-reliance on models. Organisational challenges include cultural change, managerial support, and the selection of an adoption strategy. Financially, this approach demands significant upfront investments in tools, training, and coaching.

4. Values and requirements for MBSE adoption

4.1 Introduction

This chapter addresses research sub-question 3 by exploring the requirements for the successful adoption of MBSE. Understanding these requirements is crucial to ensure that the proposed adoption is both feasible and aligned with the needs. Section 4.2 starts by outlines the structured approach to formulate an adoption proposal, detailing the steps to translate identified needs into a complete design. Section 4.3 explores MBSE applications in other industries, aiming to draw valuable lessons and best practices that could enhance the effectiveness for the construction industry. Section 4.4 presents an analysis of data collected through semi-structured interviews. Building on these findings, Section 4.5 defines values and derives requirements for successful MBSE adoption. Finally, Section 4.6 summarises the main insights and conclusions from this chapter.

4.2 Workflow MBSE adoption

To effectively adopt MBSE in an organisation, a certain workflow must be followed. This is a sequence of steps need to establish effective adoption. As explained in Chapter 2, the ISO 15288 is a standard approach for Systems Engineering. This standard start with analysis of requirements before selecting design options and the actual designing of a system. Such an approach will be used for this research, as it has widely been adopted in other industry MBSE adoptions and SE in general. This sequence of steps and comparison to ISO 15288 have also been applied by Suryadevara & Tiwari (2018), illustrated in Figure 4.1.

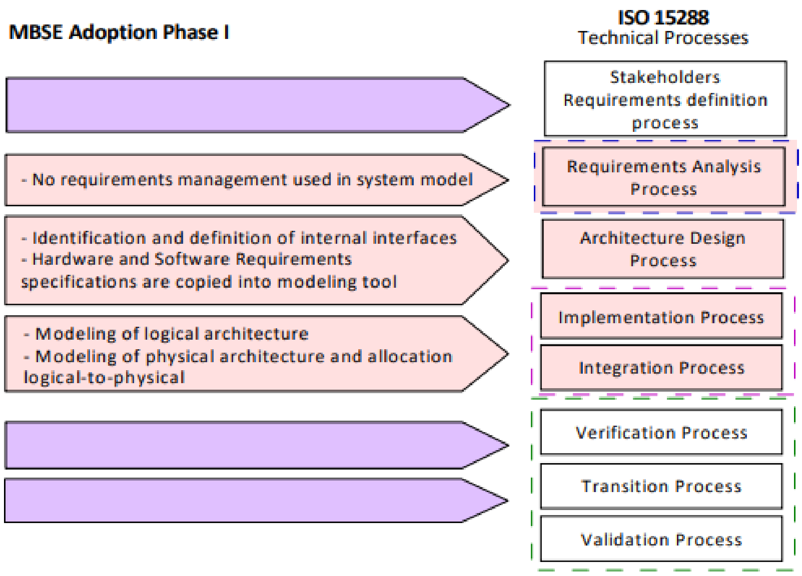

Figure 4.1: MBSE adoption steps and comparison to ISO 15288 (Suryadevara & Tiwari, 2018)

To effectively adopt MBSE for a contractor in the construction industry, first the requirements for adopting MBSE should be established. Based on the challenges of MBSE, the comparative industry analysis, and semi-structured interviews with BAM employees, such requirements can be derived. Next, appropriate methods, tools, and languages can be selected. Sideris (2024) also first established the capabilities and requirements before selecting the MBSE methods, tools, and languages. The research workflow should at least include one iterative loop. At the end of this research, the expert session and case study will serve as iterative loops for improvement of the MBSE adoption proposal.

4.3 Comparative industry analysis

To investigate how MBSE should be adopted in the construction industry based on other industries, a comparative industry analysis will be conducted. This analysis will provide insights on steps taken in various adoption examples and valuable lessons they have discovered. The analysis may also provide standards for requirements the MBSE adoption at a contractor must adhere to.

Before comparing and analysing industries, it must first be clear which industries will be analysed. Industries that widely adopted MBSE and industries which has been intensively cited in literature regarding MBSE will be selected for this analysis. The industries that meet these two conditions are the aerospace and automotive industry.

After these industries have been selected, a consistent set of comparison criteria must be established. These criteria can be derived from the goal of the comparative industry analysis. The goal is to identify adoption approaches, and success factors or lessons learned. In the two sections below, the aerospace and automotive industry will be analysed on these three components of the analysis' goal.

4.3.1 Aerospace industry

The aerospace industry is characterised by the creation of highly complex and safety-critical systems. Examples of such systems are aircrafts. These systems necessitate precise design, verification, and validation processes to ensure they meet strict performance and safety standards. Aerospace industry was one of the first to introduce MBSE to make sure this complexity could be managed (Pratt & Dabkowski, 2022). This industry used a stepwise MBSE adoption approach. This helped monitoring progress and making necessary adjustments without huge effects, keeping integration complexity manageable. Zhao et al. (2024) and Zhang et al. (2019) initiated such an MBSE adoption approach through pilot projects or pilot-like initiatives before scaling up.

The first critical insight from adopting this innovation concerned not having a unified approach to using MBSE, as different institutions have their own methods. Engineers must understand clearly the MBSE models. Standardising the modelling process and methodologies is crucial for this, making it easier to manage complex systems and ensure everyone is on the same page (Wenyue et al., 2022). This underscores the importance to clearly set up modelling guidelines describing what information should be captured in which tools or models.

New tools and languages can be challenging for entire organisations to learn. Therefore, organisations should prioritise adopting the simplest tools or languages or limit the introduction of new ones when adopting MBSE. This approach helps reduce resistance to change (Pratt & Dabkowski, 2022). Lastly, it is beneficial to focus on performance expectancy by inspiring the future workforce. For example, by highlighting MBSE successes and publishing metrics that demonstrate improvements in projects utilising MBSE (Pratt & Dabkowski, 2022).

4.3.2 Automotive industry

The automotive industry includes the creation of motorised vehicles. Examples of such vehicles are cars, motorcycles, and trucks. This industry has been experiencing a transformation with the advent of autonomous, connected, and electric vehicles. This evolution has resulted in increased system complexity, requiring an advanced engineering approach like MBSE. The automotive industry also applied an adoption strategy that starts small with targeted use cases (Brenk et al., 2024). This could involve only focusing on a pilot project in a specific domain such as embedded systems.

One of the best practices found by the automotive industry was to establish multiple maturity levels of MBSE and use point or gates for these levels to check (Fritz et al., 2014). In this way, MBSE can be integrated in steps. This helps by first experimenting with MBSE to build experience, implement adaptations, and helps reducing the risk of early resistance. Other lessons learned, similar to the aerospace industry, were the sharing of success stories and pilots and the standardisation of processes and clear guidelines. As a final note, integrating MBSE methods, tools, and processes with existing tools, processes, and systems is known as a technical bottleneck in the automotive industry (Fritz et al., 2014). There is a lack of easy-to-integrate tool solutions available for existing tool landscapes, partly due to the complexity of MBSE.

Practice in the automotive industry has shown that gaps in the flow of information often lead to inconsistencies or data loss, resulting in errors that are only discovered during reviews or testing (Brenk et al., 2024). Many companies rely on Requirements Management tools as the single source of truth, as MBSE tools are often less practical for communication with stakeholders and disciplines, and are less widely accepted (Brenk et al., 2024). This indicates that models are not sufficiently aligned due to a lack of integration with MBSE tools. As a result, a truly unified and model-based single source of truth has not yet been established in many cases.

4.4 Semi-structured interviews

The semi-structured interviews of this study are conducted with six employees of the company BAM. The participants are engineers and managers from diverse disciplines and business units to minimise bias. But also, by making sure the number of years working experience differed largely between the participants. This creates a variety in background, leading to a high variety of insights.

4.4.1 Goal and process of the interviews

The objective of the interviews is to identify requirements the MBSE adoption must adhere to. This includes design requirements of the MBSE system model, but also the available resources needed for successful adoption. Additionally, by comparing MBSE to other digital transformations, challenges and experiences can be obtained. Lastly, the limitations of the current processes and added value of MBSE from literature findings can be compared to the findings of interviews with employees of a contractor.

The participants have been selected based on experience with SE processes, design and information management, and digitalisation. The interviews have been prepared beforehand by creating a protocol including an introduction and establishing a number of questions. The interview questions can be found in Appendix A. Consequently, the data have been collected during interviews and have been processed by creating anonymised summaries. The summaries have been created detailed to not miss any information and are provided in Appendix B.

4.4.2 Thematic analysis

These anonymised summaries have been analysed based on a thematic analysis method. This analysis included four themes on which the interviews have been analysed. This includes the following themes:

- **Limitations current processes and added value MBSE.** To check if limitations experienced by employees have similarities with SE limitations from literature and if new limitations can be discovered. As well as to check if these limitations can partly be mitigated by the added value of MBSE.
- **Challenges of past digital advancements.** To identify recurring challenges within an organisation from previous digital advancements. These insights can serve as a foundation for MBSE adoption strategies by learning from past experiences.
- **Principles or requirements for MBSE adoption.** To uncover system principles and requirements that can be considered critical for successful MBSE adoption. This includes both technical and organisational aspects.
- **Resources for successful MBSE adoption**. To determine which resources are needed to enable successful and efficient MBSE adoption within organisations.

The analysis itself can be found in Table C.1 in Appendix C.

4.4.3 Result of analysis

The results of this analysis are provided in this section.

Limitations current processes and added value MBSE

The current processes at contractors face several limitations, according to the participants. A significant limitation is the absence of clearly defined requirements and requirements hierarchy from clients, leading to misinterpretation, late error detection, and overlooked dependencies. Additionally, outdated, or incomplete information, caused by poor documentation or data loss, further reduces reliability. Decision-making frequently relies on undocumented, judgement-based reasoning, resulting in a lack of traceability and difficulty in understanding rationale behind decisions. Furthermore, repetitive data entry and manually storing large volumes across multiple systems introduces delayed processes and increases the risk of inconsistencies.

Many of these limitations lead to delays and a higher number of errors as a result of a document-based SE approach and no single source of truth in the current situation. This aligns with SE limitation findings from the literature of Chapter 2. The practical limitation of no clearly defined requirements from clients was not found in the literature.

MBSE is viewed as an approach to mitigate the lack of traceability and repetitive data entry. It also facilitates better communication between various disciplines and stakeholders through visual models and a shared system. The MBSE system will reduce the number of errors due to transparent information exchange. Another, not previously mentioned, advantage of MBSE is the standardisation of activities. Reusing standard models, for example for a bridge system, 80% of the project elements can be copied and only 20% needs to be modified. Most of the benefits will lead to improved efficiency and management and shortened design phases as MBSE does not rely on manually repetitive documentation. These benefits are expected to contribute significantly to address several of the identified limitations.

Challenges of past digital advancements

Several digital advancements participants have experienced were discussed, like the implementation of 3D modelling, Relatics, PowerBI, 4D planning, and drone technologies. The most significant challenges mentioned by the participants are organisational and human related. In particular, human resistance due to a lack of understanding, unclear added value of the change, and fear of losing control. Organisational factors, such as the fragmentation of disciplines and departments, limit effective collaboration and knowledge sharing, which hinders the adoption of new practices or innovations.

Organisation must focus on change management by communicating a clear reason and motivation of the benefits for end users. Furthermore, success depended on introduction of pilot project, user-friendliness, and easy integration with existing systems.

Principles or requirements for MBSE adoption

To manage MBSE effectively, a standardised approach is preferred, but the MBSE system must remain flexible to support unique demands of different projects. This flexibility is essential because contractors operate as project-based organisations and thus must adapt to varying project requirements. Some participants preferred a more standardised system and some a more flexible. However, the system should aim for internal standards, as this leads to better communication, data traceability, and reusability. As an example, a standardised approach is used for tools like Relatics and ThinkProject. As clients might differ in communication and standards, the interface level should be flexible and adaptable for each client. The system or tools should also include automated alerts to prevent unintended changes.

Other requirements are user-friendliness, connection to and use of existing systems, minimisation of new tools, and usage of MBSE tools with support and widely usage. Current tools, like Relatics, are indispensable, as it is widely used and supported in the Dutch construction industry. It is recommended to integrate MBSE into the current system, while limiting new methods, tools, and languages or even better to consider avoiding them.

Another requirement is the establishment of clear processes and responsibilities of MBSE, as roles will change. Participants emphasised the importance to maintain traditional principles of SE to minimise the extent of change and to use a tool, method, and language that is based on open standers. The last requirement noted is the necessity of early-stage model validation. Regular model reviews are essential to ensure the accuracy and reliability of the models, helping engineers maintain control. This can be achieved, for instance, by examining the rules behind decision-making of the system model.

Resources for successful MBSE adoption

A key resource increasing user acceptance is the demonstration of practical benefits to end users, as discussed at the section of challenges of previous digital advancements. The technological infrastructure will not raise concerns due to the technical and IT knowledge within the company. As mentioned before in the past digital advancements section, MBSE should be adopted in phases and through pilot projects to build end user confidence and to avoid high risks of failure.

Resources related to the human aspect are emphasised, like training and coaching on projects, continuous support and monitoring, introduction with success stories, and the involvement of enthusiastic and influential personnel across departments and disciplines. Thereby, management plays a pivotal role, as it can support the distribution of success stories. If management conveys a clear and consistent message about the benefits for the organisation, employees more easily accept and adopt the change. As a final note, such a technological implementation requires development and preparation time, budget, and available employees.

4.5 MBSE adoption values and requirements

When considering a technological adoption like MBSE, it is essential to define clear and structured requirements from the beginning. Without understanding the needs, the risk of implementing a solution that fails to deliver value arises. This also applies to construction industry projects, in which clearly defined requirements are crucial to ensure the final structure meets its intended purpose. As architectural and regulatory specifications guide the construction of a building, the successful deployment of MBSE depends on a thorough understanding of the operational, technical, and organisation needs.

Each stakeholder involved in MBSE adoption has its own values of what they consider important. These values are the basis for the specific and detailed requirements. The values are derived from the MBSE challenges, comparative industry analysis, and semi-structured interviews. Values considered to be important for MBSE adoption are as follows:

- **Integration**. MBSE must improve collaboration between disciplines, departments, and tools. Integration of systems, models, and tools is essential to enable this.
- **Standardisation rate**. Standardisation ensures reusability and prevents miscommunication. On the other hand, a system must be flexible to make project-specific modifications and to scale up.
- **User experience.** User experience of a systems and its processes allow for easier and faster acceptation of the change. Teams can work more effective if the system is user-friendly, accessible, and reliable.
- **Controllable change**. A change must proceed gradually to keep the change controllable and to learn from previous situations.
- **Accountability.** MBSE must lead to accountable choices and modifications, increasing trust and quality as a result of consistency.
- **Continuous learning**. To be able to adopt MBSE effectively, a culture must be established in which development is considered a crucial aspect.
- **Leadership engagement.** Adopting MBSE requires clear leadership from management to build support and motivation amongst employees.

Specific requirements can be derived from these values, based on the sources of these values. The requirements are categorised into Technical and Organisational requirements. Table 4.1 provides the specific requirements, including the value, categorisation, and the source of these requirements. Below Table 4.1, a short description of each specific requirement is provided.

Value	Categorisation	Specific requirement	Source
Integration	Technical	Seamless system/tool integration	Comparative industry analysis. Interviews. MBSE challenges.
Standardisation rate	Organisational	Standardised MBSE framework	Comparative industry analysis. Interviews. MBSE challenges.
	Technical	Flexible standardisation of system	Interviews.
User experience	Organisational	Reliable tool adoption	Comparative industry analysis. Interviews.
		User-friendly MBSE approach	Comparative industry analysis. Interviews.
	Technical	Open standard compliance	Interviews.
Controllable change	Organisational	Minimal expansion	Comparative industry analysis. Interviews. MBSE challenges.
		Pilot-based adoption	Comparative industry analysis. Interviews. MBSE challenges.
		MBSE maturity framework	Comparative industry analysis. Interviews.
Accountability	Technical	One single source of truth	Comparative industry analysis. Interviews.
		Traceability of decisions	Interviews.
		Early-stage model analysis	Interviews. MBSE challenges.
Continuous learning	Organisational	Extensive capability development	Comparative industry analysis. Interviews. MBSE challenges.
Leadership engagement	Organisational	MBSE success communication	Comparative industry analysis. Interviews.
		Management commitment	Comparative industry analysis. Interviews. MBSE challenges.

Table 4.1: Requirements for MBSE adoption with its related values, categorisation, and source

Requirements with description:

- **Seamless system/tool integration.** To ensure that the MBSE system is technically compatible with the current system by successfully integration with current tools, such as Relatics, without data loss, manual data import, or double data entry.
- **Standardised MBSE framework.** Define and create a MBSE document including clear MBSE processes, guidelines, terminology, and modelling methods. Also, 80% of the users must understand this to apply it in their daily practices.
- **Flexible standardisation of system.** A standardised MBSE framework or system must be available to keep internal processes constant. This framework should at least be applicable to three different projects, and projects can make project-specific modifications without affecting the standard framework or system.
- **Reliable tool adoption.** The tools should include active helpdesk support and be widely adopted or accepted in at least two other sectors.
- **User-friendly MBSE approach.** The MBSE adoption should be user-friendly according to at least 75% of the end users, while they must be able to create models independently within two months.

- **Open standard compliance.** The system should not rely on a single supplier. Ensuring open standard methods, tools, and modelling languages will avoid the risk of vendor lock-in, a situation in which an organisation becomes dependent on a single supplier for products or services. This limits flexibility and increases switching costs.
- **Minimal expansion.** The transition to MBSE tools, methods, processes, and languages should not be overly complex or intensive. This includes limiting the number of new methods, tools, and modelling languages. Additionally, the method should cover the ISO 15288 standard process steps to limit the changes of processes.
- **Pilot-based adoption.** At least one pilot project must be executed to evaluate the proposed adoption and to collect lessons learned before scaling up, to avoid high risks. This also includes creating a lessons-learned document.
- **MBSE maturity framework.** Define and establish MBSE maturity levels to measure progress, set goals, and guide improvement efforts. This includes establishing MBSE characteristics defined across at least three maturity levels.
- **One single source of truth.** A single source of truth must be established, ensuring data consistency across systems. In this way, data can be shared effectively between tools without inconsistencies, allowing disciplines to use the correct and consistent set of information.
- **Traceability of decisions.** Ensure each model decision, including modification, is traceable by linking it to metadata and entering it into a model.
- **Early-stage model analysis.** Enable early-stage validation and simulation of models to detect design issues and improve decision-making before design decisions have been made. Ensure at least one simulation is conducted before the design phase.
- **Extensive capability development.** Offering extensive training and a coach on each project helps team members to develop competence and confidence in using MBSE.
- **MBSE success communication.** Communicate benefits and successes of MBSE initiatives through at least three success stories increases support, motivation, and understanding amongst end users.
- **Management commitment.** Management must ensure active involvement of management through a clearly documented vision and support.

4.6 Summary

This section provides a summary of Chapter 4.

Chapter 4 addresses the requirements for the successful adoption of MBSE in the construction industry, specifically for contractors. It answers research sub-question 3 and discusses the defined workflow, a comparative industry analysis, semi-structured interviews with BAM employees, and the derivation of values and requirements for adoption MBSE effectively.

The proposed workflow for MBSE adoption is based on ISO 15288, which focuses on first identifying systems requirements before selecting appropriate methods, tools, and modelling languages. Iterative feedback loops, by conducting an expert session and case study later in this research, are essential for the last refinement of the MBSE proposal.

The comparative analysis of the aerospace and automotive industry reveals key success factors such as phased adoption, standardisation of processes, user-friendliness, and integration with existing systems. Both industries highlight lessons learned, like pilot projects, sharing of success stories, and minimising the introduction of new tools to reduce resistance, delays, and integration challenges.

Semi-structured interviews with BAM employees confirm these insights and reveal additional SE challenges, like the lack of clearly defined client requirements. MBSE is regarded as a solution to these issues by improving traceability, communication, and efficiency. The interviews also reveal new adoption challenges, such as a fragmented organisation and human resistance to change. The participants of the interviews emphasise requirements for successful MBSE adoption, such as standardisation with a degree of flexibility, easy traceability of choices and modifications, and the use of open standard based methods, tools, and languages. Lastly, it was recommended to limit the introduction of new methods, tools, and languages or even consider avoiding new ones.

From the previous findings, seven core values for MBSE adoption are identified: integration, standardisation rate, user experience, controllable change, accountability, continuous learning, and leadership engagement. These values form the basis for both technical and organisational requirements, including seamless system and tool integration, open standard compliance, standardised MBSE framework, early-stage model analysis, extensive capability development, and management commitment. These specific requirements provide a comprehensive strategy for adopting MBSE at a contractor.

5. MBSE methods, tools, and languages

5.1 Introduction

This chapter delves into the MBSE methods, tools, and modelling languages to partly answer research sub-question 4 about the MBSE adoption proposal. The change in Digital Information Management, the other part of this sub-question, is covered in Chapter 6. Section 5.2 starts with defining a method, tool, and modelling language before discussing the most frequently mentioned MBSE methods, tools, and languages in the literature. These three pillars are analysed in Section 5.3, based on the derived requirements for MBSE adoption of Chapter 4. Finally, Section 5.4 summarises the main insights and conclusions drawn throughout the chapter.

5.2 Available methods, tools, and languages

In Section 3.2.4, the definitions of a method, tool, and modelling language were discussed. To recall, a method is a set of procedures or processes together with supporting modelling languages and tools. A modelling language is used to describe the models and can define symbols or rules of models. Modelling languages can be used by various tools and in various methods. A tool is a software application to help create, manage, analyse, and visualise models. MBSE tools may occur in several methods and some support multiple modelling languages. Many MBSE methods, tools, and languages have been described in academic literature, and if used collectively and effectively they can realise characteristics of MBSE. The MBSE methods, languages, and tools have been selected for this study, based on the frequency of citations in academic literature.

The MBSE methods that have been investigated for this study include Object-Oriented Systems Engineering method (OOSEM), Object Process Methodology (OPM), ISE&PPOOA, IBM Telelogic Harmony, Systems Modeling Toolbox (SYSMOD), Rational Unified Process for Systems Engineering (RUP SE), MagicGrid, ARCADIA, and ViTech MBSE methodology. The researched MBSE languages are Unified Modeling Language (UML), Systems Modeling language (SysML), Object-Process Diagrams (OPD) / Object-Process Language (OPL), System Definition Language (SDL), ArchiMate, Business Process Model and Notation (BMPN), and Modelica. The included tools for this study are Cameo, Capella, CORE/GENESYS, Enterprise Architect, IBM Rational Rhapsody, Modelio, Object-Process CASE Tool (OPCAT), and OpenModelica. An overview of the characteristics of these MBSE methods, tools, and languages is provided in, respectively, Table 4.2, Table 4.4, and Table 4.3.

Method and sources	Characteristics	Modelling language	Tool support
Object-Oriented Systems Engineering method (OOSEM) (Estefan & Weilkens, 2022) (Baron et al., 2023) (Filho et al., 2021)	- Consistent with V-model and ISO 15288 standard - Object oriented and usage driven approach - Flexible methodology - Supports analysing stakeholders' needs, defining system requirements and logical architecture, synthesise allocated architectures, and V&V - Highly used in industries	SysML	Tool-neutral but can be used by Cameo, Enterprise Architect, IBM Rational Rhapsody, Modelio
Object Process Methodology (OPM) (Estefan & Weilkens, 2022) (Filho et al., 2021)	- Object- and process-oriented approach - Combines structure and behaviour in one model - Objects can have states (conditions) at given times - Supports requirements specifying, analysing, and designing, implementing, maintaining - Highly used in industries	Object-Process Diagrams (OPD) / Object-Process Language (OPL)	Object-Process CASE Tool (OPCAT)
ISE&PPOOA (Estefan & Weilkens, 2022)	- Object- and process-oriented approach - Suited for software intensive mechatronic systems - Supports stakeholders needs analysis, requirements definition, architecture definition, design definition, system analysis, integration, and V&V	UML/SysML	Tool-neutral, but can be used by diverse commercial SysML tools
IBM Telelogic Harmony (Hoffmann, 2011) (Suryadevara & Tiwari, 2018)	- Consistent with V-model - Service request-driven approach - Suited for software-intensive and embedded systems - Supports stakeholders needs and requirements definition, architecture definition, design definition, integration, and V&V	SysML	Tool-neutral, but frequently used with IBM Rational Rhapsody
Systems Modeling Toolbox (SYSMOD) (Estefan & Weilkens, 2022) (Filho et al., 2021)	- Focus on roles, methods, and products - Used for pragmatic modelling of systems - Practical and mapped to ISO 15288 standard by supporting stakeholders' needs and requirements definition, architecture definition, design definition, and V&V - Highly used in industries	SysML	Tool-neutral, but can be used by Cameo, Enterprise Architect, IBM Rational Rhapsody, Modelio
Rational Unified Process for Systems Engineering (RUP SE) (Estefan, 2008) (Cantor, 2003)	- Not consistent with V-model - Emphasis on business modelling, business actors, and flow of events - Object oriented approach - Used for development of large scalable systems including software, hardware, and information	UML/SysML	IBM Rational Rhapsody
MagicGrid (Aleksandravičienė & Morkevičius, 2021) (Plattsmier, 2019)	- Aligned with ISO 15288 processes by using a matrix with domains (phases) and pillars like requirements, behaviour, structure, and parametric - Supports hardware and software systems - Less used in industries	SysML	Tool-neutral as long as the tool supports SysML. Cameo is a primary used tool
ARCADIA (Baron et al., 2023) (Filho et al., 2021)	- Based on ISO 15288 standard - User-friendliness for beginners and flexible - Add-ons needed for simulation (e.g., Simulink) - Excellent in functional modelling - Used for designing systems, hardware, and software - Highly used in industries	Domain specific language	Capella
ViTech MBSE methodology (STRATA) (Estefan, 2008) (Suryadevara & Tiwari, 2018)	- Concurrent design and incremental approach - Supports requirements, behaviour, architecture, and V&V - These processes are executed at a level of detail before transitioning to the next layer ('Onion model')	System Definition Language (SDL)	GENESYS

Table 4.2: MBSE methods with its characteristics, modelling languages, and tools

Modelling language and sources	Characteristics
Unified Modeling Language (UML) (Hause, 2006)	- To model the structure and behaviour of systems - Visual language based on fourteen structure and behaviour diagrams - Widely used in software industries - Requirement and simulation support is limited - Open standard
Systems Modeling Language (SysML) (Hause, 2006)	- Extension of a subset of UML - General purpose modelling language for SE applications, not only on software systems - Graphical language based on nine types of diagrams (including four of the UML diagrams): Activity, Sequence, State Machine, Use Case, Requirement, Block Definition, Internal Block, Parametric, and Package - Elements from structure, requirements, behaviour, and parametric can be cross-connected - Widely used and acceptance in industries like aerospace and defence - Strong requirement and partly simulation (parametric) support - Not meant for beginners and the functional analysis is a limitation - Open standard - Used by many tools
Object-Process Diagrams (OPD) / Object-Process Language (OPL) (Dori et al., 2004)	- Diagrams (OPD) are automatically translated into language (OPL), which can be read by non-technical stakeholders - Suitable for requirements, system design, and simulation - Requirements are modelled as objects, not in a diagram - Only used by the tool OPCAT - Open standard - Used in industries but less than SysML
System Definition Language (SDL) (Nutting, 2014)	- Used to create a schema that defines potential relationships between different elements in the model - Less interoperable compared to UML and SysML as it does not expose a robust metamodel - Easier to understand for non-specialised systems' stakeholders - No open standard - Only used by the tool GENESYS
ArchiMate (Band et al., 2015)	- Graphical language, focused on enterprise architecture and business goals and models, not on engineering systems behaviour or physics - Open standard - Supported by many tools, like Enterprise Architect
Modelica (Qui et al., 2024)	- Used for modelling dynamic behaviour of physical systems (simulation) in building and energy sector - No focus on requirements modelling and system architecture - Open standard - Supported by tools, like OpenModelica
Business Process Model and Notation (BPMN) (Aagesen & Krostie, 2015)	- A standard language for business process modelling - Not Systems Engineering focused as it does not support requirements, architecture, and behaviour of systems - Open standard - Widely used and supported by industry and tools like Microsoft Visio and Modelio

Table 4.3: MBSE modelling languages with its characteristics

Tool and sources	Characteristics
Cameo (Dassault Systemes, 2025) (Alai, 2019)	- An extension on core product MagicDraw - Supports UML/SysML and BPMN - It provides requirements, system design, simulation, analysis, and V&V - Traceability management through traceability matrix - Used in various industries to design and analyse complex systems and architectures - Commercial
Capella (Baron et al., 2023) (Eclipse Capella, 2025)	- Supports only its own specific language, but easier to learn than SysML - It provides requirements, system design, simulation, analysis, and V&V with add-ons - Based on four levels: Operational and functional analysis, and logical and physical architecture - No parametric modelling, which SysML tools do have - Flexible software and easy to use - Used in various industries to successfully design systems architecture - Open source
Enterprise Architect (Sparx Systems, 2025)	- Supports UML/SysML, BPMN, ArchiMate - It provides requirements, system design, simulation, analysis, and V&V - Used in various industries to design complex systems - Commercial
GENESYS (Vitech, 2025)	- The successor of CORE - Supports only the System Definition Language (SDL) - It provides requirements, system design, simulation, analysis, and V&V - Used in various industries to design complex systems - Commercial
IBM Rational Rhapsody (IBM, 2025b) (Beery, 2016)	- Supports UML/SysML - It provides requirements, system design, simulation, analysis, and V&V - Focuses primarily on improving collaboration and communication - Available version for systems design and for software design - Used in various industries to design complex systems - Commercial
Modelio (Modelio, 2025)	- Supports UML/SysML, BPMN, ArchiMate - It provides requirements well, but less suitable for simulation - Suited for simple projects - Open source for community edition / commercial for pro edition
Object-Process CASE Tool (OPCAT) (Dori et al., 2003)	- Supports OPD/OPL - It focuses on requirements, system design, simulation, and V&V - Used for higher education and scientific purposes, thus not scalable for large projects and less useful for collaboration - Commercial
OpenModelica (Modelica, 2025)	- Supports Modelica for simulating physical systems - It provides system modelling, simulation, and V&V, but no requirements - Used for industrial and academic usage - Open source
Relatics (Relatics, 2025)	- Currently used as main tool by Dutch infrastructure and construction sector for Systems Engineering and information management - Used as project management and control tool - Supports requirements management, objects structures, risk and interface management, deviations, work package management, and V&V - No formal modelling options (like behaviour and structure), only relational diagrams, tree views, and dashboards - Commercial

Table 4.4: MBSE tools with its characteristics

5.3 Comparative analysis of methods, tools, and languages

Based on the characteristics of these modelling methods, tools, and languages for MBSE and together with the requirements for MBSE adoption from Chapter 4, a comparative analysis can be conducted to determine which best align to the application of MBSE for a contractor. This analysis revealed that no single combination of method, tool, and language is optimal. Instead, different combinations are better suited for certain requirements and contexts. It has previously been observed that there is no universally optimal combination. As an example, Sideris (2024) found that no optimal combination exists for applying MBSE in the design of naval vessels.

Regarding the MBSE methods, each of them is specific. Currently, a contractor has its own set of internal procedures and processes. As mentioned in Section 2.2.3 and Section 2.3.1, these are based on and aligned with the ISO 15288 standard and the SE Guideline, especially for the Dutch construction industry. Thus, based on the specified requirements, it might be better to stick with the specific set of internal procedures currently used by an organisation. Although, by analysing the MBSE methods, it is possible to determine which fit well for an organisation that would like to adopt MBSE.

The MBSE methods that align best with the requirements include the OOSEM, SYSMOD, and ARCADIA. These align well with the ISO 15288 processes and are widely used in industries. OOSEM and SYSMOD are also tool-neutral. ARCADIA is not flexible as it only integrates with Capella and has its own specific modelling language. However, it has been reviewed as user-friendly and is open-source. The method MagicGrid is also aligned with ISO 15288 and is tool-neutral but has less widely been adopted. Other methods, like ViTech, OPM, and IBM Telelogic Harmony, are less suited because they are dependent on one single tool or a specific language and has not widely been used. RUP SE is not consistent with the V-model and ISE&PPOOA is only suited for software-related systems.

SysML is well suited as MBSE language as it is widely used, applicable for SE, based on an open standard, and supported by many tools and methods. However, SysML is hard to learn and to understand which requires time-investment and expertise. UML, the predecessor of SysML, is not well suited for hardware-related systems and is less suited for SE applications. The advantage of OPD/OPL is the easy understanding for non-technical stakeholders, but it is not widely adopted and is only supported by one single tool. The latter also applies to SDL, while SDL is also not open-source. ArchiMate and BPMN are not suited because they are misaligned with the core MBSE needs and objectives, as they primarily focus on business-related processes. Lastly, the disadvantage of the modelling language Modelica is its applicability for only simulation and optimisation of physical systems, and not for requirements management and architecture.

In terms of tooling, there is no specific tool that best matches the requirements for MBSE adoption. Cameo, Enterprise Architect, and Capella generally match most of the requirements. Cameo and Enterprise Architect support the widely used SysML modelling language, are widely used in industries, and can execute many SE processes. The disadvantage of these tools is their commercial nature. Capella, on the other hand, is open-source, user-friendly, and easier to learn than SysML. The downside of Capella is its connection to the ARCADIA method, uses a specific modelling language, and does not support parametric modelling. IMB Rational Rhapsody could also be used to adopt MBSE as it also supports many SE processes, but the tool focuses primarily on collaboration and communication and is a commercial tool.

GENESYS and OPCAT are less suited as MBSE tools because they only support one specific modelling language and are both commercial, while OPCAT can only be applied for educational and scientific purposes. The tool Modelio is used for simple projects and not suited for simulation processes, while OpenModelica does not support requirements and is also used for educational and industrial purposes. Relatics is already widely being used and supported as an indispensable information tool in the Dutch construction industry. Although, Relatics has limited visual capabilities and does not support formal modelling options, like structure, behaviour, and parametric. These options introduce the capabilities of analysing and simulating systems or models. This indicates that Relatics alone is insufficient to realise the potential benefits of MBSE.

To conclude, some combinations are more applicable than others. Such combinations are associated with features making it more suitable for certain requirements while less for other requirements. One of the better suitable combinations is ARCADIA/Capella, as it supports ISO 15288, is user-friendly, easy to learn, open-source, and is widely supported and adopted in industries. However, it can only be used in combination and uses a specific modelling language. Although it is an open-source combination, this leads to forms of vendor lock-in, as it restricts an organisation to one modelling language and tool. Lastly, Capella does not support parametric modelling in which relationships and dependencies between parameters are modelled. Tools compatible with SysML do support this due to the functionalities of SysML.

Another applicable combination is the OOSEM or SYSMOD method with the SysML language and the Cameo, Enterprise Architect, or IBM Rational Rhapsody tool. This combination also aligns well with ISO 15288, has more flexibility due to multiple available tools, and is well suited for SE application and is widely used and accepted due to its supporting modelling language SysML. However, SysML is hard to learn and model high level of details, creating a steep learning curve and might create an excessive workload for smaller of simpler projects. It must be noted that integration of new methods, tools, and languages should limited. As a result, it must be investigated if characteristics of MBSE, as mentioned in the interviews, can be realised without integrating new methods, tools, and languages. This could limit the added value of MBSE, such as visualisation and simulation characteristics, but can reduce challenges, like integration issues and resistance to change.

5.4 Summary

This section provides a summary of Chapter 5.

Chapter 5 explores the three core adoption pillars of MBSE: methods, tools, and modelling languages. The chapter starts by repeating the definition of these three pillars. A method is a set of procedures and processes, supported by languages and tools. The latter refer to software applications that enable models and a modelling language defines the semantics for creating these models.

Subsequently, the most frequently cited methods, tools, and modelling languages in academic literature are identified and analysed. Some of these methods included are OOSEM, OPM, SYSMOD, ARCADIA, and MagicGrid. Examined modelling languages are UML, SysML, OPD/OPL, SDL, ArchiMate, Modelica, and BPMN. Lastly, MBSE tools, such as Cameo, Capella, GENESYS, Enterprise Architect, and IBM Rational Rhapsody are reviewed. Characteristics of these three pillars are compared, such as alignment with ISO 15288, licensing type, and usability in other industries.

In Section 5.3, a comparative analysis is conducted using the requirements defined in Chapter 4. The results highlight no single combination of method, tool, and language is universally optimal. Instead, the suitability of each combination depends on the specific needs and context of the organisation. For example, OOSEM and SYSMOD are both tool-neutral and align well with ISO 15288, making them flexible and widely applicable. ARCADIA, while user-friendly and open-source, is only linked to the Capella tool and its own domain-specific language, which limits flexibility and introduces a form of vendor lock-in.

SysML appears to be a promising option for the MBSE modelling language due to its wide adoption, support for SE processes, open standard, and support across many tools. However, its steep learning curve and complexity may introduce challenges, especially for smaller projects or less experienced employees. On the other hand, OPD/OPL is a more accessible language for non-technical stakeholders but lacks widespread adoption and tool support. SDL, ArchiMate, BPMN, and Modelica are found to be less suitable due to limited applicability to core MBSE needs or lack of support for SE processes.

Although Cameo and Enterprise Architect are commercial tools, they are recognised for their extensive capabilities and robust support for SysML. Capella is appreciated for its usability and open-source nature but is limited to only the ARCADIA method. Other tools like GENESYS and OPCAT are less suitable due to their reliance on specific languages and limited scalability or industry use. Relatics is regarded as indispensable due its wide usage in the Dutch construction industry, but it has limited capabilities to achieve the potential of MBSE.

While certain combinations, like the OOSEM or SYSMOD method with SysML and tools like Cameo or Enterprise Architect, are promising, organisations should avoid introducing an excessive number of new elements at the same time. Instead of adopting entirely new MBSE methods, tools, and languages, organisations may benefit more from gradually improving existing processes with selected MBSE characteristics. However, this should not eliminate characteristics and added value of MBSE.

6. MBSE adoption proposal for a contractor

6.1 Introduction

This chapter presents a proposal for the adoption of MBSE within a contractor organisation to partly answer research sub-question 4. Building on the requirements and values defined in Chapter 4 and the analysis of MBSE methods, tools, and languages in Chapter 5, this chapter translates those insights into a practical and structured adoption proposal. Section 6.2 outlines the current digital landscape generally found in contractor organisations, including the roles of various tools used across the project lifecycle. In Section 6.3, the MBSE-related digital landscape is described, in which existing tools are preserved and complemented by a single MBSE tool. Subsequently, in Section 6.4 this change in Digital Information Management is applied to the Dutch contractor BAM. The current and MBSE digital tool landscapes and information flows at BAM are analysed, and specific recommendations are made for how MBSE can be integrated into existing processes and systems. Finally, Section 6.5 summarises the main insights and conclusions from this chapter.

6.2 Current digital landscape of a contractor

Many contractors use a variety of digital tools to document, store, and manage relevant project information across different lifecycle phases. Each of these tools has its own properties and functionalities, such as geospatial representation, 2D and 3D modelling, asset and maintenance management, documentation management, and project control management. Before adopting MBSE in the existing digital landscape, it is essential to understand the role and functionalities of these tools. An overview of the functions grouped per type of tool is provided in Figure 6.1 below. The light-yellow marked rectangles represent the functions and the dark-yellow marked containers are the type of tools.

Geographic Information System (GIS) tools are used to collect, visualise, and analyse geographic data. Such tools support activities such as location analysis, mapping, and linking inspections or tests to specific geographical locations. Additionally, 2D and 3D modelling tools, also referred to as Building Information Management (BIM) tools, are used to create and manage 2D and 3D design models of infrastructure or building components. BIM tools support collaboration across disciplines, integration of 2D and 3D sub-models, and allow to test, render, and simulate these models. Asset and maintenance tools are being used during the operational phase of projects in order to plan, monitor, document, and verify maintenance activities. A documentation management tool is the platform that facilitates project-related documentation management, by storage, publishing, and creation of documentation. It can be described as a central repository for documentation and is used in every project phase. The project control management tools are widely used in the Dutch construction industry, like Relatics, to support management of requirements, objects, work packages, deviations, risks, interfaces, and verification and validation activities. This is often managed by links between project information.

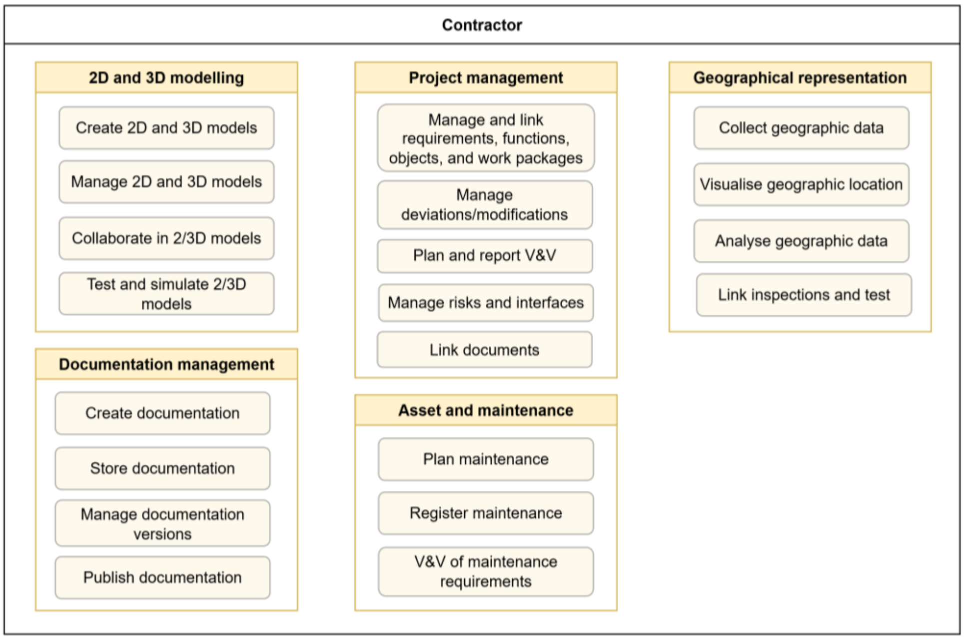

Figure 6.1: Overview of functions per type of tool at current contractors

6.3 Proposed MBSE digital landscape of a contractor

Each of the tool types of Section 6.2 serves a specific role in the project lifecycle and is integrated in existing processes. In the context of adopting MBSE, the core functionalities of these tools must be preserved while enabling enhanced modelling, integration, and traceability capabilities. In accordance with the defined requirements of Chapter 4, the MBSE adoption proposal must preserve current tools and workflows to a maximum extent to minimise resistance to change and ensure feasibility of the adoption. One of the requirements specified that the number of new tools should be limited and integrated only when they offer significant added value. This includes to remain existing functionalities in tools and continue using familiar tools if feasible. In an MBSE context, existing tools, such as those used for geographic information, 2D and 3D modelling, asset maintenance, documentation management, and information management, maintain their core functionalities.

One additional MBSE tool must be integrated within the existing system of a contractor as it adds extra functionalities not available in the current situation. The MBSE tool, like Capella, Enterprise Architect, or Cameo, can create formal models in different architectural detail levels. These models facilitate early-stage analysis of system elements, such as functions, behaviour, and requirements, allowing for the detection of errors or inconsistencies. Integrating such a MBSE tool includes linking information elements across several tools. For example, importing and connecting requirements from the project control management system to functions and behaviour within the MBSE tool. This enables early validation, simulation, and traceability. If changes occur, the MBSE tool can generate warnings or errors based on dependencies in the models, improving change management and reducing design errors. An overview of the functions and types of tools in the MBSE proposal is illustrated in Figure 6.2 below.

A key principle in integration and consistency is to establish the single source of truth by centralising the entire data in one tool or central repository. Theoretically, to achieve one single source of truth each information type should be stored in one location or tool. In practice, this is unfeasible due to the variety of tools used by contractors, each with specialised functions and outputs. As a result, specific types of information are distributed across different tools, with certain data elements designated as authoritative in one of the tools. Other data elements may be considered authoritative in other tools. If it is clear which tool or system holds the authoritative source for each information type, and each tool can manage this data, a federated single source of truth is established across multiple systems (Borgstein, 2025). This approach ensures consistency without compromising the specialised capabilities of the tools.

According to data management literature, determining which tool holds authoritative information depends on two key factors. The first factor concerns the functional capabilities of the tool to generate and modify information (Melzer et al., 2023). The second factor involves the origin identification of information and the assignment of responsibility for ensuring the accuracy of the content is, including specifying which tool is used by the accountable person (Sargiotis, 2024). Before implementing a federated single source of truth, information flows must be analysed to identify the storage and usage locations of information. Section 6.4.3 demonstrates this process through a practical application involving the Dutch contractor BAM.

In addition to integrating a single MBSE tool, other changes to the current system are necessary to completely realise the benefits of MBSE. Such a change includes transitioning from documents to models. Each information element should be stored in a model rather than a document. As some documents are authoritative in the documentation management tool, traceability lacks as no link is established to other tools. Avoiding such authoritative documents, if possible, is required to create a more traceable system. Over time, documentation management tools may be phased out in favour of model-based communication, in which documents are generated directly by models for external stakeholders. In the future, a contractor could send models instead of documents to client for approval and informing them.

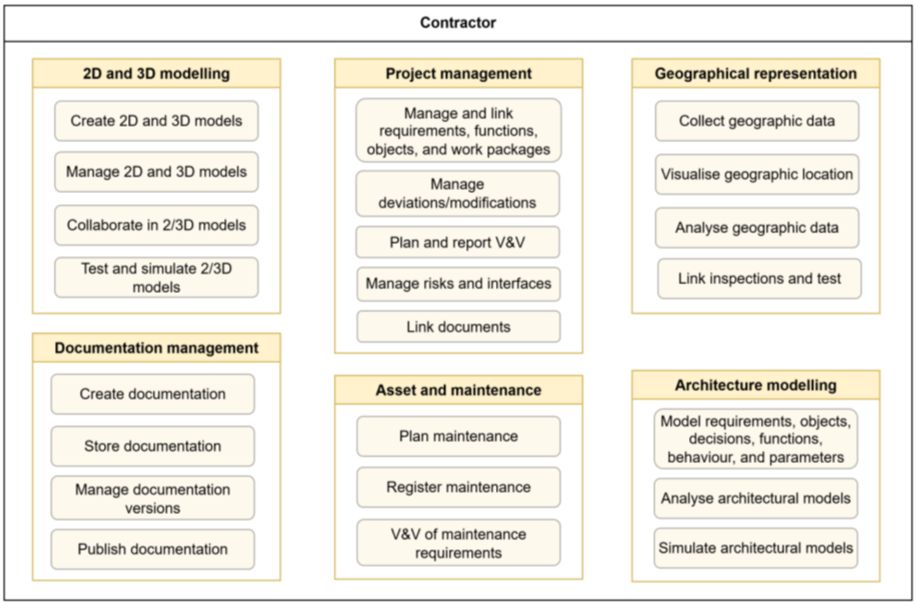

Figure 6.2: Overview of functions per type of tool in MBSE proposal contractors

6.4 MBSE adoption: Application to BAM

This section dives into the application of the MBSE adoption to the Dutch contractor BAM. The contractor BAM has not adopted any form of MBSE and wants to adopt MBSE effectively. Section 6.4.1 describes the current tools and its functionalities at BAM and Section 6.4.2 discusses how these changes in an adopted MBSE proposal. In Section 6.4.3, information swimming lane diagrams are created, illustrating the change in information elements and flows between the current situation and the proposed MBSE adoption. The information used for this section is extracted from the tools itself, an analysis of internal documents from BAM, and websites of the tools. The internal documents can be found in Appendix D.

6.4.1 Current tooling and functionalities

Several tools are used to document and store the relevant information, each with its own properties and goals. The key tools used by BAM Infraconsult involve ArcGIS, Autodesk, Maximo, Microsoft SharePoint, and Relatics. In this section, each tool is explained and an overview of the tools including its functionalities is illustrated below in Figure 6.3, which overlays the structure presented in Figure 6.1. The blue coloured containers represent the tools. The specific exchanges between tools that BAM has established in its digital landscape are visualised with black arrows.

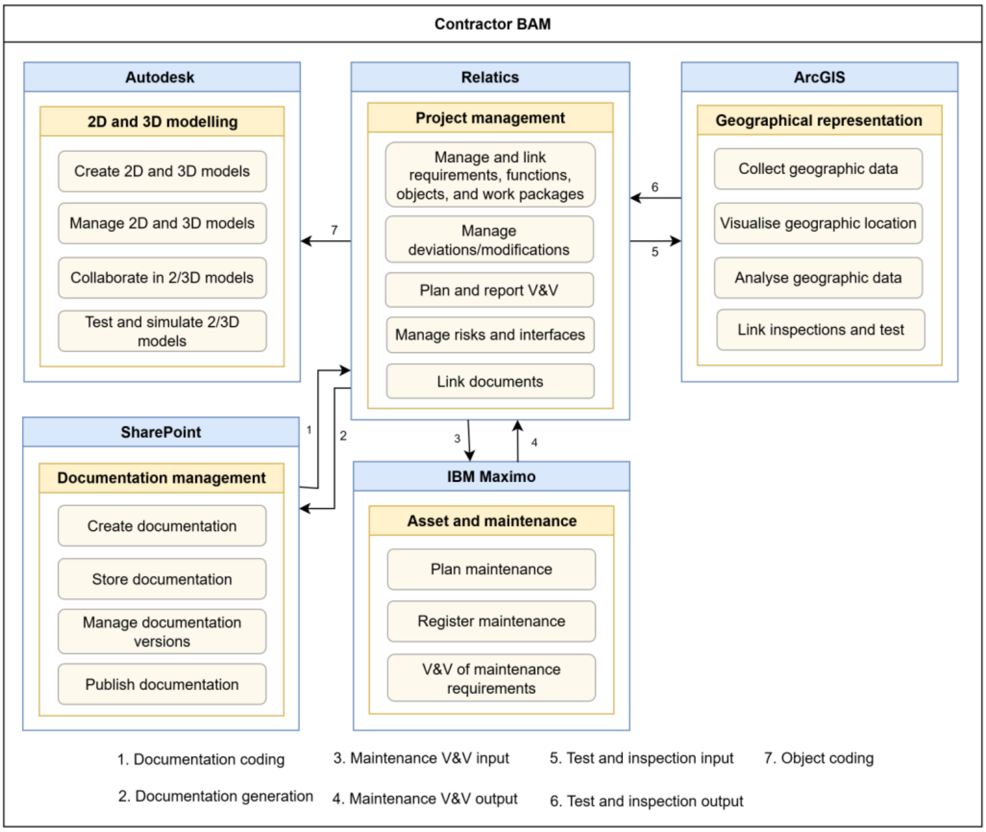

Figure 6.3: Overview of current tools with its functionalities at BAM

ArcGIS

ArcGIS is a Geographical Information System (GIS) tool used to collect, process, analyse and visualise geographical data (ArcGIS, 2025). In ArcGIS, the geographical coordinates of a project can be viewed, and its geographical representation can be displayed. ArcGIS can use open-source data, like Google Maps, or data from an executed drone flight. Additionally, 3D design models can be integrated in ArcGIS. Finally, inspections and tests can be linked to a geographic location in ArcGIS so they can be performed and documented. ArcGIS is mainly used in the design, work preparation, and execution phases.

Autodesk

Autodesk is a company that offers several tools for architecture, engineering, and construction, like Revit, Civil3D, Navisworks Manage, and AutoCAD (Autodesk, 2025). These tools are mainly used during the design and work preparation phase. In the Autodesk Construction Cloud (ACC), the 3D models and drawings from these tools can be viewed, opened, and stored. ACC thus serves as the Model Management System. Each discipline in a project has its own sub-model in Autodesk. Modifications of one discipline that impact sub-models of other disciplines, can be registered in either Relatics or Autodesk, but there is no link between these two tools.

Revit is a BIM software used for designing and modelling. Contractors use Revit to create detailed 3D models that cover every objects of a construction project. These models help with visualising the design in a 3D environment, which makes it easier to change objects or explain the project to stakeholders. Revit is also used for material calculations and clash detection. Clash detection identifies and resolves conflicts between components within a system.

AutoCAD is a Computer-Aided Design (CAD) software that is used to create exact 2D and 3D drawings. In this way, detailed blueprints and models of building components can be created. A drawing from AutoCAD can be included as an external reference in Revit, and modification of a CAD drawing will automatically change the model in Revit. But the original CAD drawing will not be adjusted.

Civil 3D is a civil engineering and documentation software that supports BIM workflows. It is used to plan, design, and manage civil infrastructure and provides tools for designing structures like roads or sewer systems. Civil 3D helps to automate design processes. Civil 3D files can be coupled to Revit models and can establish a 'live' link that automatically updates the data. Civil 3D is different from AutoCAD due to advanced functions for design, like corridor modelling and pipeline network modelling.

Navisworks Manage is a 3D design review software used to open and combine 3D models and to navigate and review these models in real-time. Clash detection, 4D and 5D simulation, and renders, like safety walks, can be executed in Navisworks. Navisworks can import Revit models, AutoCAD drawings, and Civil3D models.

Maximo

IBM Maximo is a tool specifically used during the maintenance phase. Maintenance activities can be planned efficiently per object and the results can be accurately recorded (IBM, 2025a). Maximo delivers dashboards about states of objects and automated workflows to validate and verify maintenance requirements. GIS and Autodesk are partially integrated with Maximo, allowing the assets to be viewed on a GIS map and in a 3D model. Using Maximo, a contractor ensures that assets remain in good condition.

Microsoft SharePoint

Microsoft SharePoint is a collaboration software tool that helps teams to work together efficiently (Microsoft, 2025). For projects, SharePoint is used as the Documentation Management System for projects, allowing users to upload, save, and share documentation efficiently. At the start of a project, a SharePoint page will be requested and created. Only people who are granted access can enter the SharePoint page of the specific project. SharePoint is used at almost each process as most processes require documentation. For example, the design is supported by a design note which includes 2D drawings and calculations. This design note is documentation stored on the SharePoint page.

Relatics

Relatics is a relational database developed for Systems Engineering and Project Management (Relatics, 2025). Relatics operates on a database in which the entire project data is stored. The software uses a relational structure to organise and present the information, allowing users to easily understand the status of the project in one shared database. Relatics has expanded to a project management tool and is considered a critical business tooling within construction companies to design and manage complex systems. Relatics can support the following aspects: Requirements, Objects, Functions, Deviations and modifications, V&V, Work packages, Documents, and Risks and interfaces. Regarding documents, Relatics only provides document structure by receiving the code and text from SharePoint. In this way, verifications, objects, and other information element types can be connected to this document information in Relatics.

Due to a wide range of features, Relatics is used during many of the contractor's processes. Relatics is mainly used for the requirements analysis and project decomposition but also for processes during the design, work preparation, and execution phase, like configuration, verification, and validation. Relatics is useful in organising information and generating tables based on this information. In addition, Relatics can perform checks to verify if certain data has been entered correctly. Based on the information captured in Relatics, it can automatically generate documents, like verification plans, verification reports, and risk files. These outputs are produced only from the data available in Relatics, and not by performing complex analyses. For example, design notes cannot be created by Relatics as design choices are described in design documents, which are stored on SharePoint. In Relatics, there is a link with ArcGIS and SharePoint, but the SharePoint link only serves as a link to open a specific document in SharePoint. In ArcGIS, the inspections and tests conducted during the realisation phase can be imported from the Relatics database, executed with ArcGIS on-site, and then be transferred back into the Relatics database.

6.4.2 Proposed MBSE tooling and functionalities

How adopting MBSE can impact the tool landscape including functionalities of the tools is illustrated in Figure 6.4. Again, this overlays the structure presented in Figure 6.2. In the future MBSE environment, the main functionalities of existing tools, such as ArcGIS, Autodesk, IBM Maximo, and Relatics should remain unchanged, as discussed in Section 6.3. To maintain stability and avoid any disruptions, no modifications should be made to these systems and its functionalities. Instead, a single additional MBSE tool, such as Capella, Enterprise Architect, or Cameo, should be integrated into the current tool environment to provide enhanced modelling capabilities. SharePoint should continue to serve as a document repository, but its role should be limited to storing documents that are generated by models, rather than being used as documentation management tool by creating and publishing documents.

To achieve the full potential of MBSE, it is necessary to integrate a maximum of one additional MBSE tool into the current tool environment. Such a tool, like Capella, Cameo, or Enterprise Architect (E.A.), are discussed in Chapter 5 and should provide extra enhanced capabilities. This includes the ability to model functions and behaviours and link them to objects and requirements. According to Section 6.4.1, this will help with detecting errors earlier and impact analysis if modifications occur. Requirements, functions, and objects are documented in the current situation, but they are neither modelled nor visualised which can be supported by the additional MBSE tool. In addition, functions are currently not captured for every project. Lastly, such a tool has the ability of parametric modelling which can further enhance the design process. In such MBSE tools, the models can be created in several architectural layers, like operational, system, logical, and physical. For example, in the logical architecture, requirements can be linked to functions, functions can be assigned to objects, and behaviour and sequence of functions can be modelled.

Additionally, a transition from documents to models is required to completely realise the potential of MBSE. For example, currently design decisions of the 3D design are captured within design documents but should directly be stored in the models itself. If modifications occur, models can automatically generate warnings or errors if the decision is linked to other information types. As a result, Microsoft SharePoint should be used less by eliminating document collaboration and document creation. Documents generated directly by models may be stored in SharePoint in order to inform clients. But also, documents with information that cannot be modelled must remain authoritative in SharePoint, like contract documents.

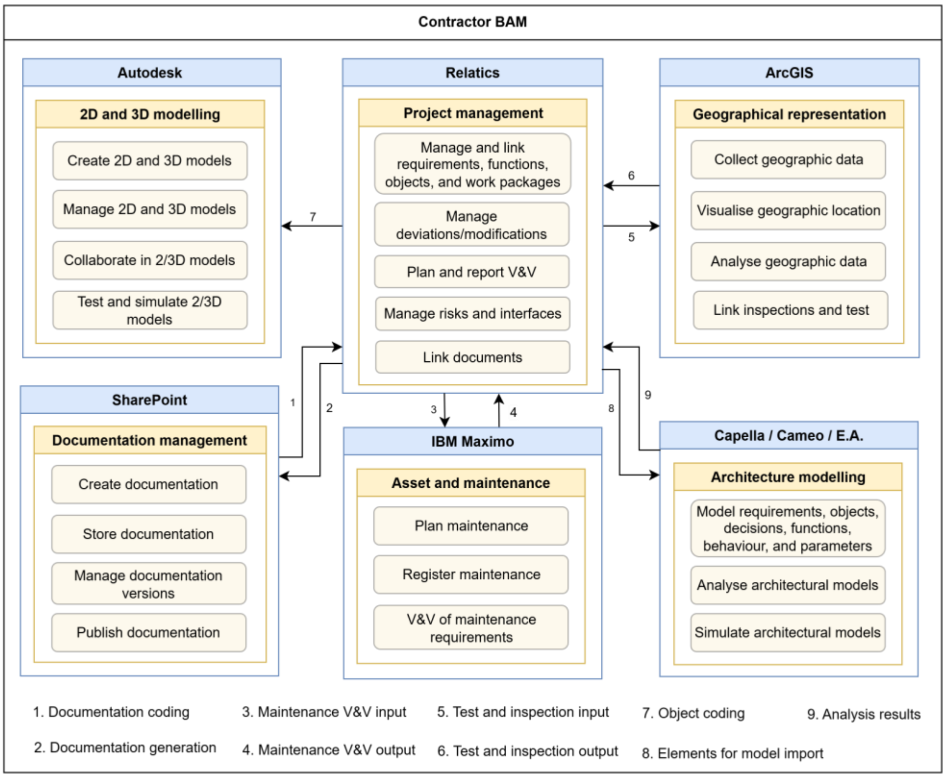

Figure 6.4: Overview of tools with functionalities in MBSE proposal at BAM

6.4.3 Information flows and changes in the proposed MBSE adoption

As demonstrated in Section 6.4.1, there is minimal to no connection between existing tools. Achieving the federated single source of truth requires seamless integration between tools and a clear definition on which tool holds the authoritative or leading data for each type of information. Figure 6.5 and Figure 6.6., respectively, illustrate information swimming lane diagrams of the current and future MBSE situation at BAM.

An information swimming lane provides insights on how information elements are distributed across the several digital tools. Each vertical lane represents a digital tool. Within each tool, rectangles symbolise the information elements used by that tool. Arrows indicate the flow of information elements from one tool to another. This does not necessarily imply that the tool transmitting the information is the authoritative source, as the information may have originated from a different tool. The 'crown' symbol inside an information element indicates what should be considered as the authoritative element in the proposed MBSE situation, as this is not explicitly determined in the current situation. It is important to note that these diagrams illustrate information exchange between tools only and do not show how information flows through specific processes or phases.

An example of how certain information can be used and processed by several tools and to enable clarity on which tool serves as the authoritative source for each type of information, the link between Relatics and the additional MBSE tool will be explained. As illustrated in Figure 6.6., the information elements 'requirements', 'objects', and 'functions' can exist in these two separate tools. Relatics could operate as the authoritative source, primarily because Relatics is widely adopted by clients and stakeholders and because these information elements are linked to many other information types in Relatics. However, these requirements, functions, and objects should ideally be imported into the MBSE tool to enable further modelling, analysis, and simulation. Within the MBSE tool, these elements and the element 'behaviour' can be modelled. This approach facilitates early error detection and supports a more integrated and traceable system. Additionally, early validation and verification in the design phase can be executed by modelling each of these elements.

V&V plans from Relatics can be used to validate and verify early elements in the additional MBSE tool. This tool subsequently generates a V&V report, which can be imported back into Relatics, as it functions as the central V&V management tool. V&V reports originated from the MBSE tool, ArcGIS, and Maximo are marked as authoritative in Figure 6.6 given that these tools execute, generate, and modify these system elements. Subsequently, Relatics executes specific V&V plans and maintains the authoritative source for the total V&V plan and its associated reports.

In terms of information management in SharePoint, the goal in the MBSE proposal is to minimise the storage of information within static documents. This recommendation arises from the limitation that information embedded in documents does not automatically update when changes occur in other tools, and vice versa. As previously discussed, the intention is to transition away from using SharePoint as a source of authoritative information. Consequently, the use of document-based information elements such as trade-off matrices and diverse types of design documents is being avoided. Instead, the information captured in such documents, like design decisions, rationales, drawings, and calculations, should be stored and maintained within models of other tools. In this approach, SharePoint functions primarily as a repository for model-generated outputs, such as work plans, delivery files, as-built documentation, and progress reports. However, certain document types, such as in project management plans and contract documents, are not suitable for modelling and infrequently updated. These types of documents should continue to be stored in SharePoint.

The information element 'design decisions/rationales' could be stored across several information tools. Due to the fact that designers are responsible for these decisions and typically operate in Autodesk tools, Autodesk may be considered the authoritative source for this information. Subsequently, the additional MBSE tool could import, model, and link these decisions or rationales to other information types, leading to warnings or errors by analysis and simulation if modifications occur. Establishing traceable links between these design decisions and requirements, objects, and functions creates a more consistent, traceable, and maintainable system. Warnings or errors generated by the MBSE tool can be imported into Autodesk tools to update designers on critical issues.

One of the outputs of the MBSE tool is the generation of warnings or errors, triggered by modifications of elements in models or by inconsistencies. Such warnings or errors should be considered authoritative in the MBSE tool as they are generated by this tool. Modellers or project managers should subsequently be notified of these warnings through integration with Autodesk and Relatics to efficiently execute their tasks. In addition, the MBSE tool can leverage parameter information, related to system behaviour, to enable parametric modelling and perform analyses in case of changes. Examples of such parameters are response time or luminous intensity. While Autodesk also defines parameters, these are limited to the physical properties of objects, such as material and dimensions.

Through the use of models in the MBSE tool, system interfaces may emerge, such as those between subsystems or functions. These interfaces may be exported or synchronised to Relatics, which manages the entire interfaces and can link them to responsible actors.

It is essential to maintain consistency of information across tools. This can be achieved by live synchronisation, reducing the risk of outdated or incorrect data. Specific information elements not supported by tools in the swimming lane diagram may still be recorded in these tools if it enhances the efficiency and effectiveness of disciplines. For instance, disciplines may require the ability to link information to other elements. As an example, functions defined in Relatics can be reused within an Autodesk tool, allowing functions to be associated with physical objects. However, this approach introduces additional effort to establish and maintain synchronisation of information elements across tools.

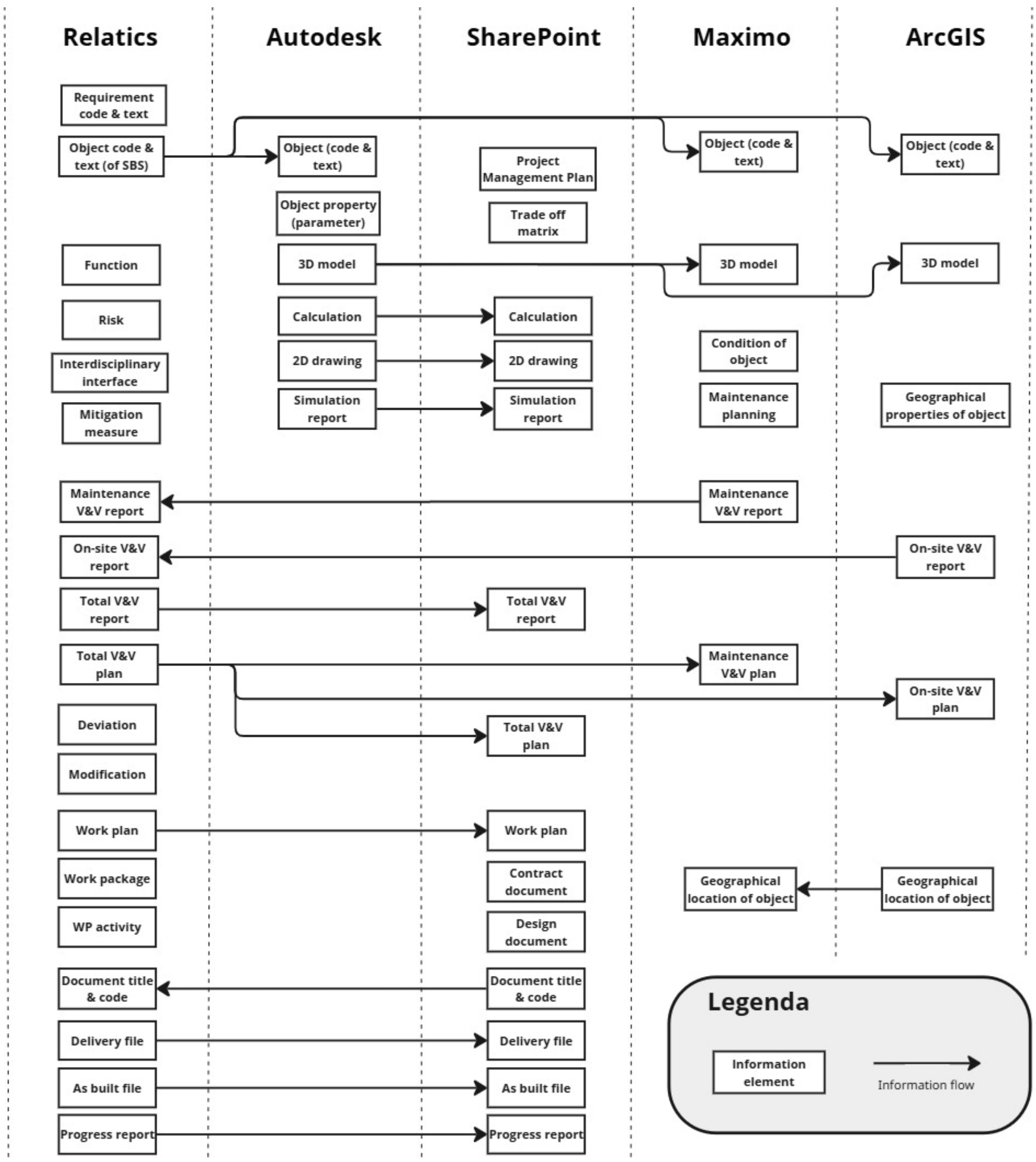

Figure 6.5: Information swimming lane diagram in current situation BAM

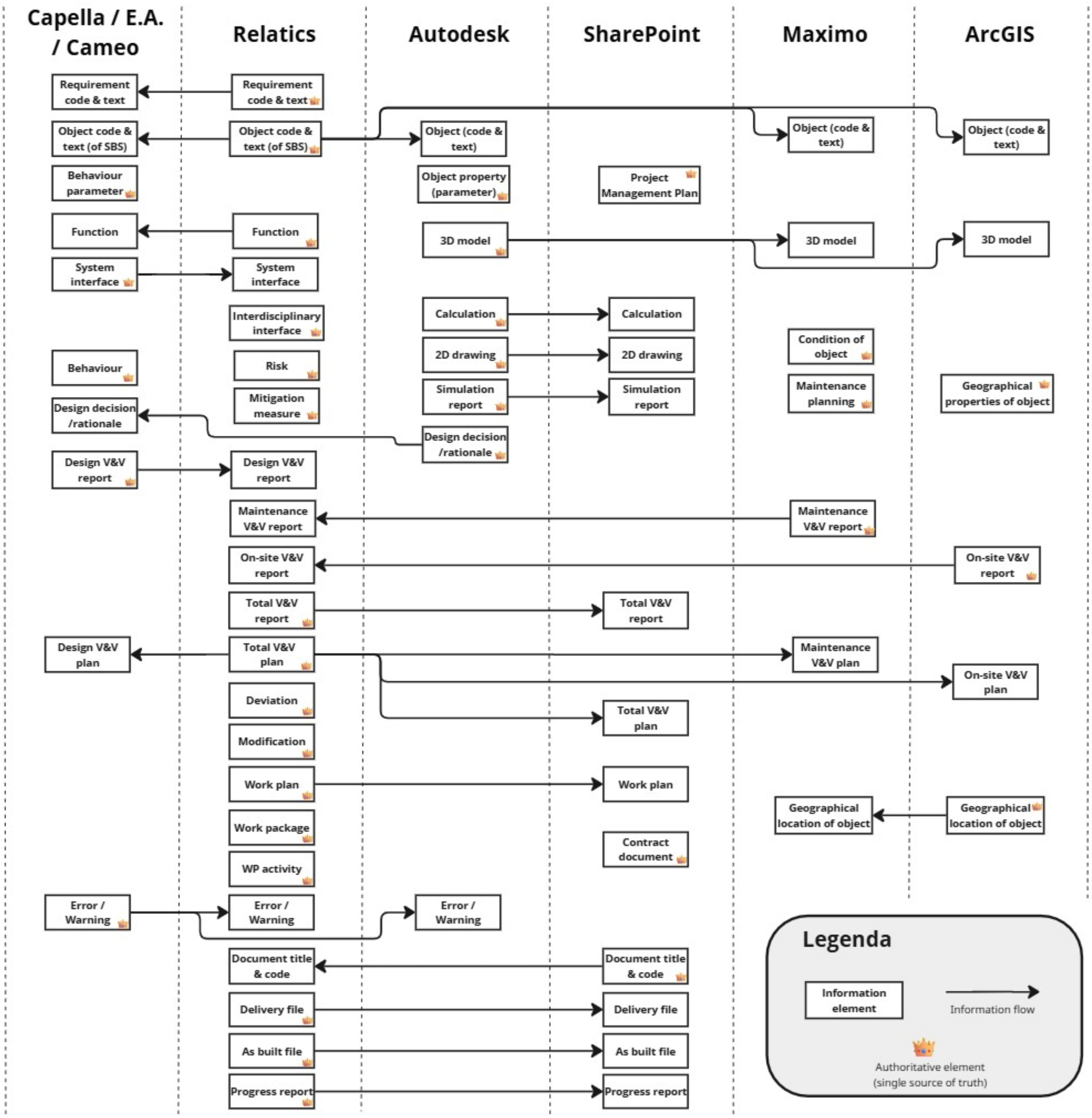

Figure 6.6: Information swimming lane diagram in the MBSE proposal BAM

6.5 Summary

This section provides a summary of Chapter 6.

Chapter 6 presents a practical proposal for adopting MBSE within contractor organisations, using BAM as a use case, to provide an answer on research sub-question 4. Building on the requirements outlined in Chapter 4 and the analysis of MBSE methods, tools, and languages in Chapter 5, this chapter translates theoretical insights into a practical adoption proposal. The chapter starts describing the current digital landscape commonly found in contractor organisations. The roles of various tools used throughout the project lifecycle phases are outlined, including GIS, BIM, asset management, documentation management, and project control tools. Each tool serves a specific purpose and is deeply embedded in existing workflows.

The proposed MBSE adoption retains these existing tools and introduces a single additional MBSE tool, such as Capella, Cameo, or Enterprise Architect, to enhance modelling, traceability, and integration. This tool enables formal architectural modelling and supports early error detection and simulation. The proposal advocates for a federated single source of truth, rather than centralising the total data in one tool. Authoritative data is distributed across tools based on their functional capabilities and the responsibilities of users. Synchronisation between tools ensures consistency while remaining specialised functionalities.

Section 6.4 applies the MBSE proposal to the Dutch contractor BAM, illustrating how MBSE can be integrated in an existing digital landscape. First, BAM's current toolset and functionalities are analysed, including ArcGIS, Autodesk, Maximo, SharePoint, and Relatics. These tools maintain their roles, while SharePoint transitions from document-based collaboration to a passive repository for model-generated documents. The additional MBSE tool uses information elements from other tools to link and model this data, enabling early analysis and validation and verification.

Information swimming lane diagrams are created, applied to the case of BAM, to show how data flows between tools in both the current and proposed MBSE situation. These diagrams clarify which tool holds authoritative data and which information is exchanged. For example, Relatics should remain the authoritative source for requirements and functions, while the MBSE tool support modelling and simulation of these elements. Design decisions and rationales should be stored in models in Autodesk tools instead of documents and these can be linked to other models and tools, enabling impact analysis. In this way, SharePoint moves away from holding the authoritative source for information elements. The chapter concludes that successful MBSE adoption requires clearly defined data ownership across tools, based on user wishes, responsibilities, and tool capabilities.

7. Case study validation

7.1 Introduction

This chapter addresses research sub-question 5 by conducting a case study including an expert session. The case study focus only lies on the integration of a MBSE tool, while not on the single source of truth. This leads to validation of the added value of adopting a MBSE tool, as well as insights into the practical application of MBSE. Section 7.2 starts by outlining the use case for the case study, the bridge of Spooldersluis project. Section 7.3 explores the Capella MBSE tool, by creating models in several architectural layers. Section 7.4 presents an analysis of the collected data through an expert session, which serves as a foundation for providing the practical insights of adding an MBSE tool to a project. This section also compares the findings to the literature of MBSE. Building on these findings, Section 7.5 defines the organisational maturity levels in a roadmap. Section 7.6 provides a summary of this chapter.

7.2 Use case: Spooldersluisbrug

The use case that will be used for this research is the Complex Spooldersluis project. The Complex Spooldersluis, located in the municipality of Zwolle, is a lock-bridge combination for ships and connects the IJssel with the Zwarte Water. Complex Spooldersluis is also a connecting water barrier between dike ring Salland and dike ring Mastenbroek. The movable bridge of Complex Spooldersluis is important for the underlying road network of the municipality of Zwolle. Complex Spooldersluis was in an inferior state of repair and contains obsolete components. In addition to the components being severely outdated, Complex Spooldersluis also did not comply with the Machinery, Health, and Safety acts and regulations. For these purposes, the contractor BAM has been selected to be responsible for the renewal and renovation of Complex Spooldersluis. In Figure 7.1 below, the location of Complex Spooldersluis is circled.

Figure 7.1: Complex Spooldersluis location

Spooldersluis project was selected as the case study for this research because the project was completed exactly at the time the case study was conducted. For the expert session, the information about the project was still fresh in mind for domain experts. In addition, the size of the project made it suitable and representative as a case study. In fact, the Spooldersluis project has a moderate size in terms of, for example the number of works and requirements. This introduces a good balance between complexity and manageability. For this study, the lock of the Spooldersluis project is excluded and only the bridge is included to not make the case study overly complex and keep it even more manageable and comprehensible.

The information that has been used for conducting the case study of Spooldersluis was located on the Relatics platform, especially for requirements and functions. For other information and to get familiar with system behaviour, internal documents of the project have been investigated, like the system design document and the use cases document.

7.3 Modelling in Capella

Chapter 5 presented an analysis of MBSE methods, tools, and modelling languages, concluding with a selection suitable for adoption within contractor organisations. Building on these findings, a MBSE tool including its respective language and method, will be selected in this chapter to model the use case. The tool used for this study is Capella and the rationale behind will be explained below.

The predefined methodology of Capella, ARCADIA, serves as an advantage rather than a limitation in this particular study. This is due to the flexibility in the sequence of model and diagram creation that the ARCADIA method provides. Additionally, its user-friendliness and simplicity make it a practical choice, especially considering the time constraints of this study. Furthermore, Capella and its specific modelling language is easier to learn compared to SysML, which is also crucial considering the time constraints. The structured guidance of the ARCADIA method is particularly beneficial for users with limited experience in MBSE tools. Lastly, the fact that Capella is an open-source tool without a commercial license requirement was a key factor in its selection.

Section 7.3.1 introduces the Capella tool and the core features of the ARCADIA method. The specific application and outcomes of this tool are examined per architectural layer in Section 7.3.2, Section 7.3.3, and Section 7.3.4. Finally, the use of the tool is evaluated by the authors' experience during the development of the case study in Section 7.3.5.

7.3.1 Introduction to Capella

It is essential to outline the key features of Capella, before proceeding to the modelling process. As mentioned earlier, Capella is built upon the ARCADIA method, which supports a multi-layered structured analysis. This analysis includes four successive layers: Operational Analysis, System Analysis, Logical Architecture, and Physical Architecture. The Operational and System Analysis layers offer detailed insights into the functional needs and objectives of the system, while the Logical and Physical Architecture focus on modelling potential solutions using architectural design (Eclipse Capella, 2025).

For this study, Capella version 7.1 was used in combination with the 'Requirements Viewpoint' add-on. To provide additional requirement features, like linking model elements to requirements, this add-on was installed. Capella supports several add-ons that extend its functionality, such as the 'M2Doc' add-on to generate Microsoft Word documents from Capella models. Before actual modelling in Capella, tutorials and examples were explored carefully to understand the tools capabilities and gain experience with the tool. The tutorial Catapult Toy project from the Capella website expresses various modelling options and the authors' preferences and opinions (Arikan & Jackson, 2023). The example In-Flight Entertainment System is available in the Capella tool and has helped to gain experience in the tools' abilities (Thales, n.d.).

Figure 7.2 illustrates the user interface of the Capella tool. On the left the Project Explorer enables navigation between projects, layers, and model elements. On the right, the view of the project 'MBSE' is displayed, showing the four layers of the ARCADIA method. Within this view, diagrams can be opened and modified according to the selected layer. At the bottom of the interface, the 'properties' and 'semantic' tabs display detailed information and relationships for the currently selected modelling element.

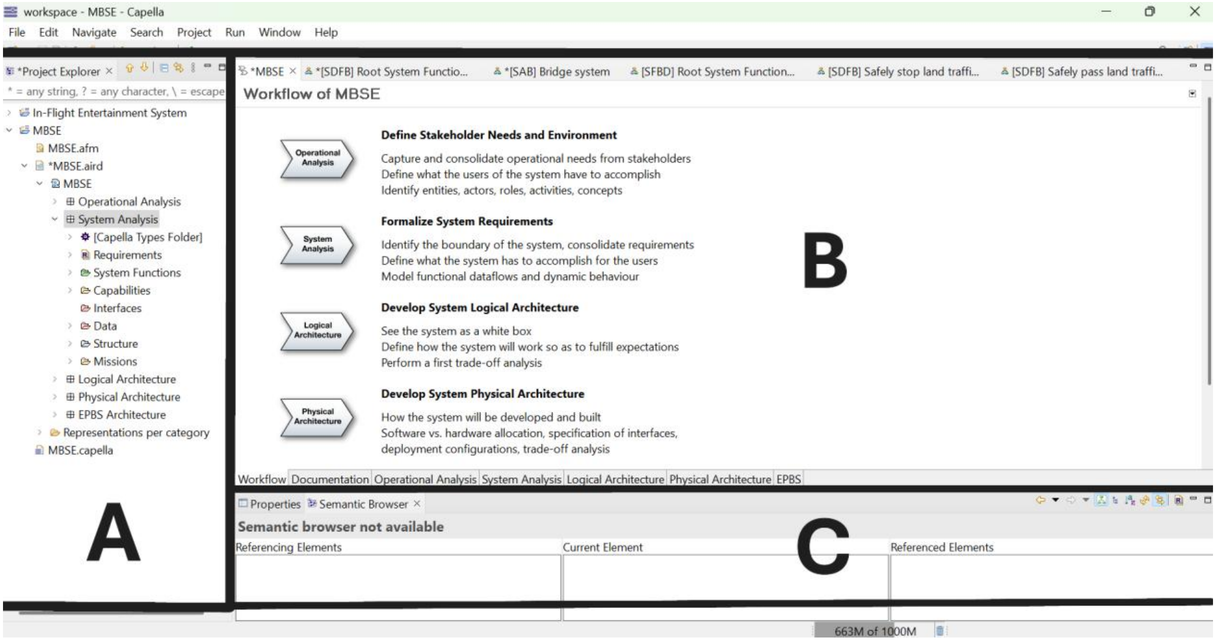

Figure 7.2: Capella user interface

The first layer of the ARCADIA method within Capella is the Operational Analysis, which focuses on identifying the system's environment, mission, and activities or needs of the involved actors. For the case study in this research, the Operational Analysis was omitted due to its limited relevance. This information is typically already provided by the client and can be integrated directly at the start of the System Analysis.

The System Analysis layer addresses the functionalities of the system, referred to as 'system functions.' These functions can be allocated to the system itself or an external actor. The interactions between these functions are modelled as 'functional exchanges,' resulting in a representation of system behaviour. Additionally, behaviour-related requirements can be linked to system functions to support traceability and verification.

The subsequent layer, the Logical Architecture, introduces the first principles regarding design solutions. The system functions are transitioned to logical functions and can be analysed and grouped into subsystems, called 'logical components.' Each function can also be decomposed in more detailed sub-functions. It is important to avoid incorporating technological considerations at this stage, as these are addressed in the next layer.

Transitioning to the Physical Architecture layer includes the decomposition of subsystems into physical objects. Again, to verify that the system meets the intended requirements, object-related requirements can be linked to these decomposed physical objects. This involves both lower-level and higher-level requirements, using the 'satisfy' relationship to establish traceability.

7.3.2 Modelled diagrams in System Analysis

As the Operational Analysis was omitted, the actors, system capabilities and system mission were introduced at the start of the System Analysis using several diagrams. One of Capella's advantages is its automatic synchronisation of diagrams whenever actors or capabilities are modified or added during the development process. The system and its involved System Actors (SA) are illustrated in Figure 7.3 and the system's mission and capabilities in Figure 7.4. The 'M' symbolises the mission and 'C' the capability.

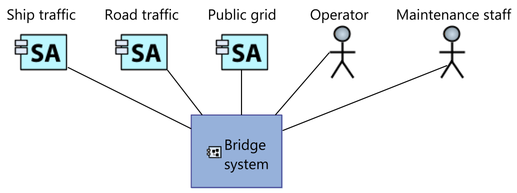

Figure 7.3: Contextual System Actors diagram

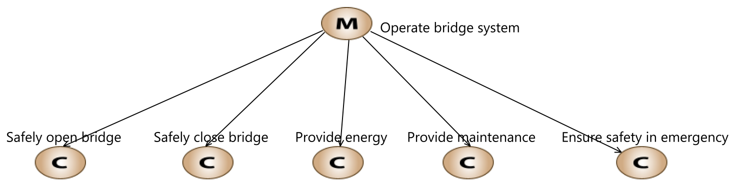

Figure 7.4: Mission Capabilities diagram

For each capability of the system, a use case or scenario can be created. A scenario or use case is a sequence of functions that are executed consecutively by either actors or system components. The six scenarios created for the moveable bridge of Spooldersluis are: open bridge, close bridge, provide energy, provide emergency energy, provide maintenance, and ensure safety in emergency bridge. An example of such a scenario is illustrated using an exchange scenario diagram in Figure 7.5. Each dotted line represents a system actor or the system itself and a green rectangle symbolises a function. The rest of the Exchange Scenario diagrams of the System Analysis can be found in Appendix E. Part of creating these scenario diagrams is to allocate functions to actors or the system and determine the sequence of functions.

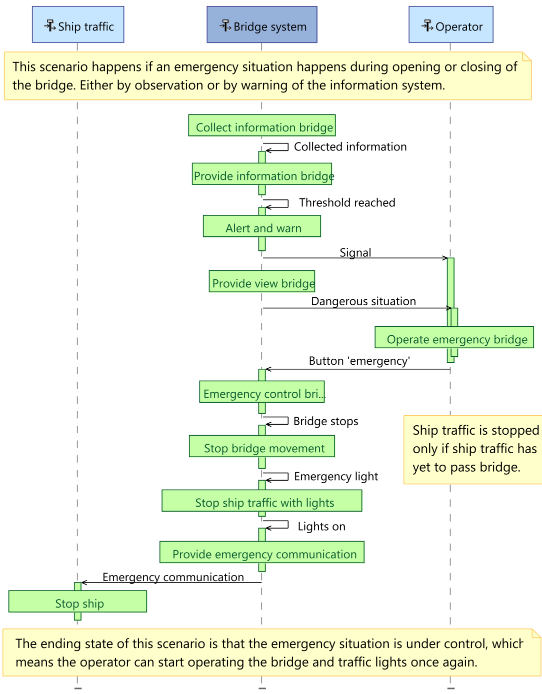

Figure 7.5: Exchange Scenario (ES) diagram of ensure safety in emergency bridge scenario

Based on these scenarios, functional chains can be identified, each representing a distinct path within the overall sequence of functions. A functional chain does not allow re-execution of functions that already have been performed within the chain, whereas a scenario can execute the same function more than once. One of these functional chains is represented by the provide maintenance scenario, illustrated below in Figure 7.6. The blue rectangles represent actor functions, and the green are system functions. An overview of the other functional chains is provided in Appendix E.

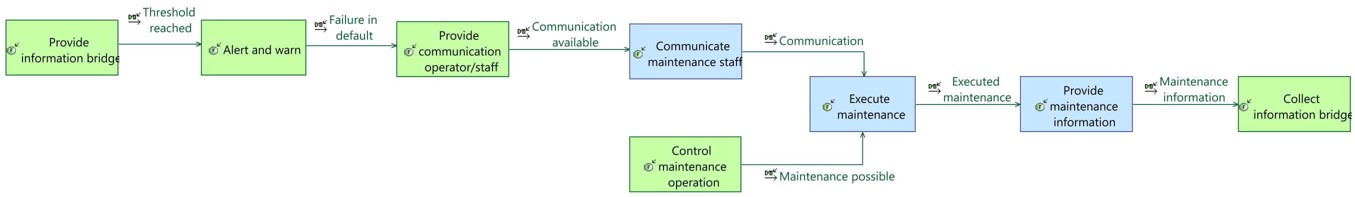

Figure 7.6: System Functional Chain Description (SFCD) of provide maintenance scenario

A system functional breakdown diagram in Capella shows an overview of the decomposition of functions, to show if functions are specified in sub-functions. This diagram is illustrated below in Figure 7.7. As an example, for this study two functions have been specified using sub-functions, illustrated in Figure 7.8 and Figure 7.9. The large green rectangle is the parent function, and the smaller green rectangles inside represent the sub-functions.

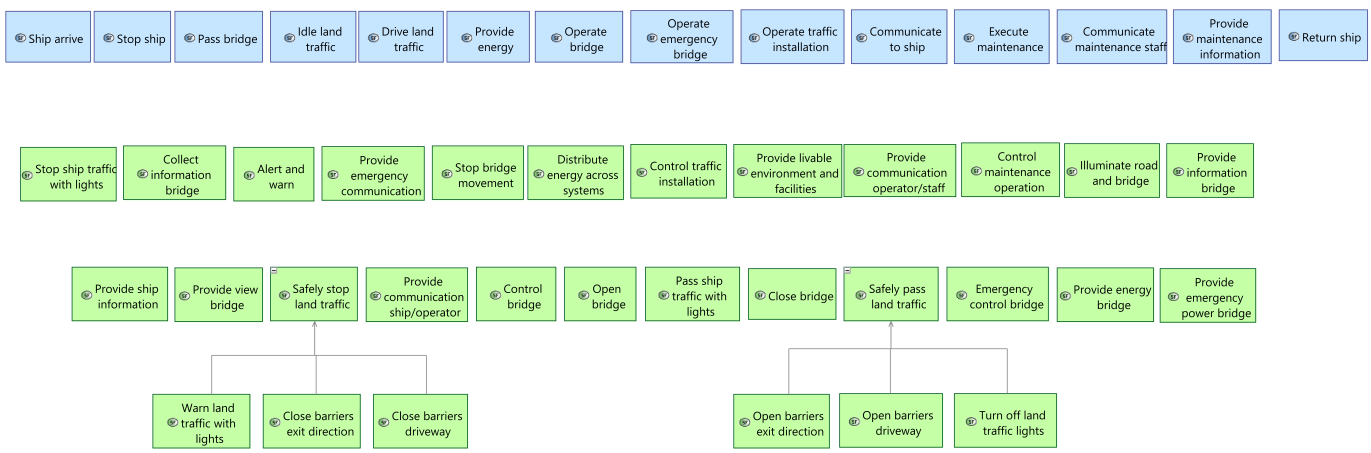

Figure 7.7: System Functional Breakdown Diagram (SFBD)

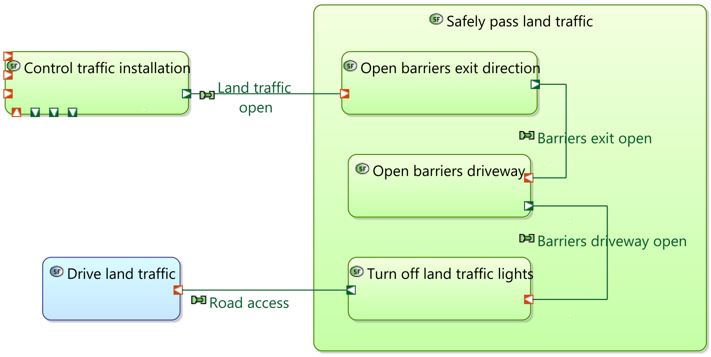

Figure 7.8: System Data Flow Blank (SDFB) of Safely pass land traffic function

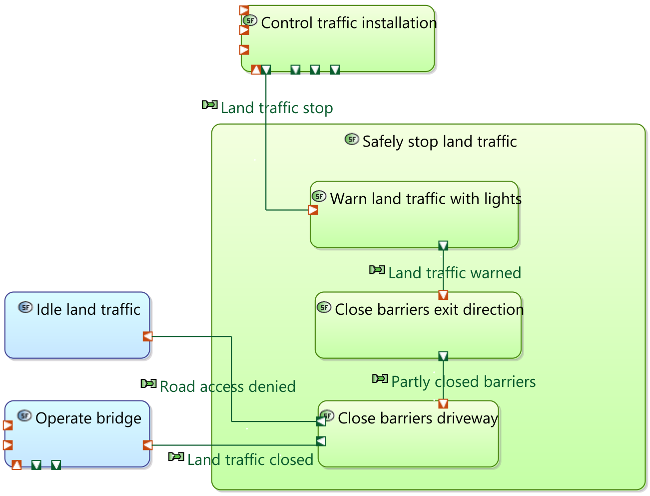

Figure 7.9: System Data Flow Blank (SDFB) of Safely stop land traffic function

As a result of the System Analysis a total overview has been created of the system architecture, which is illustrated in Figure 7.10. The functions are represented as green rectangles, actors are light blue coloured, and the system has a dark blue colour. Several functional chains (coloured bold lines) are integrated in this view, as well as requirements allocation to functions. Lower-level requirements are represented in a grey colour and higher-level in purple. The relations of requirements are presented using 'derive' or 'satisfy' relationships. It must be noted that not each requirement is added as this does not provide additional value for this study.

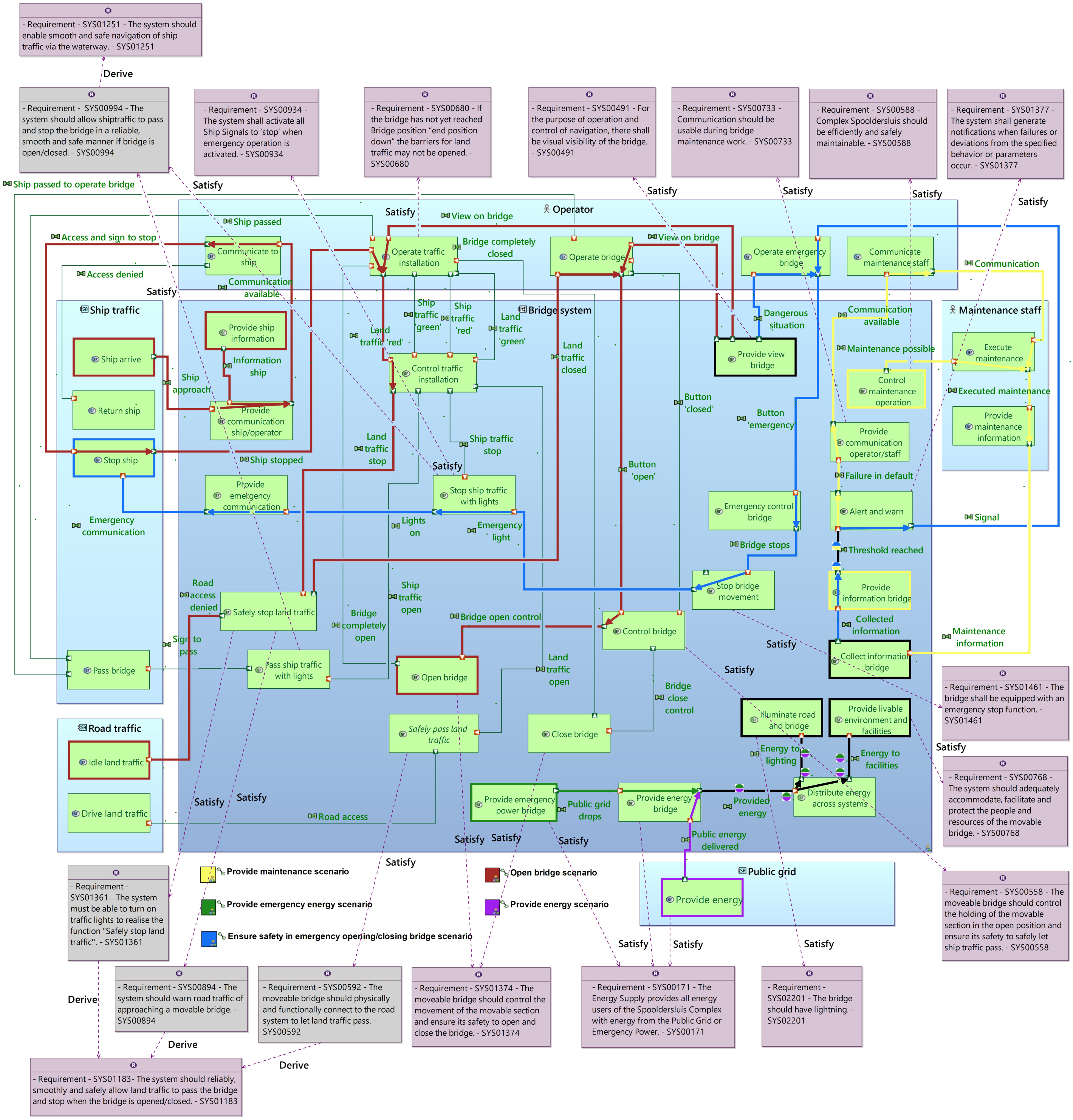

Figure 7.10: Total System Architecture Breakdown (SAB)

7.3.3 Modelled diagrams in Logical Architecture

Capella offers automated transitions to facilitate the switch to a next layer. The transition from system analysis includes automated transition of system functions to logical functions, system actors to logical actors, and system capabilities to logical capabilities. In the Logical Architecture functions can be decomposed further into sub-functions. Decomposing system functions into more detailed logical functions has been partially conducted for the case study as the System Analysis was already relatively specific, like the decomposition of the functions 'Safely pass land traffic' and 'Safely stop land traffic'.

Although Capella enables extensive specification and decomposition of system functions, this study marked both the authors' initial experience with system modelling in Capella and first in-depth exploration of a movable bridge system. Detailed information about such specific systems is often challenging to interpret. Modelling the system at a higher level of detail may introduce unnecessary complexity for readers and will not offer additional value to the objectives of this study. Therefore, a conscious decision was made to model the system at a level of abstraction consistent with the functional definitions provided in Relatics, while selectively specifying several functions if relevant. Lastly, no requirements have been added to the Logical Architecture, as these are included in the subsequent Physical Architecture.

As an example, three functions have been further decomposed in the Logical Architecture, illustrated in Figure 7.11, Figure 7.12, and Figure 7.13. This results in a new breakdown structure which is presented in Figure 7.14. The grey coloured functions in this Logical Functional Breakdown Diagram represent the new further decomposed functions.

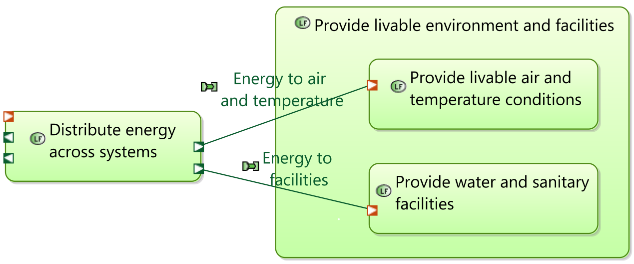

Figure 7.11: Logical Data Flow Blank (LDFB) of provide liveable environment and facilities function

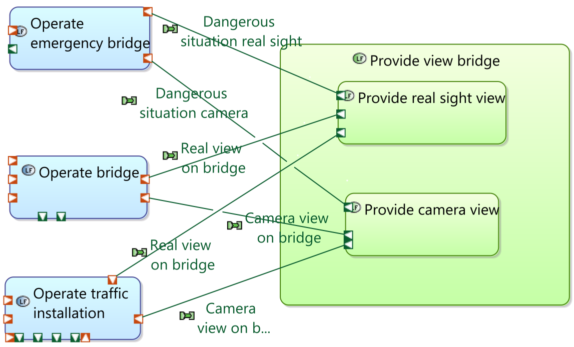

Figure 7.12: Logical Data Flow Blank (LDFB) of provide view bridge function

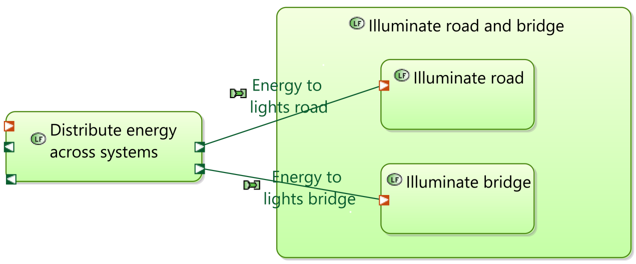

Figure 7.13: Logical Data Flow Blank (LDFB) of illuminate road and bridge

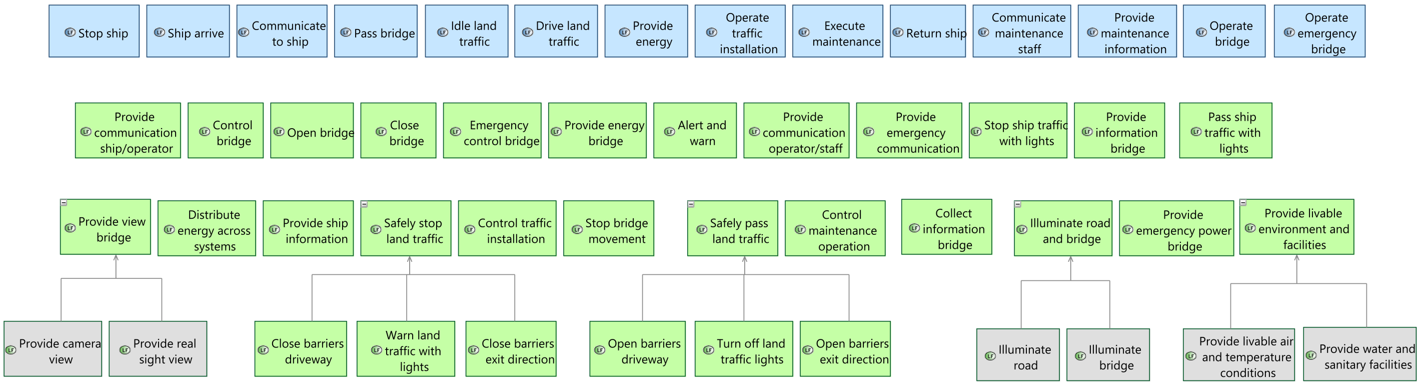

Figure 7.14: Logical Functional Breakdown Diagram (LFBD)

This layer primarily focuses on decomposing the system into subsystems based on the logical functions. The system has been decomposed into eight subcomponents, which is illustrated in the Logical Component Breakdown diagram in Figure 7.15. The subcomponents have been determined based on functions sharing the same goal, responsibilities, or domains.

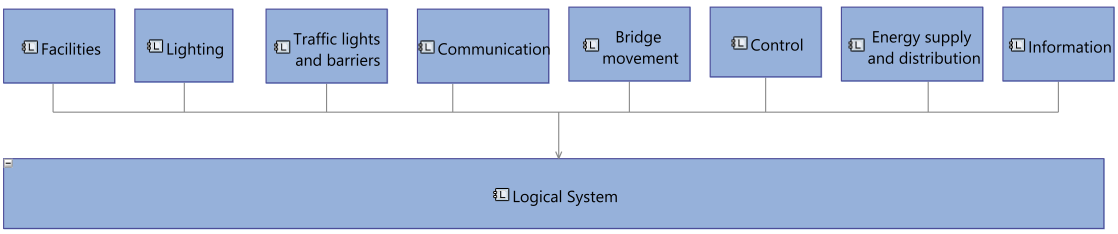

Figure 7.15: Logical Component Breakdown Diagram (LCBD)

For each scenario, a Logical Architecture Breakdown Diagram (LAB) or an Exchange Scenario Diagram (ES) can be developed to allocate function to the corresponding subcomponents within the system. In the case of the 'close bridge' scenario, an ES diagram was chosen over an LAB, as it provides a clearer overview when functions are executed multiple times within a scenario. This particular scenario is extensive, involving several functions that are repeated throughout its flow. The resulting LAB and ES diagrams of the Logical Architecture are presented in Appendix E.

At the end, a total Logical Architecture Breakdown (LAB) was created, focusing only on the allocation of functions to subcomponents. To maintain clarity and structure, functional exchanges, which represent the link between functions, were excluded from this overview, which is illustrated in Figure 7.16.

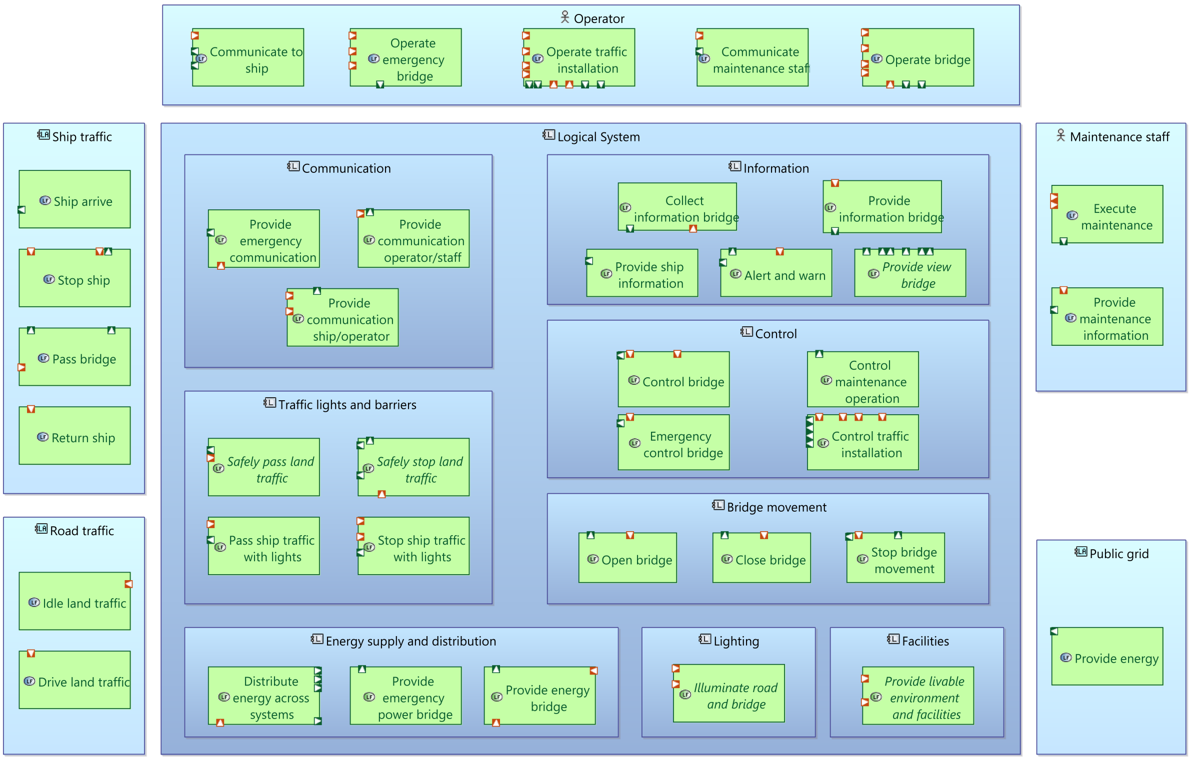

Figure 7.16: Total Logical Architecture Breakdown (LAB)

7.3.4 Modelled diagrams in Physical Architecture

In transitioning to the Physical Architecture, Capella uses the same capabilities used during the shift from System Analysis to Logical Architecture. This includes transitioning the logical functions, components, functional exchanges, capabilities, and actors to their physical derivatives. Subsequently, each subcomponent can be further specified using several 'node physical components', representing physical objects by a yellow colour.

The Physical Component Breakdown represents the decomposition of the subsystems to specific physical objects, which is illustrated in Figure 7.17.

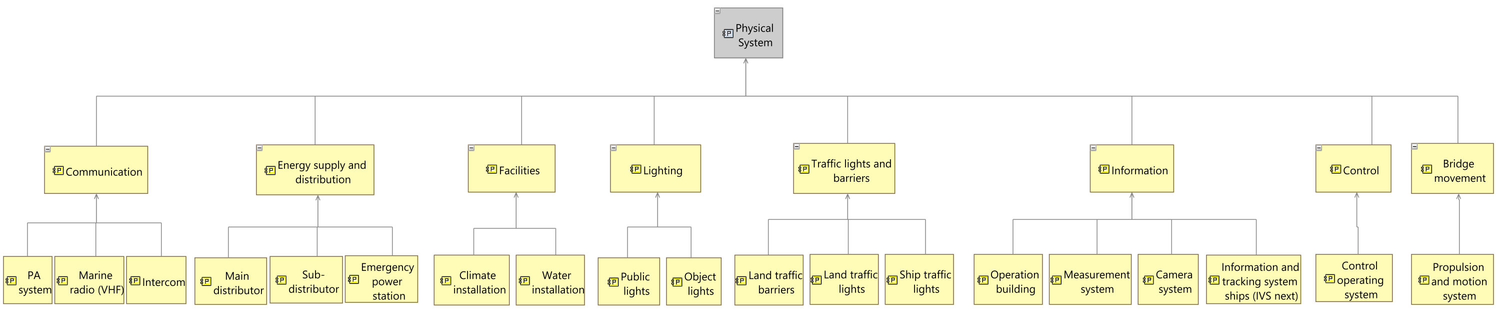

Figure 7.17: Physical Component Breakdown Diagram (PCBD)

The total Physical Architecture Breakdown is shown in Figure 7.18, excluding the functional exchanges to maintain clarity without intersecting lines. This diagram incorporates object-specific requirements, many of which differ from those identified during the System Analysis phase. The advantage of using an MBSE tool such as Capella is the ability to efficiently reuse modelling elements, like requirements, across several architectural layers. These requirements relate either to the inclusion of specific objects within the physical system or to defined parameter constraints.

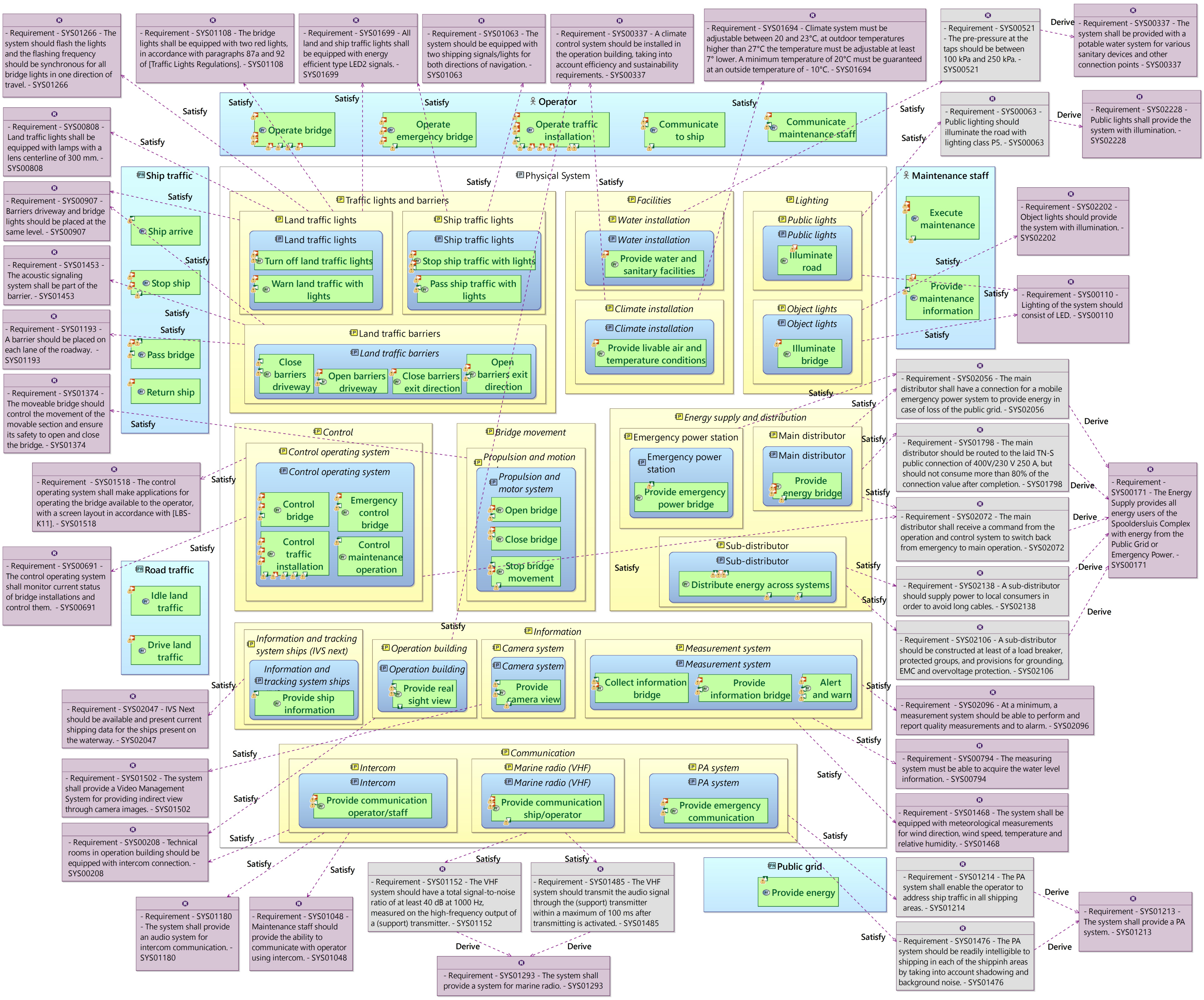

Figure 7.18: Total Physical Architecture Breakdown (PAB)

Capella offers various add-on functionalities, like the Properties Values Management Tools, to parameterise modelling elements, such as the system, subcomponents, and physical objects. Where relevant, parameters like SBS coding, dimensions, or electric load can be assigned to the modelling elements in diagrams. However, parametric modelling was excluded from this study, as Capella does not support calculations or comparisons based on these parameters. This makes inclusion of parameters unfeasible and therefore parametric requirements could not be formally verified. These requirements were only included for visual traceability.

Furthermore, Capella provides several viewing options of its elements, which is useful for traceability or large dataset analyses. For example, a traceability table illustrating the requirements and its relations added in the Physical Architecture is presented in Table 7.1. The requirements were manually added to the model using the 'Requirements Viewpoint' add-on. Although Capella supports the import of requirement files, this functionality was not used in the case study due to the limited number of requirements.

	ReqIFLongName	ReqIFChapterN...	Allocating Elements	Internal Relation	Parent	Owned Relations	Internal Relation
	Requirement ...	SYS01152	Marine radio (VHF)		Requirements	[Derive] SYS01293	SYS01293
	Requirement ...	SYS01485	Marine radio (VHF)		Requirements	[Derive] SYS01293	SYS01293
	Requirement ...	SYS01293		SYS01485, SYS01152	Requirements		
	Requirement ...	SYS01214	PA system		Requirements	[Derive] SYS01213	SYS01213
	Requirement ...	SYS01476	PA system		Requirements	[Derive] SYS01213	SYS01213
	Requirement ...	SYS01213		SYS01214, SYS01476	Requirements		
	Requirement ...	SYS01048	Intercom		Requirements		
	Requirement ...	SYS01180	Intercom		Requirements		
	Requirement ...	SYS00208	Operation building, Intercom		Requirements		
	Requirement ...	SYS02047	Information and tracking system ships (IVS next)		Requirements		
	Requirement ...	SYS01502	Camera system		Requirements		
	Requirement ...	SYS01518	Control operating system		Requirements		
	Requirement ...	SYS01063	Ship traffic lights		Requirements		
	Requirement ...	SYS01468	Measurement system		Requirements		
	Requirement ...	SYS00794	Measurement system		Requirements		
	Requirement ...	SYS02056	Main distributor, Emergency power station		Requirements	[Derive] SYS00171	SYS00171
	Requirement ...	SYS01798	Main distributor		Requirements	[Derive] SYS00171	SYS00171
	Requirement ...	SYS02072	Main distributor, Control operating system		Requirements	[Derive] SYS00171	SYS00171
	Requirement ...	SYS02096	Measurement system		Requirements		
	Requirement ...	SYS02138	Sub-distributor		Requirements	[Derive] SYS00171	SYS00171
	Requirement ...	SYS02106	Sub-distributor		Requirements	[Derive] SYS00171	SYS00171
	Requirement ...	SYS00691	Control operating system		Requirements		
	Requirement ...	SYS00596	Propulsion and motion system		Requirements	[Derive] SYS01374	SYS01374
	Requirement ...	SYS00611	Propulsion and motion system		Requirements	[Derive] SYS01374	SYS01374
	Requirement ...	SYS01193	Land traffic barriers		Requirements		
	Requirement ...	SYS01453	Land traffic barriers		Requirements		
	Requirement ...	SYS00808	Land traffic lights		Requirements		
	Requirement ...	SYS01699	Land traffic lights, Ship traffic lights		Requirements		
	Requirement ...	SYS00907	Land traffic barriers, Land traffic lights		Requirements		
	Requirement ...	SYS01266	Land traffic lights		Requirements		
	Requirement ...	SYS01108	Land traffic lights		Requirements		
	Requirement ...	SYS00337	Climate installation, Operation building		Requirements		
	Requirement ...	SYS01694	Climate installation		Requirements		
	Requirement ...	SYS00521	Water installation		Requirements	[Derive] SYS00337	SYS00337
	Requirement ...	SYS00337		SYS00521	Requirements		
	Requirement ...	SYS02202	Object lights		Requirements		
	Requirement ...	SYS02228		SYS00063	Requirements		
	Requirement ...	SYS00110	Object lights, Public lights		Requirements		
	Requirement ...	SYS00063	Public lights		Requirements	[Derive] SYS02228	SYS02228

Table 7.1: Requirements and its relations added in the Physical Architecture

Capella supports model validation for each diagram created through built-in validation rules that assess completeness, integrity, and design consistency. This process was applied to the model of the Spooldersluis bridge and may result in validation warnings and errors. Validation errors indicate significant issues and were resolved before progressing to the next diagram or layer, while validation warnings highlight less significant mistakes and suggest areas for improvement. Addressing validation warnings was not prioritised in this research due to time constraints.

7.3.5 Evaluation of modelling in Capella

The author, or modeller, of this study can analyse and evaluate the use of Capella after the case study has been conducted. This evaluation below is based on gained insights and presents general comments on the modelling effort in Capella.

Capella excels in the visual modelling of systems and architectures, including aspects such as system behaviour, interactions, and interfaces. This visual modelling approach leads to early understanding and analysis of the system. Furthermore, Capella implements elements like physical links and functional exchanges, which are often not modelled, and not even documented, in projects. Modelling such aspects can bring added value for projects by providing additional insights. Furthermore, while modelling in Capella interfaces between elements and critical elements of the system can be identified.

As mentioned earlier, Capella allows for automatic transitions between the different modelling layers and allows the ability to clone diagrams, which helps improve efficiency in transitioning from layer to layer and improve consistency and traceability. If diagrams have been created and modifications occur, it only needs two or three steps to update the entire information set in each layer. With the ‘semantic’ view, each element including its related information, like relations, can be viewed and adjusted.

It can be concluded that the tool’s ability to perform trade-off analysis based on parameters is limited and relies on add-ons. For performing such analyses, key parameters have to be established. Due to the parametric limitations of Capella, trade-offs have not been researched in this study. In contrast, SysML tools, can easily perform trade-off analyses and parametric requirements can therefore be verified. However, Capella supports qualitative trade-off analyses by using the ‘scenarios’. Such scenarios can be compared, resulting in comparing design options or viewing the impact of changes.

The repeated use of the same concepts for each layer allows for quicker familiarity with both the tool and the methodology. The author, or modeller of this case study, could quickly understand the tool’s capabilities. But also, the bridge system could easier and quicker be understood in Capella than in Relatics. This might be due to a straightforward modelling process of Capella and the visual capabilities of Capella.

The total architecture diagrams of Capella, like the SAB, LAB, and PAB, are fundamental parts of the modelling process. Despite their structural similarity, each has a different purpose and level of detail due to the different layer. The other diagrams, such as Exchange Scenarios, Functional Breakdowns and Data Flows, also constitute significant modelling constructs, crucial for the completeness of the system model. Each of these diagrams is interconnected, which ensures consistency across various perspectives. When changes are made in a specific model, they are automatically synchronized across each relevant view. This ensures consistency and eliminates the need for manual synchronization.

It is important to note that diagrams in Capella can become large and complex if much modelling elements are included in a diagram. Therefore, diagrams should be created with a certain detail level. For example, to create a PAB diagram for every subcomponent, such as traffic lights and barriers. This PAB diagram can specify certain objects and functions in a lower detail, while a total PAB could be created using a higher level with the parent functions and objects of this subcomponent.

7.4 Expert session

In this section, the modelling approach and capabilities of Capella and the created diagrams during modelling of the Spooldersluis project are demonstrated in a session with experts from the Spooldersluis project. The experts were asked to provide opinions on several topics to identify the added value of the proposed MBSE adoption. This section starts explaining the goal of the expert session, including the structure of the session. Additionally, the results of the expert sessions are presented, found through an analysis of the collected data. Section 7.4.3 closes this section by comparing the findings with MBSE literature of Chapter 3.

7.4.1 Goal and structure of session

The primary goal of this expert session was to evaluate the use of an additional MBSE tool like Capella to improve efficiency of the Systems Engineering processes. Participants of the session were asked to review the functionalities of the Capella tool and reflect if this could have improved the Spooldersluis project. Lastly, they were asked to identify obstacles or challenges and to provide solutions for these. An overview of the participants' role and work experience is provided in Appendix F.

The session started with an introduction of MBSE to familiarise the participants with the topic. Next, the Capella tool was introduced, including its functionalities. Before diving into the interactive part and the questions, the created diagrams of Spooldersluis were demonstrated to the experts. Subsequently, the following questions were asked, including the goal of each question.

1. *Is it clear what the MBSE concept is and which functionalities Capella has?*
   Goal: A check to validate if the demonstration and the use of Capella is clear.

2. *What are advantages of creating such models or diagrams?*
   Goal: Identify the potential benefits of integrating an additional MBSE tool, like Capella.

3. *What are disadvantages of these models or diagrams?*
   Goal: Identify the potential downsides of integrating an additional MBSE tool, like Capella.

4. *What are challenges regarding this MBSE modelling approach?*
   Goal: Investigate potential obstacles of integrating an additional MBSE tool, like Capella.

5. *How can we mitigate such challenges?*
   Goal: Investigate solutions to make sure these challenges can be mitigated.

7.4.2 Analysis of results

The answers of each participant on the five questions in the expert session are discussed in Appendix F. An analysis on the answers per question has been conducted and is presented below.

Clarity of functionalities

The demonstration and use of the functionalities within Capella are clear, but it was noted by one of the participants that it could be hard to put the modelling approach into specific context as it is a new approach/way of working and much options exist in the Capella tool.

Advantages

The participants praised the added value of Capella's modelling functionalities for both the technical installation discipline, also called Industrial Automation and Electrical Engineering (IA&EE) discipline, and the mechanical discipline. These disciplines typically employ functions and a sequence of functions to develop use cases. Specifically, for Spooldersluis project, numerous errors were observed within the IA&EE discipline because the desired behaviour of the system and its installations was not clearly determined. For example, problems occurred at the sequence of functions for the traffic barrier installation as it there was no clarity of the functions of this installation. Although the client provided functional specifications, these were not integrated into the project workflow. The absence of this led to significant errors in the system behaviour of the IA&EE discipline. Capella offers capabilities to clearly determine use cases and functional exchanges and to analyse system functions, which could have mitigated these issues. The civil discipline is a static discipline which places less emphasis on functional behaviour. Nevertheless, physical civil objects and their interconnections can still be modelled, supporting interdisciplinary integration.

Another misalignment in the Spooldersluis project was the failure to identify several interfaces between components, especially for the IA&EE and mechanical discipline. This was the case for interfaces related to the camera system. Because of the capabilities of Capella to create links between modelling elements, the interface list can be extended using physical links or functional exchanges between the camera system and other systems. Currently, interfaces are primarily discovered through physical clash detections and interdisciplinary meetings. The functionalities of Capella can enhance the completeness of the interface list by linking elements instead of having separate elements. While most physical civil interfaces did not pose challenges at Spooldersluis, the participants indicated that in more complex projects such interfaces may be overlooked without using Capella. This suggests that Capella improves alignment across disciplines.

Participants also recognised advantages in impact analyses. If elements are modified, the impact of the modification within and across disciplines can immediately be identified. Changes may affect objects, requirements, interfaces, or functions. If these relationships are captured in a model, the impact can be traced efficiently and warnings can be generated. This capability would have significantly reduced time and effort for the IA&EE discipline during the Spooldersluis project. One of the participants provided the example of the effect of a larger engine in the propulsion system on the speed at which the bridge opens and closes. This effectiveness of impact analysis is closely related to the identification of interfaces. A more complete interface list results in a more thorough impact analysis, reducing the likelihood of overlooked elements.

One participant highlighted the visual abilities of Capella, which helps to increase understanding of the system during the early phases of a project. This observation was identified by the author during the evaluation of the modelling process in Section 7.3.5 and is validated by the expert session. Instead of viewing a textual list of elements in a system, visual diagrams contribute to improve understanding of system architecture.

Another participant emphasised the potential of Capella for test protocols by recording information in models. If scenarios and use cases elements can be used for test protocols, test protocols can be modelled and subsequently be generated as documentation. Future projects could benefit from this feature as models including the test protocols can be reused. Currently, the V&V phase demands significant effort for test protocol development. This aligns with participant opinions regarding the potential to reduce modelling time through model reuse in future MBSE projects.

Finally, participants highlighted another added value for the V&V process. By linking requirements to functions and specific objects, it becomes possible to verify requirements both at the object-requirement and function-requirement levels. Although this approach is not currently implemented, it holds potential for enhancing the V&V process by ensuring extensive requirement verification.

Disadvantages

One disadvantage of using a MBSE tool like Capella is that it requires extra work. At the start of a project, the diagrams in the MBSE tool must be created. Especially in the beginning of implementing such a MBSE tool because models should be created from scratch. However, by investing in such models, future projects can be executed faster as preliminary work is already done. Reusing such models and making project-specific adjustments saves much time in future projects. For example, designing a traffic barrier currently takes one week, but can be reduced to two hours.

Furthermore, Capella faces several tool-specific limitations. There is the limited number of predefined elements. Capella does not have standard elements such as design rationales and parameters. Another limitation is the additional add-ons of the tool. This may lead to incompatibility with older versions, may require additional effort for seamless integration or may lead to limited support.

Challenges and solutions

The first challenge identified by the participants is the difference in added value for each discipline. The added value for the IA&EE discipline is higher and clearer than for the civil discipline. So, it should be clear for each discipline what is expected from them to contribute to these models. As MBSE is multidisciplinary, communication between disciplines is key, mitigating the risk of modelling unnecessary effort or modelling gaps.

Related to the clarity and establishment of guidelines is the management and responsibilities of the created models. It must be recorded how the models should be managed and who is responsible for the creation of the models. One of the participants suggested to give responsibility to the Systems Engineer and Design Manager to create the MBSE models.

Another challenge of adding an MBSE tool is the risk of human resistance. Employees need to change their workflows while MBSE will be adopted. For these employees, the reason to change, or the added value, must be clear to mitigate this risk. As a result of a lack of knowledge or changing the current workflow, human resistance can emerge. A related challenge to changing the workflow is the integration of the adoption into the current workflow. In order to seamlessly integrate such an MBSE tool, a new clear process model should be established.

A final challenge includes the required time to learn and get familiar with the MBSE adoption. This is also verified by the opening clarity statement that it is hard to put the tool adoption into context as it is new. Trainings and tutorials should be provided to employees to guide the use of such a new tool.

7.4.3 Findings against literature

After the findings of the case study have been analysed, this section compares these findings to the literature. In this way, it can be examined if the findings from the application to the construction industry aligns with findings from MBSE practices in other industries. The advantages, disadvantages, and challenges are compared in respectively Table 7.2, Table 7.3, and Table 7.4 on the next page.

Most findings have been mentioned in academic literature. While the case study of this research has been applied to the construction industry specific, some aspects were not explicitly mentioned before and are only related to this sector. For example, the finding that a MBSE tool adds more value for the IA&EE discipline compared to the civil discipline.

The comparison presented in the tables below demonstrates that many of the benefits and challenges associated with MBSE, as discussed in Chapter 3, were also recognised by the participants during the expert session. Examples of these benefits are enhanced communication and collaboration across multidisciplinary teams, better knowledge capture and reuse through models, visualisation, traceability, and early impact analyses and detection of issues. The latter is explicitly mentioned by the participants through the early complete identification of, specifically interfaces. The literature highlights the single source of truth and early validation and simulation, which are not identified as benefits during the expert session.

Examples of MBSE-related challenges mentioned in both the academic literature and the expert session are the steep learning curve, human resistance due to a lack of familiarity and knowledge, integration of workflows, and management and responsibilities of models. However, the literature also includes challenges such as a lack of management commitment, adoption strategy selection, over-reliance on models, financial upfront investment, lack of consistency and standardisation, and the complexity of projects.

Advantages	Mentioned in literature?
Most added value for disciplines using behaviour and functions	Partly. Madni & Sievers (2018) mentioned the enhanced analysis of system behaviour with MBSE. But it is not mentioned in literature that most value arises for disciplines at contractors using system behaviour, compared to disciplines not utilising system behaviour. The civil discipline is an example of such a discipline.
Interface identification and interdisciplinary alignment	Yes. Coordination and communication between disciplines is mentioned by Campo et al. (2023). Specifically interface identification has been described as a benefit by Hause (2018).
Early and fast impact analyses	Yes. Walden et al. (2015) identified the added value of MBSE to track the impact of a change due to the connection of elements.
Visual understanding of the system	Yes. Heydari (2023) and Walden et al. (2015) describe MBSE's ability for early understanding of a system.
Reduce time by reusing models	Yes. The reduced design time by reusing models in future projects is highlighted by Walden et al. (2015) and Wilking et al. (2024).
Enhance V&V by extensive requirement verification	Partly. Mentioned that requirements can be traced back to each element by Walden et al. (2015), but not specifically that object- and function-verification can extend and enhance the V&V process.

Table 7.2: Findings of advantages against literature

Disadvantages	Mentioned in literature?
Extra work or effort	Yes. Madni & Sievers (2018) and Henderson et al. (2023) mention the extra effort needed when adopting MBSE.
Capella tool-specific limitations	Partly. It was already clear that Capella is simple and easy to learn (Baron et al., 2023). But the construction industry prefers to include elements that are not available as add-ons.

Table 7.3: Findings of disadvantages against literature

Challenges	Mentioned in literature?
Expectation and communication between disciplines	Yes. The cross-disciplinary communication aspect has been discussed in literature by Kellner et al. (2016). The expectation of discipline interaction has been identified by Madni & Sievers (2018).
Management of models	Yes. Carroll & Malins (2016) highlight that organisations must establish clear processes to ensure effective management of models.
Human resistance	Yes. Human resistance due to a lack of knowledge or adapting workflows has been identified by Hallqvist & Larsson (2016) and Carroll & Malins (2016).
Integration into current workflow	Yes. Heydari (2023) and Chami et al. (2018) describe the difficulty of integrating MBSE into current workflows.
Time-investment for learning	Yes. Time-investment for MBSE is highlighted by Friedenthal et al. (2014). This includes learning due to a steep learning curve.

Table 7.4: Findings of challenges against literature

7.5 Roadmap

Based on the findings of the case study retrieved from the expert session, the requirements for the MBSE adoption, and the findings from academic literature, a roadmap can be established. This roadmap can be used by organisations in the construction industry as a stepwise guide to adopt the MBSE approach. Because it forms the basis for the new activities an organisation must realise, it is also called implementation framework in research studies. Section 7.5.1 describes the application of the PARiHS framework for MBSE adoption. Subsequently, Section 7.5.2 develops several maturity levels for this adoption.

7.5.1 PARiHS framework

An implementation framework that is one of the most cited implementation frameworks is Promoting Action on Research Implementation in Health Services (PARiHS) (Bergström et al., 2020). It originated from the Health Services sector but has also been applied in other sectors and contexts. PARiHS will be used as the implementation framework for this study, due to the focus on organisational culture and support, and on successfully implementing evidence-based practices. As this research showed the evidence of added value regarding the MBSE modelling approach, it should subsequently be implemented successfully. The PARiHS framework is a commonly used conceptual framework that considers Successful Implementation (SI) as a function (f) of the Evidence (E), Context (C), and Facilitation (F). This results in the following function:

$$SI = f\ (E, C, F)$$

Evidence (E) stands for the nature and type of the evidence, including the quality and relevance of the evidence. As mentioned in academic literature, organisations in other sectors praised the potential of MBSE to improve communication and knowledge capture, prevent design errors, reduce rework, and to support traceability and consistency. Based on the case study of this research, the added value is the largest for the IA&EE discipline within a contractor. Regarding the Evidence aspect, this results in the fact that this discipline should adopt and use the additional MBSE tool, and that other disciplines should limit their MBSE work as their added value is lower.

Context (C) considers the quality of context, like culture, leadership, and evaluation. The organisation should be ready for the change. For example, this includes to limit human resistance. As discussed earlier in this research, this can be established by providing a clear added value for employees, strong managerial support and communication, and knowledge sharing. Furthermore, the management of models and workflows should be clearly defined, which has already been discussed in the requirements and the case study. Lastly, the progress should be measured in a way the adoption can be tracked and evaluated. This can be established by creating requirements or maturity levels.

Facilitation (F) includes the way the implementation process is facilitated, by internal or external people enabling the implementation process. A common recommendation in the literature is to establish a core network of MBSE experts to ensure knowledge sharing and collaboration (Chami et al., 2018) (Kellner et al., 2016). This network consists of dedicated expert modellers, a core MBSE implementation team, and teams to offer training and support. In this way, training, coaching, and support can effectively be realised.

7.5.2 MBSE adoption maturity levels

The PARiHS framework described certain barriers and enablers which influences the outcome of the implementation process. The organisational development stages and their sequence are not described in the PARiHS framework. These aspects can be covered in a road map of maturity levels, as this provides progression levels including the goal, necessary responsibilities, and resources per task. Each organisation can adapt this phased adoption strategy to suit its specific needs and context.

To support a structured and phased adoption, according to the requirements from Chapter 4 an organisation must establish at least three maturity levels. These levels outline progressive levels of integration and capability. Each level builds upon the previous one and reflects increasing alignment with MBSE principles and characteristics. As discussed in the PARiHS framework progress should be measured, which can be established using these maturity levels.

Maturity level 1: Federated single source of truth. At the first level of MBSE adoption, the current digital landscape of the organisation must be consistent and correct before implementing new methods, tools, languages, or processes. This stability ensures that higher maturity levels are built upon a reliable foundation. As a result, an organisation should define which tool is the authoritative source for each specific type of information. Although tools remain largely disconnected, clarity should be established regarding where data is created, maintained, and accessed. However, this can differ significantly between organisations depending on operational context and the choice of systems and information elements. Since this difference, this maturity level can be tailored to various levels of detail, allowing organisation to align this with their goals and preferences. The concept of a federated single source of truth can be expanded and refined in more detail as the organisation progresses in maturity level.

Maturity level 2: MBSE preparation. The establishment of a MBSE process, model management, and a core MBSE network can be regarded as a second preparational phase before the actual adoption phase. First, an adjusted process and model management must be documented. This considers responsibilities and activities regarding the MBSE approach, making integration between functions, disciplines, and tools easier. As mentioned within the Facilitation aspect of PARiHS, the core MBSE network includes a MBSE implementation team, dedicated MBSE modellers, and a support team. If the MBSE process has been established, the federated single source of truth of maturity level 1 may be adjusted as MBSE related information will be added and current information elements might shift its authoritative source.

At this maturity level, basic training and explanation of added value sessions must be provided to its employees on various levels based on each role. According to Henderson et al. (2023), there are four distinct groups who need to be trained to a certain degree, which are model reviewers, developers, architects, and administrators. Model reviewers are the employees who need to make decisions based on the models. Developers can be regarded as the dedicated MBSE modellers. The third group is the architects, which provide developers with discipline specific content and will have a lower understanding of the models itself. Lastly, the administrators are responsible for the provision of the software tools, including management of extensions and licenses.

Maturity level 3: MBSE tool integration. At the third level, the organisation should consider introducing a MBSE tool if the current digital landscape lacks functionalities to support MBSE. Implementing a MBSE tool enables structured modelling of system and information elements such as requirements, functions, behaviours, and objects. The selected MBSE tool should be capable to integrate data from other existing tools and link them in the formal models of the MBSE tool. This facilitates early analysis, simulation, and validation. In alignment with the PARiHS Evidence aspect, it is recommended to adopt the tool selectively for disciplines where it delivers the highest added value, like the IA&EE discipline. This level also presents the opportunity to execute a pilot project, enabling employees to apply their basic MBSE knowledge in a practical setting and continue learning. Providing ongoing coaching and support is essential to ensure continuous skill development and active participation over time.

Maturity level 4: Document replacement. At the most advanced level, the organisation transitions to a complete model-centric system. Models become the primary medium for storing, communicating, and validating information elements. This includes capturing design rationale and decisions directly in models and replacing traditional documents with model-generated outputs. This reduces the reliance on documentation management tools and eventually such tools can be phased out.

7.6 Summary

This section provides a summary of Chapter 7.

This chapter presents the findings of a case study and expert session regarding the adoption of MBSE. These insights form the basis for establishing a roadmap for MBSE adoption within organisations. In this way, an answer on the last research sub-question 5 can be provided. Regarding the MBSE proposal of Chapter 6, this chapter focuses solely on conducting a case study based on the integration of the MBSE tool Capella.

The added value of MBSE for a contractor is validated by the use case of Spooldersluis bridge project. The Capella tool was selected to model this system due to its structured relation to the ARCADIA method, user-friendliness, and open-source licensing type. In Capella, several models were created starting with the System Analysis and continuing to the Logical and Physical Architectural layer. Following each of these phases enables the system to be defined in further detail.

It starts with defining actors, system functions, functional exchanges, and scenarios or use cases. Later, the system functions are grouped into subcomponents and functions can further be specified. Finally, physical objects are determined based on the created subcomponents. A requirements add-on is integrated into Capella to link and trace requirements to several information elements.

Following this modelling process revealed user experienced strengths of Capella, such as visualisation of information, identification of interfaces, automated transition and synchronisation of elements per layer, straightforward process, and modelling of crucial undefined elements and links. However, weaknesses include limited parametric modelling and add-ons for extended capabilities.

The expert session with team members of Spooldersluis project validated the added value of the MBSE tool Capella. The participants highlighted the added value especially for the IA&EE discipline, as they include functional behaviour. Furthermore, it completes interface identification, helps to analyse impacts, and helps to early understand systems due to visualisation. Modelling of test protocols to enhance the test phase is mentioned as a potential. Participants discussed challenges such as additional effort, human resistance, and integration into existing processes. To overcome these challenges, clearly defined responsibilities, training, and establishment of a MBSE network are suggested. These main findings were also discovered by literature of MBSE in other industries. This study provided the unique added value for application to the construction industry.

The PARiHS framework is used in this study for successful implementation of MBSE, consisting of the aspects Evidence, Context, and Facilitation. Evidence considers the relevance and quality of the evidence of the added value. Context includes organisational aspects, like culture, strong managerial support, clearly defined processes, and progress measurement. Facilitation considers the resource support for successful implementation.

The chapter concludes with four MBSE maturity levels, based on the PARiHS framework. These include establishment of a federated single source of truth, MBSE preparation by creation of model management and an MBSE team including trainings, MBSE tool integration using a pilot project, and complete transitioning from document-centric to model-centric communication.

8. Discussion

The discussion chapter includes implications, limitations, and recommendations of this study. Section 8.1 discusses the implications, which include the added value and consequences of this research for both theory and practice. The limitations are aspects that restricted the research, which may influence the results negatively. The limitations of this research are discussed in Section 8.2. Finally, recommendations for future research are discussed in Section 8.3, based on this research's limitations.

8.1 Implications

This study investigated MBSE adoption for the construction industry. In the literature, many findings regarding MBSE have been provided. However, this study focused specifically on the application to the construction industry, which provided new insights. Requirements for the adoption of MBSE based on a contractor organisation have been determined. Some requirements have also been applied by other industries, such as a reliable tool adoption, pilot-based adoption, and management commitment. Other requirements have specifically been established for the construction industry, such as the flexible standardisation of the system, open standard compliance, minimal expansion, and alignment with the ISO 15288 standard.

This research also investigated applicable MBSE methods, tools, and languages for the adoption within contractors. Literature have already investigated several methods, tools, and languages, but not addressing the ones from this study based on established requirements for specifically the construction industry. Contractors can use this analysis for a selection of methods, tools, and language for their MBSE adoption.

Regarding the digital information landscape of contractors, it has been concluded that it lacks functionalities to effectively adopt MBSE. The literature describes the potential of MBSE but lacks attention to functionalities of current situations. This research complements the literature with describing digital landscape and adopting MBSE with its functionalities in this landscape. For contractor organisations, information swimming lane diagrams can help to practically determine information flows and authoritative information elements in their digital tools. In this way, a federated single source of truth can be established for contractors.

Eventually, it resulted in the modelling of a construction industry project within a MBSE context using the Capella tool, which has not been done in literature. This provided new insights for the added value and potential of MBSE in contractor organisations and confirms many general MBSE benefits to be applicable to the construction industry as well. For example, the MBSE tool is especially helpful for design of disciplines using system behaviour and functions, helps to identify interfaces, has potential for efficient testing, and helps to understand systems due to the visual interface. The results of the expert session and its comparison to literature have already been described in Section 7.4.3, in which the findings are related to previous studies.

Regarding the Capella tool, this study confirms that Capella and its associated ARCADIA method is user-friendly, is easy to learn, and uses several add-ons for extended capabilities. However, it complements literature with the fact that Capella has limited elements embedded in the tool for standard information types used in the construction industry.

Lastly, the research emphasises to carefully adopt MBSE using the PARiHS implementation framework and four maturity levels. This is valuable for organisations to maintain control and measure the adoption progress. By first creating a consistent and correct digital landscape, MBSE can be prepared and integrated.

8.2 Limitations

As the research provided valuable contributions to both practice and literature, the study faced several limitations that should be recognised. Limitations are shortcuts or simplifications implemented due to constraints of this research.

The first limitation is related to the scope of the case study. MBSE includes the integration of MBSE methods, tools, processes, and languages, as well as efficient Digital Information Management, like a single source of truth. The case study only tested the use of the MBSE method, tool, and language. However, the MBSE proposal of the information flows and single source of truth has not been applied to a use case. Furthermore, processes including responsibilities and management of models are not included in the scope of this research but is considered important for effective adoption.

While this study focused on the MBSE tool Capella, there are several other available MBSE tools suited for contractors. The results from this study may not be applicable to other tools or new results may emerge if other tools are used. However, for this research only the Capella tool has been examined due to time constraints, as Capella is an easy to learn tool. This does not imply that organisations should integrate Capella for successful MBSE adoption. Tools compatible with SysML, like Enterprise Architect and Cameo, have extensive modelling capabilities, use the standard MBSE language, and are more widely accepted and used compared to Capella, which might be preferred by organisations.

Furthermore, this study is bounded by limited data usage. During conduction of the expert session and interviews, the results were based on a limited number of participants. In combination with execution of these methods at the research venue of BAM, resulted in possible negative influences on the findings of this study. It limits representativity of other contractors and the broader construction sector and constrains the completeness of the findings. In this research there is no attention to collaboration with clients, subcontractors, or collaborating parties. It is crucial to define the interface between contractors and other stakeholders. The limited data usage is also present in the case study of testing only one project, as use cases can vary in type, complexity, and quantity. The use case of Spooldersluis is a mid-size and dynamic type of project, including several technical installations.

Finally, limitations have been faced related to modelling in Capella. In this MBSE tool, parameters and verification of requirements have been excluded due to capabilities of the tool. The Operational Analysis layer and links between physical objects are omitted due to limited relevance and time constraints. These Capella-related limitations result in a less complete overview of the functionalities of the tool.

8.3 Recommendations

Based on lessons, findings, and limitations from this research, future MBSE projects can be informed and helped. This includes recommendations to practice and future research about the adoption of MBSE for contractors in the construction industry.

Future research

The first recommendation for future research is to analyse the wishes and needs of several other contractors within the construction industry. This will ensure a broader perspective of the characteristics and needs of the industry. Future research may also focus on the interface between a contractor and other involved stakeholders for collaboration and communication. The MBSE adoption will affect such interfaces by a change of information exchange and collaboration. This change between contractors and subcontractors, clients, or partners should be investigated to avoid dissatisfaction and improve efficiency of the MBSE adoption.

For example, communication between stakeholders includes receiving and sharing the relevant information to them. This relevance may be defined by specific viewpoints or sub-models, such as in Capella, where diagrams are created based on a level of detail or specific part of the system. Models, sub-models, or generated documentation can be shared, allowing each stakeholder to obtain their own relevant information of the overall system. It should be investigated how to manage these shared models or documentation due to diverging workflows and standards amongst stakeholders.

Another future research proposal is to evaluate other MBSE tools by applying constructions projects. The choice of a tool can result in different outcomes. Testing other MBSE tools leads to a comparative tool analysis for specifically the construction industry. Apart from multiple tools, multiple projects should also be tested to the MBSE adoption. In this way, scalability of the adoption can be investigated by testing projects with a higher quantity of information.

Practical application

Practical recommendations are steps that are proposed for guiding organisations in their adoption. This has partly been described by the maturity level framework in Section 7.5.2. One of these proposed steps is to apply a federated single source of truth. This should be tested using a pilot project, resulting in insights about the use of information elements in tools and the integration options of a MBSE tool with current tools. Furthermore, it is important to gain understanding of creating synchronisation links between tools.

Investigating the change of processes for an organisation adopting MBSE is a second practical recommendation. This includes examining responsibilities and effective management of models. It is related to practice as this can differ largely between organisations. As mentioned in the maturity levels for MBSE adoption, an organisation must carefully prepare before integrating an MBSE tool. Aspects, such as training, a core MBSE team, consistent information flows, and standardised processes, must be arranged. This includes responsibilities for providing and receiving training but also for the several positions within the core MBSE team.

After an organisation is prepared, a pilot project must be executed using the MBSE proposal from start to finish. This enables practical lessons learned and measurement of effectiveness and efficiency of the established processes.

9. Conclusion

This final chapter summarises the results on the research sub-questions and the main research question. The general goal of this study is to address how MBSE can be adopted for contractors in the construction industry to enhance current SE processes. This study's findings contribute to efficiently adopting MBSE by offering several advantages.

Research sub-question 1

How does Systems Engineering processes at a contractor currently work and what are the limitations?

The Systems Engineering (SE) processes at a contractor consist of requirements analysis, functional analysis and allocation, design synthesis, design realisation, verification and validation, and several supporting processes. SE includes components such as interdisciplinary, iterative, lifecycle, transparent, and requirements. The application of SE for the Dutch construction industry is based on the V-model, ISO 15288 standard, and the Guideline SE. Although SE has extensive advantages, it faces several limitations. SE processes are prone to errors and inefficient due to the document-based nature of SE and the increasing amount of complex project information. Information is distributed across several tools and systems, increasing search time and the risk on errors. Due to the use of distinct sub-models by disciplines and the limited interoperability between these tools and systems, interdisciplinary communication and integral design become challenging.

Research sub-question 2

What is MBSE, and what are its benefits and challenges for a contractor?

MBSE represents several system views by usage of interconnected models. A model is an abstract description of a selected domain of interest. MBSE can be defined as the formalised application of modelling to support lifecycle processes of a system. It complements SE with an overarching model, consisting of several types of sub-models creating different systems views and a single source of truth. Whereas SE relies on authoritative documents, MBSE manages digital models as the primary medium. To adopt MBSE effectively, alignment is required between the methods, tools, modelling languages, personnel, and processes.

If this alignment is established, MBSE offers various benefits such as consistency and traceability of information. But also, interdisciplinary advantages like enhanced communication and collaboration. Furthermore, design errors can be detected earlier and information capture and reuse become more efficient, leading to decreased processing time and higher quality of the product. As most technological advancements, MBSE faces challenges. Human related includes a steep learning curve and resistance to change due to adapting workflows and unfamiliarity. Other challenges are the technological integration with existing systems, standardisation rate of the system, and risk of over-reliance on models. Organisationally, cultural change, managerial support and adoption strategy selection are challenges. Lastly, a financial upfront investment is required for tools, training, and coaching.

Research sub-question 3

What are requirements for successful MBSE adoption at a contractor?

Based on the comparative industry analysis, semi-structured interviews, and the literature study about MBSE, values and requirements for successful MBSE adoption have been established. Comparing the aerospace and automotive industry MBSE adoption revealed successful requirements such as user-friendliness, seamless integration, standardisation, success stories distribution, limited integration of new aspects, management commitment, extensive capability development, and a phased adoption using pilot projects.

The semi-structured interviews confirmed MBSE literature findings about the advantages and challenges. Furthermore, additional MBSE challenges were revealed, like organisational fragmentation, and SE challenges, such as inadequately defined requirements. Additional requirements emphasised by interview's participants are flexible standardisation, easy traceability, early-stage model analysis and usage of open standard methods, tools, and languages. The requirements provide a comprehensive strategy for adopting MBSE at a contractor and are derived from seven core values: integration, standardisation rate, user experience, controllable change, accountability, continuous learning, and leadership engagement.

Research sub-question 4

Which methods, languages, and tools can be used to adopt MBSE, and what adaptations are required in Information Management to enable this transition?

The research explored several MBSE methods, tools, and languages. The most commonly referenced of these have been analysed based on its features and by using the requirements established for MBSE adoption. The analysis resulted in no single optimal combination of MBSE method, language, and tool. However, some combinations are preferred above others.

Regarding methods, OOSEM and SYSMOD are widely supported, aligned with the ISO 15288, and tool-neutral. ARCADIA is more user-friendly and open-source but is limited to tools and languages. Concerning languages, SysML is recommended as it is the standard MBSE modelling language, supports SE processes and many tools, and is based on an open standard. However, SysML has a steep learning curve. Languages like SDL, ArchiMate, BPMN, Modelica, and OPD/OPL are less recommended due to its lack to support SE processes and to apply MBSE features. Cameo, Capella, and Enterprise Architect are MBSE tools preferred for implementation, supporting SE processes. While Capella is open-source and user-friendly but limited to the ARCADIA method, Cameo and Enterprise Architect have extensive capabilities and support the widely accepted SysML language. Relatics has limited capabilities for MBSE benefits but is considered indispensable in the Dutch construction industry. To conclude, the combination of the OOSEM or SYSMOD method with the SysML language and the Cameo or Enterprise Architect tool is the first promising option. However, ARCADIA with the Capella tool is suitable as well.

Regarding adaptations to Digital Information Management, the current digital landscape including its functionalities and information flows at contractors have been analysed to establish a MBSE adoption proposal. Current digital landscapes at contractors include GIS, BIM, asset management, documentation management, and project control tools. Due to limited functionalities of these tools to apply MBSE, an additional MBSE tool integration is proposed. This tool has functionalities to model architectures and analyse and simulate these models. As the digital landscape consists of several digital tools containing information, a federated single source of truth should be established to ensure consistency and traceability. Each information element should be authoritative in one of the tools and can be applied by other tools through synchronisation.

The MBSE proposal has been applied to BAM, showing the practical integration of this proposal. Information swimming lane diagrams illustrate information flows and a federated single source of truth across BAM's toolset, including ArcGIS, Autodesk, Maximo, SharePoint, Relatics, and the additional MBSE tool. The authoritative data per tool is based on functional capabilities and user responsibilities. For example, functions, requirement, and object codes should be managed in Relatics, while the MBSE tool applies these elements for modelling and simulation. The documentation management tool SharePoint transitions from creation of documents to storing of documents generated by the models. Authoritative information should be stored in models rather than documents. As an example, design decisions or rationales can be stored in models rather than documents to ensure traceability and impact analyses.

Research sub-question 5

How can the proposed MBSE adoption be validated within the context of Systems Engineering processes?

The added value of MBSE is validated through a case study with an expert session. The Spooldersluis bridge project has been modelled in the Capella MBSE tool, resulting in several diagrams across the System Analysis, Logical Architecture, and Physical Architecture layer. Through each of these layers, the system has been further specified, including requirements, functions, functional exchanges, scenarios, subcomponents, and physical objects. Modelling of the use case in Capella uncovered strengths and weaknesses. This includes limited parametric modelling, visual representation of information, identification of interfaces, automated transition and synchronisation of elements, straightforward ARCADIA process, and limited inclusion of standard information elements.

The expert session emphasised the added value of this modelling approach for design of the mechanical and Industrial Automation and Electrical Engineering (IA&EE) discipline, due to their extensive usage of functional system behaviour. The added value for static disciplines, like civil engineering, is considered lower. However, modelling exchanges between information elements in Capella improves interdisciplinary alignment by identifying interfaces and conducting impact analyses. Furthermore, the modelling approach helps to understand a system easier due to the visual abilities and has the potential to enhance efficiency in test phases with standardised test protocols. Lastly, it has the potential to extend the V&V process using extra options between elements to verify and validate.

Disadvantages and challenges of the modelling approach include additional effort, add-on extensions, human resistance, expectation deviation per discipline, integration into current workflow, and time-investment for development. Although it requires extra time at the start of implementation to create models, the created standardised models can be reused for future projects which significantly decreases the design time of models. These findings of the case study and expert session are mostly confirmed by the literature, whereas this research provided unique perspectives to the construction industry.

To successfully adopt MBSE, the last part of this research focused on future implementation steps for contractor organisations. The PARiHS implementation framework applied to contractor MBSE adoption revealed importance of implementing MBSE for disciplines with the most added value. But also highlighted success factors, such as managerial support and communication, knowledge sharing, clear processes, progress measurement, and a network of MBSE experts. This framework offered input for the establishment of four maturity levels, ranging from basic to advanced: a federated single source of truth, organisational MBSE preparation, MBSE tool integration, and the transition from document-based practices towards model-centric communication.

Main research question

How can Model-Based Systems Engineering be adopted to improve efficiency of Systems Engineering processes for a contractor?

For the adoption of MBSE in the construction industry a federated single source of truth, process, personnel, MBSE tool integration, and document replacement are considered crucial key components. An additional MBSE tool must be integrated as the current digital landscape of contractors lack functionalities to apply MBSE characteristics, like architecture modelling. However, the current digital landscape should be kept and the change should be limited. The use of the MBSE tool Capella has been tested with a case study and the results highlight the most added value for design of disciplines using functional system behaviour, completer interface identification, early visual understanding of the system, and potential to enhance efficiency in testing phase.

To conclude, the MBSE tool Capella thus especially enhances efficiency in the SE process of design and holds potential for the V&V process, and in particular the testing phase. However, the Capella tool has limited capabilities and can only be used with ARCADIA and a specific modelling language. SysML tools such as Enterprise Architect and Cameo have extended modelling capabilities, are more widely accepted, and SysML is the standard MBSE language. This study only focused on the use of a MBSE tool, while application of other key components of MBSE might also improve other SE processes.

As the most added value emerges for the technical installations discipline, projects with functional system behaviour should include the MBSE tool. However, for static projects, like the construction of a highway, the use of the MBSE tool might not deliver a more efficient process as the outcome might be lower than the extra work it requires for architecture modelling. In such projects, the usage of a MBSE tool including its functionalities might thus be decreased or even be omitted in the project digital landscape. This expectation should be investigated in future research. In the discussion, the investigation and testing of other projects has already been highlighted.

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Appendix A: Interview questions

After the informed consent was signed by researcher and participant, the interview could start. Each interview started with an introduction round and by thanking the interviewee for their time and effort to participate in this study. Consequently, the following questions were asked. Each question includes a description of its goal and potential follow-up questions. The interview questions were as follows:

1. *If not done before, can you shortly describe your role and how long you have been working for BAM?*
   Goal: For the interviewer, it is important to know what kind of interviewee you are talking to and in which business unit or discipline this interviewee is in.

2. *What do you think are the largest bottlenecks in the current SE process at BAM?*
   Follow-up question: In terms of efficiency or processing time?
   Goal: To identify limitations of SE processes at BAM and to see if they are in line with the findings from the literature.

3. *Are you familiar with Model-Based Systems Engineering? If so, what do you know about it?*
   Goal: The purpose of this question is to check the knowledge of the interviewee about MBSE. If the interviewee is not so familiar or its view differs from the literature findings, the interviewer will provide a short presentation about MBSE.

4. *What impact do you think MBSE will have on your work?*
   Follow-up question: And what on BAM in general?
   Goal: To identify the added value of MBSE for employees of BAM.

5. *Do you have experience with other technological advancements, like MBSE? If so, which ones?*
   Goal: This question asks which other advancements the interviewee has experienced. It will introduce the next question.

6. *What were the biggest challenges of implementations of these advancements?*
   Goal: By asking what challenges arise at other technological advancements, similar to MBSE, it provides insights on problems or challenges of digital implementations at companies in different levels (management and employees).

7. *What organisational challenges do you expect at the adoption of MBSE?*
   Goal: Identify organisational challenges for adoption of MBSE specific. The answer might also provide new general organisational challenges not mentioned before.

8. *What human challenges do you expect at the adoption of MBSE?*
   Goal: Identify human challenges for adoption of MBSE specific. The answer might also provide new general human challenges not mentioned before.

9. *What technological challenges do you expect at the adoption of MBSE?*
   Follow-up question: What about integration with other tools?
   Goal: Identify technological challenges for adoption of MBSE specific. The answer might also provide new general technological challenges not mentioned before.

10. *Looking at the MBSE system, what do you expect from such system to be able to effectively use it for your work?*
    Follow-up question: Which principles or requirements must the system adhere to?
    Follow-up question: Flexible or standard system? What about integration with other tools?
    Goal: The MBSE adoption must meet certain design principles or requirements so that it is easy to integrate and so that employees can use it easily. The interviewee will elaborate on what works best for his/her work activities.

11. *Which changes or resources must be needed for successful adoption of MBSE?*
    Follow-up question: What about training and strategy?
    Goal: This question helps to understand which resources or modifications from an organisation like BAM are necessary to make sure MBSE will be effectively adopted for projects.

12. *Could you consider any possible downsides of MBSE?*
    Goal: To identify possible negative aspects of MBSE. From these negative aspects, design requirements could be derived to counter these downsides.

13. *Do you have any other final remarks that you would like to share?*
    Goal: To end the interview and to check if the interviewee has mentioned everything or to change anything the interviewee has mentioned.

Appendix B: Semi-structured interview data

This appendix summarise the data that has been retrieved from the semi-structured interviews questions from Appendix A with employees of the company BAM. These interviews help to answer research sub-question 3. For each interview, a summary of key findings is provided in this appendix, which starts with the years of experience, role, and discipline of the participant.

Interview A

- *Years of experience: 7 years*
- *Discipline and role: Specialist Digital in the Civil discipline*

The interviewee identifies several bottlenecks in the current process, such as the large time-investment required for documentation and planning activities, due to the increasing complexity of projects. MBSE is seen as a potential solution to improve communication through visual models, reduce errors due to the transparent information exchange, and improve efficiency by decreased reliance on traditional documentation and by automation of certain processes. The interviewee explicitly likes the visual aspect.

However, challenges are also mentioned by the interviewee. The term 'MBSE' sounds complex and can hinder adoption. End user acceptance is crucial as employees are used to their traditional workflows. A key factor in increasing acceptance chances is the ability to demonstrate the practical benefits of MBSE to its end users. This aspect is often overlooked during organisational changes, according to the interviewee. The technological aspect will not cause any problems as much knowledge is available within the company BAM. However, the primary obstacle lies in managing the human aspect of change.

The interviewee relaties MBSE adoption to previous technological advancements within BAM, such as the adoption of 4D planning and drone technologies. These implementations showed that success depends on clear communication of the benefits to the end users, stepwise introduction through pilot projects, user-friendliness, and connection to existing systems or tools such as Autodesk or Relatics.

The flexibility rate of the system model is also discussed by the interviewee. A tension exists between the need for standardisation and for adaptability to individual project contexts. From a management perspective, a standardised approach is prioritised, and from an engineering and project perspective, a more flexible approach is favoured. However, there is a tendency towards a more standardised approach as it is not the case for Relatics. Other requirements, as mentioned before, are the user-friendliness, connection to and use of existing systems and tools, and dedication of specialists on the project to guide the change.

Finally, the importance of training, examples, and recognition is emphasised as an important resource. A good introduction, possible with a presentation including positive examples, helps to create support. It is also suggested to position MBSE as a step towards a digital driven organisation. Using terms such as Digital Twins will help with this, as such terms are already familiar within BAM.

Interview B

- *Years of experience: 25 years*
- *Discipline and role: Manager in the Integral Infrastructure Design discipline*

The interviewee has limited experience with MBSE but works extensively with SE. The interviewee observes that changes within projects often lack clarity and reasoning, leading to mistakes and inefficiencies. A significant challenge within current SE processes is the absence of well-defined hierarchy in requirements provided by the client. This increases the risk of misinterpretation, overlooked dependencies, and potential conflicts during later project lifecycle phases. In the design phase, errors often occur late, partly because requirements are not clearly defined.

The interviewee presents a positive attitude towards MBSE by believing the number of errors can be reduced and visibility and traceability of changes can be improved. The expectation is that MBSE could contribute to more efficient and manageable workflows, especially in projects with frequent modifications. However, the interviewee notes that MBSE should not encourage more changes but instead help manage them better.

The interviewee also reflects on previous technological advancements within BAM, including the implementation of Relatics, SharePoint, and 3D modelling. These transitions often faced resistance due to unfamiliarity and fear by users to lose control. Successful adoption requires clear communication, 24/7 support, and the involvement of enthusiastic and influential personnel across departments and disciplines.

Regarding the MBSE system, the interviewee highlights the need for balance between standardisation and flexibility. While some clients demand standardised models, BAM should aim for internal consistency. The interviewee notes that stricter standardised systems, like ThinkProject, though initially unpopular, offer better data traceability than more flexible tools, like SharePoint.

Finally, the interviewee emphasises the importance of management support and creation of success stories to promote MBSE. To maintain consistency, the interviewee suggests including initiatives into project goals. A potential downside of MBSE is the over-reliance on models, which could hinder issue identification. Maintaining traditional principles of SE and regular model reviews are essential to mitigate this.

Interview C

- *Years of experience: 32 years*
- *Discipline and role: Program Manager in the Digital Infrastructure discipline*

An important limitation of the current process raised by the interviewee is the reliance on undocumented and judgement-based decision-making. This lack of traceability complicates understanding the rationale behind decisions, especially when modification occur later in the project lifecycle. The interviewee becomes more familiar with MBSE and connects it to BAM's strategic goal of becoming a data-driven organisation. Furthermore, the interviewee highlights inefficiencies in current workflows, such as repetitive data entry.

Reflecting on previous technological advancements, the interviewee notes that the most significant challenges are not related to technology, but to organisational culture and personnel. Siloed thinking and fragmented departments hinder collaboration and learning, as it creates diverging mindsets. The importance of change management is emphasised by determination of a clear motivation of the change to overcome resistance.

Regarding MBSE requirements, the interviewee prefers standardisation, which helps to create flexibility. A standardised structure, like a shared language, allows for easier adaptation and communication. Instead of modifying internal standards for each client or project, the organisation should maintain core processes and adapt the communication aspect at the interface level. If core processes are adjusted, it will not be reusable.

The interviewee acknowledges the needed introduction of new tools but highlights the importance of minimising the number of tools to keep the system manageable and effective. This is due to the challenge of integrating new systems and tools. Therefore, tools used for MBSE should be widely supported, widely used, and well-understood.

For successful MBSE adoption, clear leadership and vision from management are essential, according to the interviewee. This is compared to the successful promotion of sustainability and safety initiatives at BAM, which benefited from consistent messaging from management. Management should convey a clear and consistent message about the goal to become a digital data-driven organisation, and that MBSE is one of the organisations' subgoals.

Potential challenges of MBSE are also identified. The interviewee warns about the reduced transparency and traceability in digital models. Engineers always want to have control and may struggle to understand how outputs are generated, which can lead to a lack of trust. MBSE must include mechanisms for traceability and be integrated into the broader strategy to ensure clarity and coherence for employees. It must be clear and traceable how the system model makes decisions.

Interview D

- *Years of experience: 15 years*
- *Discipline and role: Design manager in the Civil discipline*

The interviewee emphasises benefits of MBSE, like greater integration and improved information management, but notes practical limitations, particularly in the transition from traditional drawings to model-driven processes. One of them is the difficulty in verifying and linking elements that do not yet exist, especially when current practices rely on drawings as the primary information medium. Furthermore, the interviewee highlights that not every project component, such as an ecological zone, can easily be modelled. Inconsistencies in workflows of clients is highlighted, which complicates standardisation.

The current SE process at BAM faces several problems, like incomplete or outdated information. This is often due to poor explanation by the client, poor documentation practices, or loss of data over time. MBSE could address this by improving traceability and enhancing the clarity of information flows, especially at interfaces between various disciplines. Successful adoption requires careful planning, stakeholder alignment, and phased adoption. The interviewee stresses the importance of starting small and learn from pilot projects, which facilitates learning.

Reflecting on past technological advancements, the move from fax to digital tools and the rise of design-and-construct methodologies are mentioned. These changes face several human-related challenges, such as resistance to change, diverging levels of technical skills amongst personnel, and the need for clear and consistent communication.

The interviewee emphasises that the MBSE system must offer a degree of flexibility to address the diverse needs of project, while maintaining a clearly defined goal and process. The system should be safeguarded against unintended changes, such as including automated alerts in the system. Early versions of the MBSE system should limit functionality to reduce user errors, with the option of gradual expansion of capabilities as users can get more skilled over time. The role of the modeller becomes important, requiring close collaboration with systems engineers and clear organisational structures. This underscores the need for clear processes and changes.

Finally, the interviewee highlights the need for clear goals, sufficient resources, and transparent communication. An organisational change is inherently slow and uneven, often following an 80/20 rule where most employees adapt quickly, but the final group requires significant time. Success depends on learning from previous efforts, sharing both successes and drawbacks, and measuring and maintaining progress through strong leadership and support.

Interview E

- *Years of experience: 9 years*
- *Discipline and role: Coordinator in the Information Management discipline*

The interviewee addresses limitations in early project phases, where large volumes of client-provided documents must be organised and entered manually into the right systems. This repetitive and fragmented approach often delays processes. Furthermore, many processes are executed parallel, like the project setup and designing. This further complicates the process due to the risk of overlooking certain steps.

The term 'MBSE' sounds familiar to the interviewee and is associated with the concept of a Common Data Environment (CDE), focusing on the shift from document-based to data-centric workflows. MBSE is regarded as an approach to establish a single source of truth, enabling real-time collaboration amongst stakeholders through shared models and reduced repetitive documentations. This could decrease the timeline of design phases as disciplines and stakeholders will not focus on reading and creation of documents but can work and check in models. MBSE also improves traceability and verification. Lastly, the maintenance phase can be improved by using simulation and impact analyses on already existing systems.

The main challenges relate to human resistance as a result of a lack of understanding or perceived complexity of the change. The interviewee reflects on part technological advancements, like the implementation of OTL (Object Type Library) and PowerBI, and notes the importance of presenting clear value to the end users. This is a clear reason why a phased adoption strategy is crucial to overcome resistance.

The interviewee furthermore reflects on requirements of the MBSE adoption, by emphasising the importance of integrating MBSE into existing systems and tools, instead of using new tools, methods, and languages. Tools, like Relatics, are indispensable, as clients use these tools. In the most ideal situation, open standard methods, tools, and languages should be adopted.

Lastly, the interviewee emphasises several important resources, like trainings and clear process establishment. The processes should be aligned with current processes and the system must be aligned with these processes. MBSE should be introduced in phases, which builds confidence, knowledge, and capability amongst end users.

Interview F

- *Years of experience: 33 years*
- *Discipline and role: Process control manager in the Civil discipline*

The interviewee's responsibilities over the past years at BAM included verification, validation, and the introduction of SE within projects. One of the limitations the interviewee identified in projects was the lack of understanding and awareness of what SE involves. Many colleagues associated SE with the Relatics tool, without understanding its broader purpose and benefits. Another challenge is related to the complexity of large projects. As projects grow, they involve more stakeholders and interfaces. This makes it harder to maintain consistency and traceability within a project team.

The interviewee is partially familiar with MBSE and acknowledges BAM currently uses a document-based approach, while MBSE focuses on model as the primary medium. The potential of MBSE is mentioned, especially in improving interdisciplinary communication through a shared system. For example, using a standard model for a bridge allows future projects to reuse 80% of the elements and requires modifying 20% of the elements, known as the 80/20 rule. This enhances efficiency, especially in maintenance and replacement projects. Using MBSE, changes are made to standard models rather than in documents, which further enhances traceability and consistency.

The interviewee emphasis the importance of change management in previous organisational changes and that human resistance often arises from a lack of expertise and urgency to change. Thus, successful adoption requires clear and consistent communication of the added value of the change, consistent leadership commitment, and continuous monitoring. The technical aspect is easier to solve than the human aspect. According to the interviewee, a technological system can always be established, but the human aspects mainly introduce challenges as the employees must use the new technology. Other resources needed are the preparation time, budget, and available employees.

The MBSE system must require a standardised form, but with the ability to adapt to project-specific needs. A different client or system leads to adaptations to processes as a contractor is a project organisation, meaning that it executes different types of projects. The interviewee lastly notes that MBSE introduces new interfaces between the systems and disciplines, which can be seen as both a challenge and a benefit. More integration needs more alignment and agreements but also leads to better overall consistency across systems.

Appendix C: Thematic analysis of interviews

In Table C.1 below, the analysis of the interviews is provided based on four different themes.

Interview	Limitations and added value MBSE	Challenges of past digital advancements	Principles or requirements for MBSE adoption	Resources for successful MBSE adoption
A	Time-investment required for documentation and planning activities, partly due to the increasing complexity of projects. MBSE benefits such as better communication through visual models, reduction of errors due to unambiguous information exchange, and improved efficiency through automation of certain processes.	Other digital implementations, like 4D planning and drone technologies, show that success depends on clear communication of benefits to the user, stepwise introduction through pilot projects, user-friendliness, and connection to existing systems/tools such as Autodesk or Relatics.	From the perspective of managing MBSE, a standardised approach is prioritised. Engineers prefer a more flexible approach. But there is a tendency towards a more standardised approach, as is now the case for Relatics. Other requirements are user-friendliness, connection to and use of existing systems and tools, and dedication of a specialist on the project to guide the change.	An important factor in end user acceptance is the ability to demonstrate the practical benefits of MBSE to them, which is often insufficiently addressed. The technological infrastructure will work, as there is a lot of knowledge. However, the primary obstacle lies in managing the human dimension of change, especially human resistance. To mitigate this, the importance of examples and recognition is emphasised. A good introduction, including positive examples, helps creating support. It is also suggested to position MBSE as a step towards the future. Finally, the importance of training and coaching is emphasised.
B	The absence of a well-defined hierarchy in client-provided requirements, leading to misinterpretation, overlooked dependencies, and potential conflicts during later project phases. MBSE can improve visibility and traceability of changes. MBSE could contribute to more efficient and manageable workflows, especially in projects characterised by many modifications.	Past digital advancements, like the implementation of Relatics, SharePoint, and 3D modelling, often met human resistance due to unfamiliarity and fear of losing control.	A balance between standardisation and flexibility. While some clients demand standardised models, BAM should aim for internal consistency. Stricter standardised systems like ThinkProject offer better data traceability than more flexible tools like SharePoint. Lastly, maintaining some traditional principles of SE and regular model reviews are essential to validate them and keep control of the approach.	Successful adoption requires clear communication, 24/7 support, and the involvement of enthusiastic and influential personnel across departments and disciplines. But also, the importance of management support and creating a success story to promote MBSE. Integrating improvement initiatives into project goals to ensure continuity.
C	Undocumented, judgment-based decision-making. This complicates understanding the rationale behind decisions, particularly when modifications occur in later project phases. Other inefficiency is redundant data entry. MBSE is viewed as a promising approach for addressing these issues.	The most significant challenges of digital advancements are not technological related but organisational and personal. Siloed thinking and fragmented departments hinder collaboration and learning, as it creates different mindsets. The importance of change management is emphasised. A change must have a clear reason and motivation to overcome resistance.	A standardised structure, like a shared language, allows for easier adaptation and communication, especially with clients. Rather than modifying internal standards for each client or project, the organisation should maintain its core processes and adapt communications at the interface level. If the core will be adjusted, its reusability will be diminished. Additionally, it is important to minimise the number of new tools to keep the system manageable and effective. Tools used for MBSE should be widely supported, widely used, and well-understood. It must be clear and traceable how choices are made by, for example, the system model.	For successful MBSE adoption, clear leadership and vision from management are essential. The interviewee compares this with the successful promotion of sustainability and safety initiatives at BAM, which benefited from consistent messaging from management. The management should convey a clear and consistent message that the company needs this change as it will lead to several improvements. MBSE must include mechanisms for traceability and be integrated into the broader digitalisation strategy to ensure clarity and coherence for employees.

D	Incomplete or outdated information, often due to poor explanation by the client, poor documentation, or loss of data. MBSE improves traceability and enhancing the clarity of information flows, especially at interfaces between various disciplines.	Past digital changes, like the rise of digital tools, revealed that human factors, like resistance to change, diverse levels of technical skills amongst personnel, and the need for clear and consistent communication, are often the biggest obstacles.	The MBSE system must offer a degree of flexibility to address the diverse needs of projects, while maintaining a clearly defined goal and process. The system should be safeguarded against unintended changes, like automated alerts in the system. Early versions of the system should limit functionality to reduce user errors, with gradual expansion of system capabilities. Last principle relates to clear processes, as certain roles will change when adopting MBSE.	Successful adoption of MBSE requires careful planning, stakeholder alignment, and phased adoption. The interviewee stresses the importance of starting small and learning from pilot projects, to facilitate learning. Finally, the interviewee addresses the need for clear goals and transparent communication. Change is inherently slow, and the final group requires significant effort to change. Strong leadership and support will help with this.
E	Large volumes of client-provided documents must be stored manually onto the right places. This leads to delayed processes. MBSE enables real-time collaboration amongst stakeholders and reduces repetitive documentation. Furthermore, a model-based approach leads to shortened design cycles, as documents do not have to be created manually.	Past digital implementations, like Object Type Library and PowerBI, highlight the challenges of human resistance as a result of a lack of understanding of the added value of the change. But also, that a term sounds complex and is not explicitly explained well.	MBSE must be integrated into existing systems and tools. The adoption of new tools should be limited as this requires time and money. Tools, like Relatics, are indispensable, as clients also use these tools. Furthermore, it is recommended to use open standards, meaning that the structure behind a tool, method or language is open-source. Lastly, processes and tools should be aligned to effectively work with them and should also be aligned with current systems and processes.	Resources necessary for MBSE adoption include trained personnel and processes. The interviewee also recommends using pilot projects and to start small. Gradually introducing MBSE will build end user confidence and capabilities.
F	The lack of understanding and awareness of what SE actually involves. Additionally, as projects grow, they involve more stakeholders and interfaces, which makes it harder to maintain coherence and traceability between various parts of the system. MBSE improves interdisciplinary communication through a shared system. Furthermore, 80% can be standardised through standard element models, which requires modifications on 20% of the system for its unique use. This enhances reusability and efficiency.	A past change included changes of tooling and processes. Due to a lack of knowledge or lack of urgency to change, human resistance occurred. To overcome this, a consistent and clear communication plan is required in which the added value of the change is described.	The MBSE system must be standardised, but not entirely, as a contractor is a project organisation. This means that the system must be flexible for changes, like different client requirements for certain processes.	Resources for successful MBSE adoption include continuous monitoring, budget, preparation time, and available employees. Furthermore, a clear and consistent communication plan must be established to make sure that end users understand the urgency and reason to make the change. Lastly, a consistent management support will remove uncertainties from employees about the urgency and reason of the change.

Table C.1: Thematic analysis of interviews

Appendix D: Document analysis

The method 'document analysis' is one of the data sources to answer research sub-question 4 about the MBSE adoption proposal regarding the application to the company BAM. Table D.1 provides an overview of the internal documents of BAM Infraconsult that have been reviewed, including a description of the document.

Document name	Description
BAM SE Wijzer	Guideline of 2008 on what SE is, how BAM Infraconsult applies it, and which processes SE influences.
Project Management Systeem BAM Infraconsult 4.0	Overview of each process, divided in product, supporting, context, and management processes. The processes contain information, in text form or in leaflet form, which is a separate document.
Leaflet Borgen van contractdocumenten	How BAM secures contract documents. This is part of document analysis which is part of requirements analysis.
Leaflet Borgen van Eisen	How BAM secures requirements, which is also part of requirements analysis, including SMART.
Leaflet Trade-off matrix	How, why, and when a trade-off matrix is set up.
Leaflet Documentstructuur	Process flow of documents in distinct phases.
Leaflet Objectcodering	Overview of how objects are coded and the link to project decomposition.
Leaflet Validatieproces	Explanation of validation process in distinct phases.
Leaflet Keuringen opstellen/vastleggen via de WBS in Relatics	This leaflet addresses the steps to set up and record tests via the WBS in Relatics.
Leaflet Inventariseren van Raakvlakken	The document describes the steps for the inventory of interfaces to create a complete overview.
Leaflet Afstemmen van Raakvlakken	This leaflet builds upon the previous and explains the steps for aligning interfaces in Relatics.
Leaflet Configuratiebeheer	Explanation of how BAM applies configuration management.
Leaflet Toelichting Inrichting Werkpakketten	How work packages are organised and with which elements they connect.
Toelichting Werkpakketactiviteiten (WPA)	This leaflet describes how work package activities (WPA) are composed.
SharePoint Online Smart Working	Overview of how SharePoint is used within BAM.

Table D.1: Internal documents of document analysis

Appendix E: Modelled diagrams in Capella

System Analysis diagrams

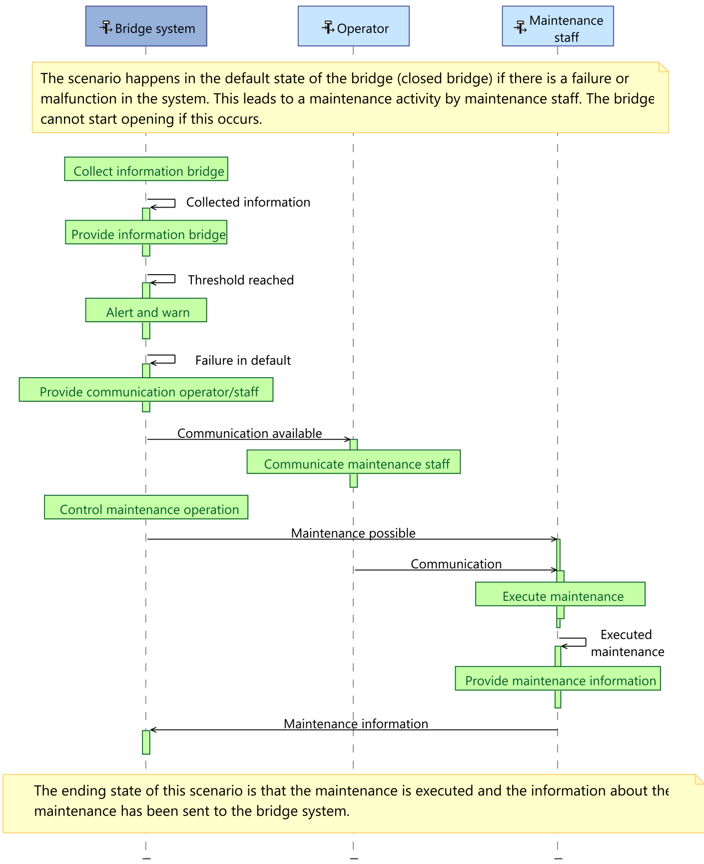

Figure E.1: Exchange Scenario (ES) of provide maintenance scenario

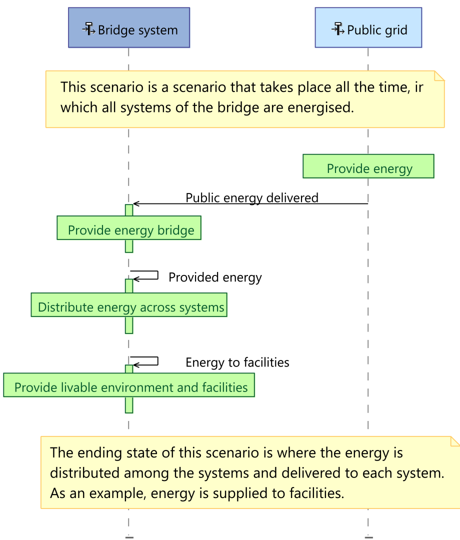

Figure E.2: Exchange Scenario (ES) of provide energy scenario

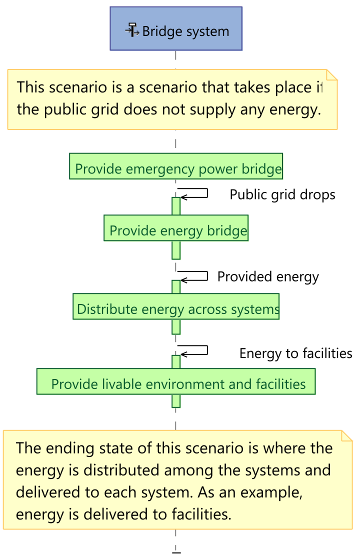

Figure E.3: Exchange Scenario (ES) of provide emergency energy scenario

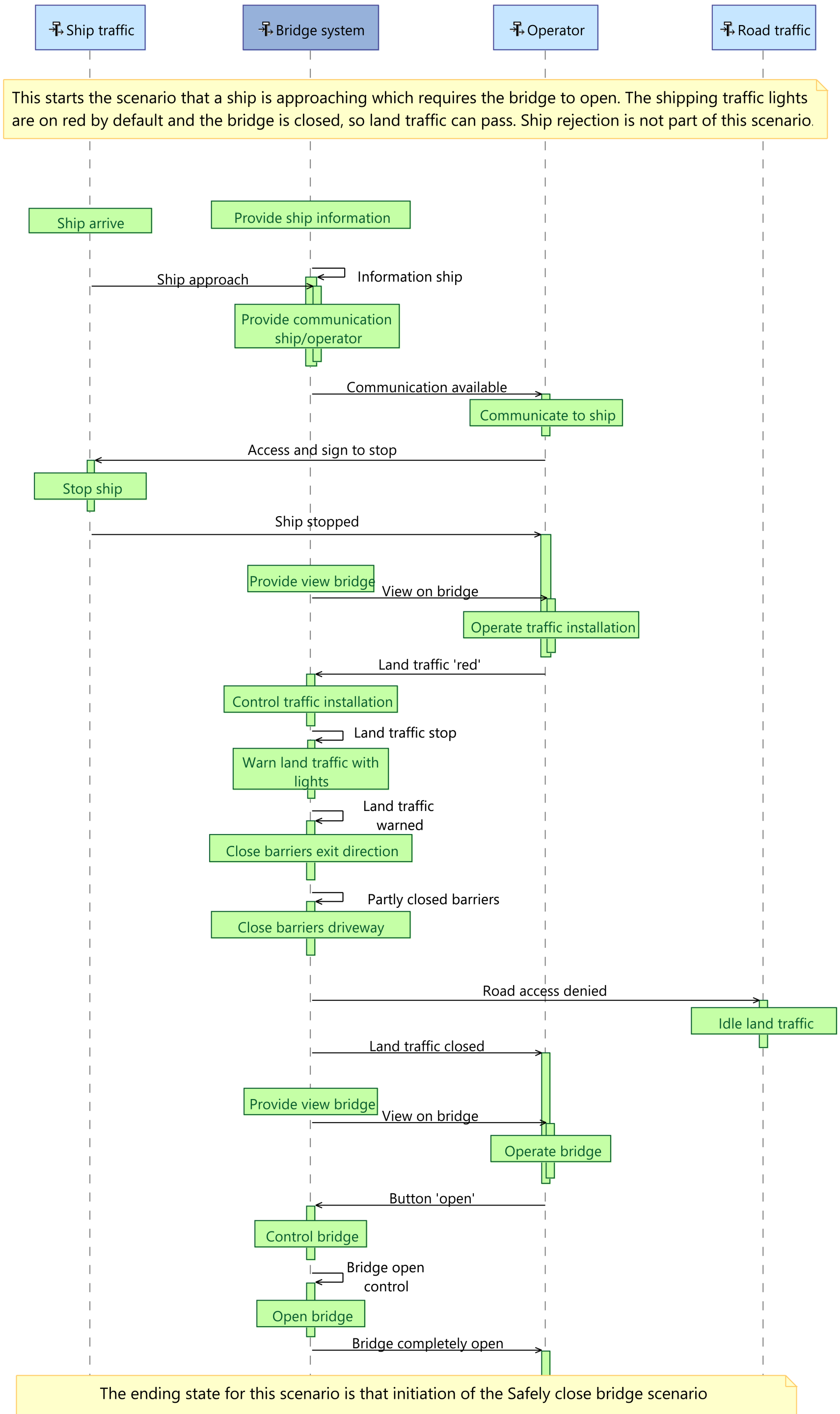

Figure E.4: Exchange Scenario (ES) of safely open bridge scenario

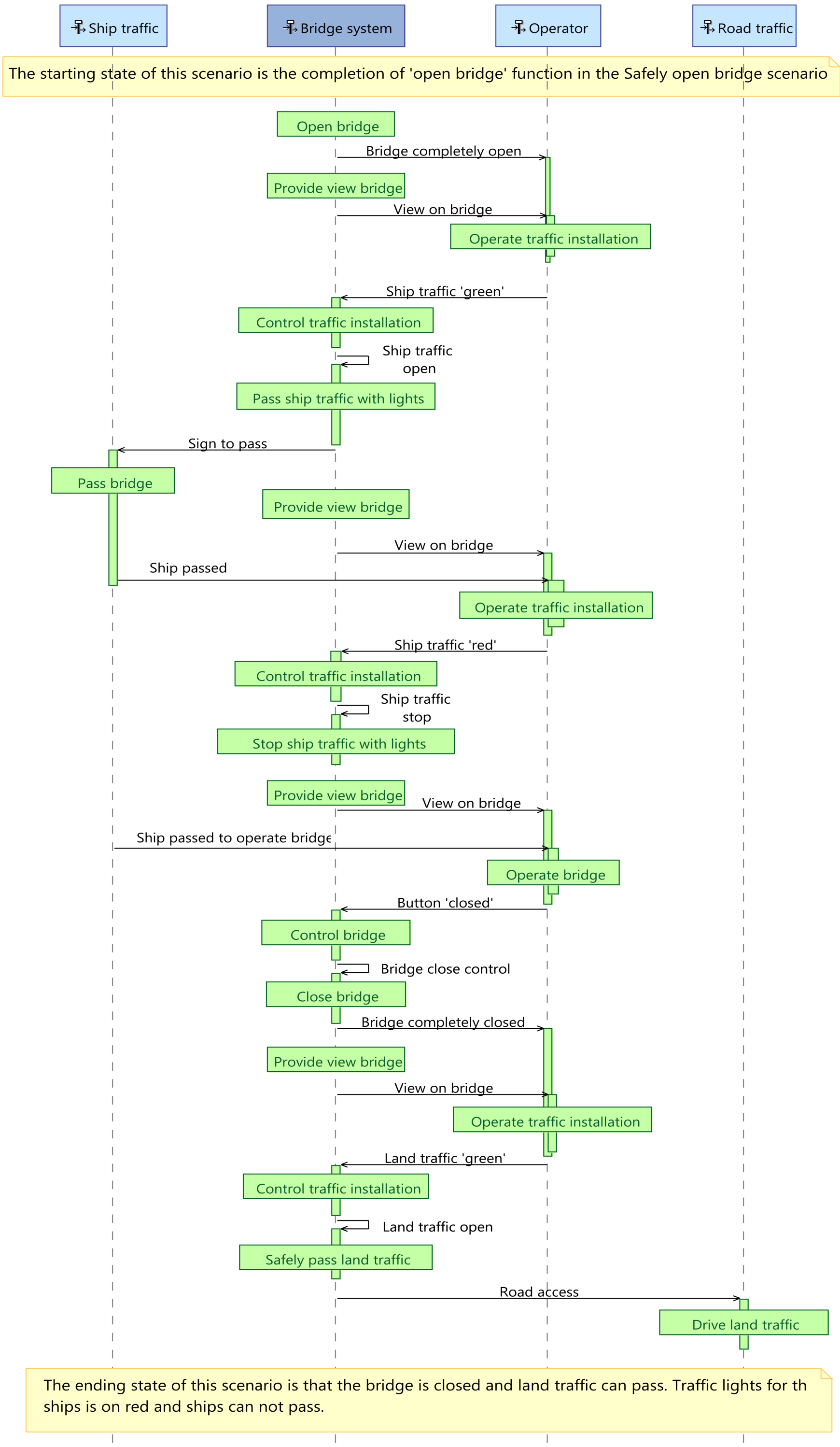

Figure E.5: Exchange Scenario (ES) of safely close bridge scenario

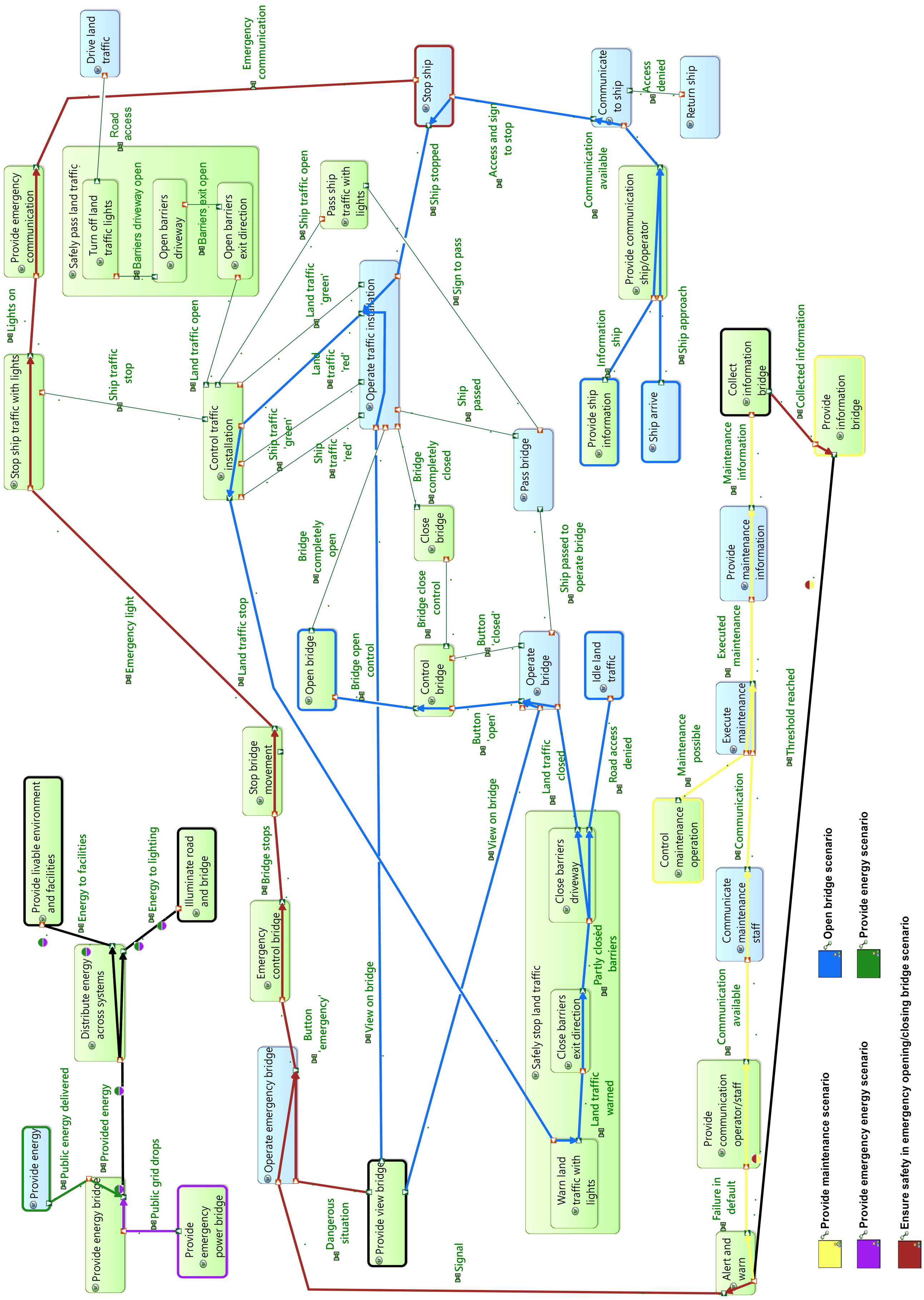

Figure E.6: System Data Flow Blank (SDFB) of the entire functional chains

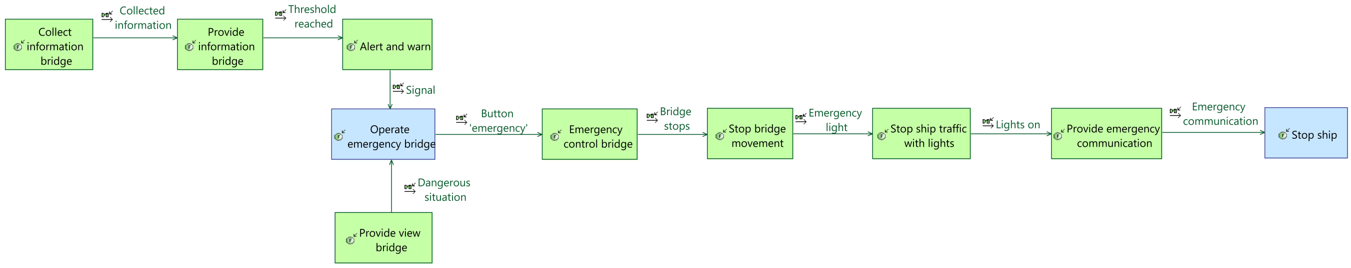

Figure E.7: System Functional Chain Description (SFCD) of ensure safety in emergency scenario

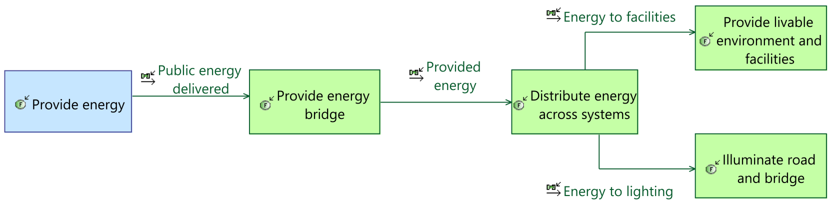

Figure E.8: System Functional Chain Description (SFCD) of provide energy scenario

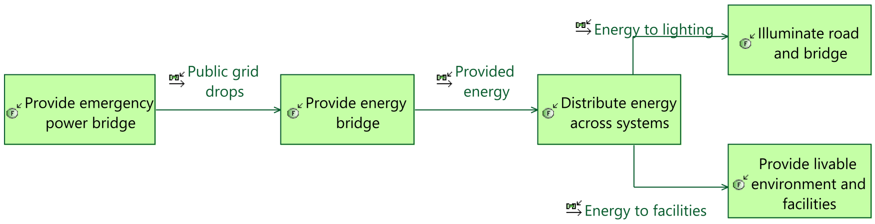

Figure E.9: System Functional Chain Description (SFCD) of provide emergency energy scenario

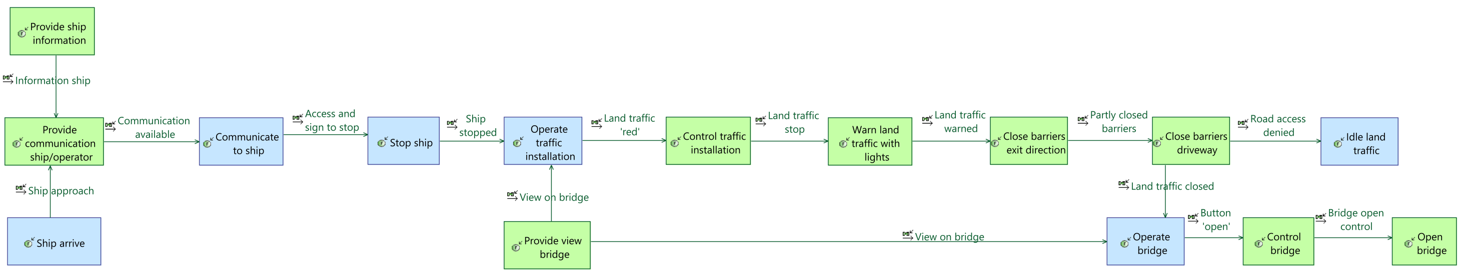

Figure E.10: System Functional Chain Description (SFCD) of safely open bridge scenario

Logical Architecture diagrams

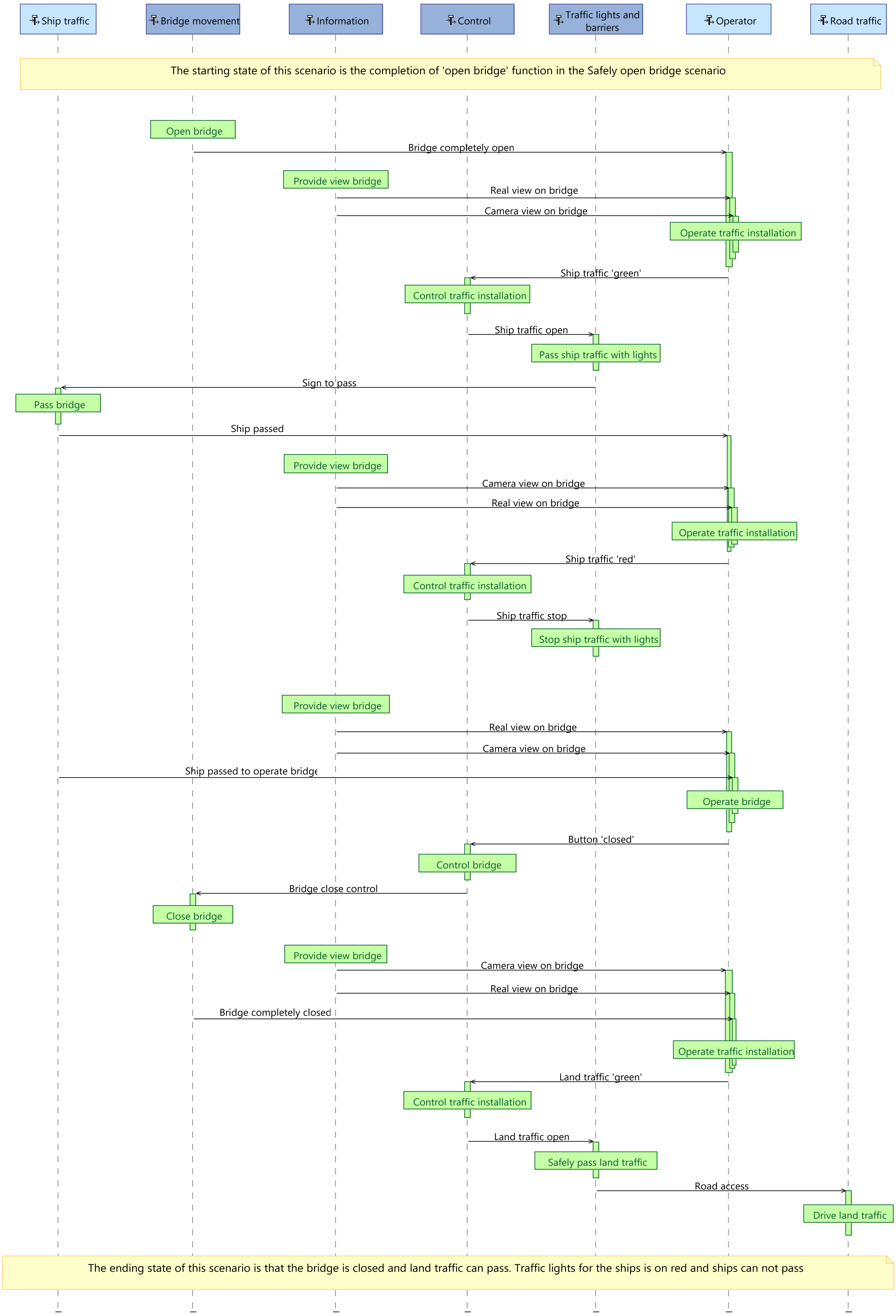

Figure E.11: Exchange Scenario (ES) of safely close bridge scenario

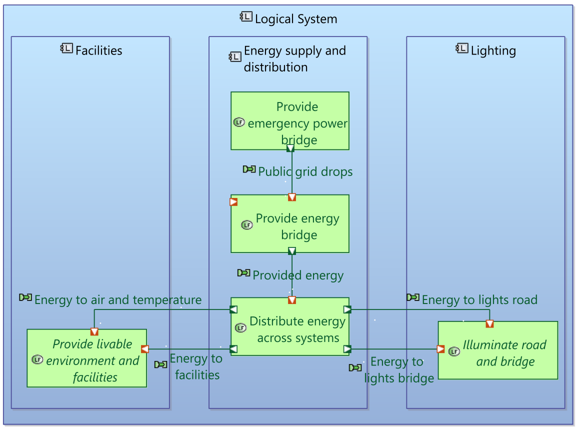

Figure E.12: Logical Architecture Breakdown (LAB) of provide emergency energy scenario

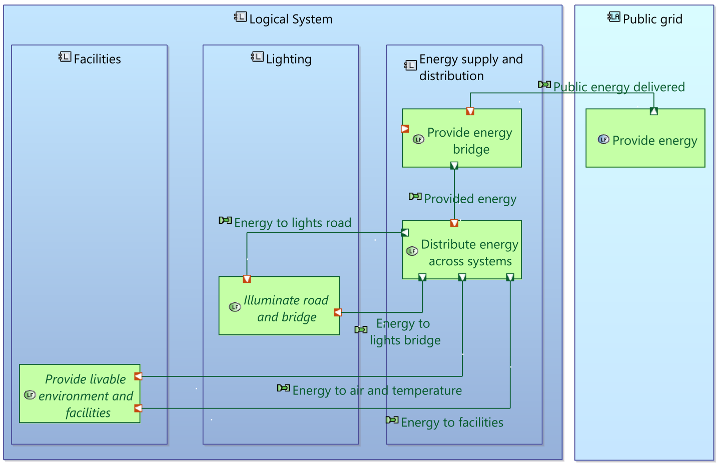

Figure E.13: Logical Architecture Breakdown (LAB) of provide energy scenario

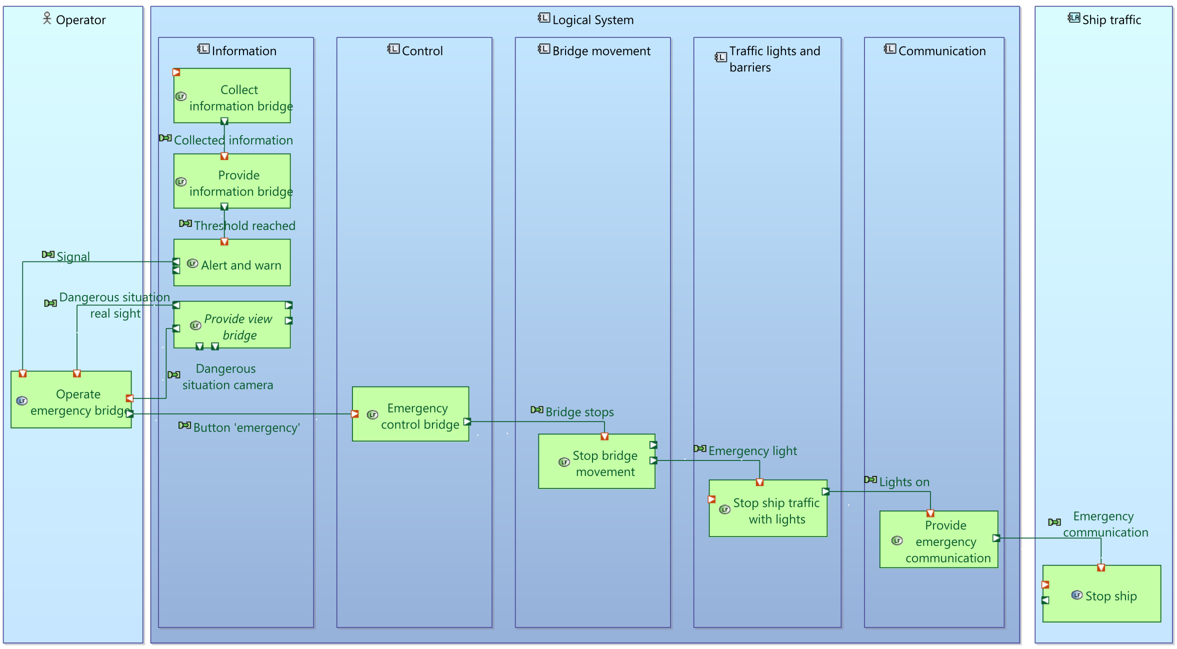

Figure E.14: Logical Architecture Breakdown (LAB) of ensure safety in emergency opening/closing bridge scenario

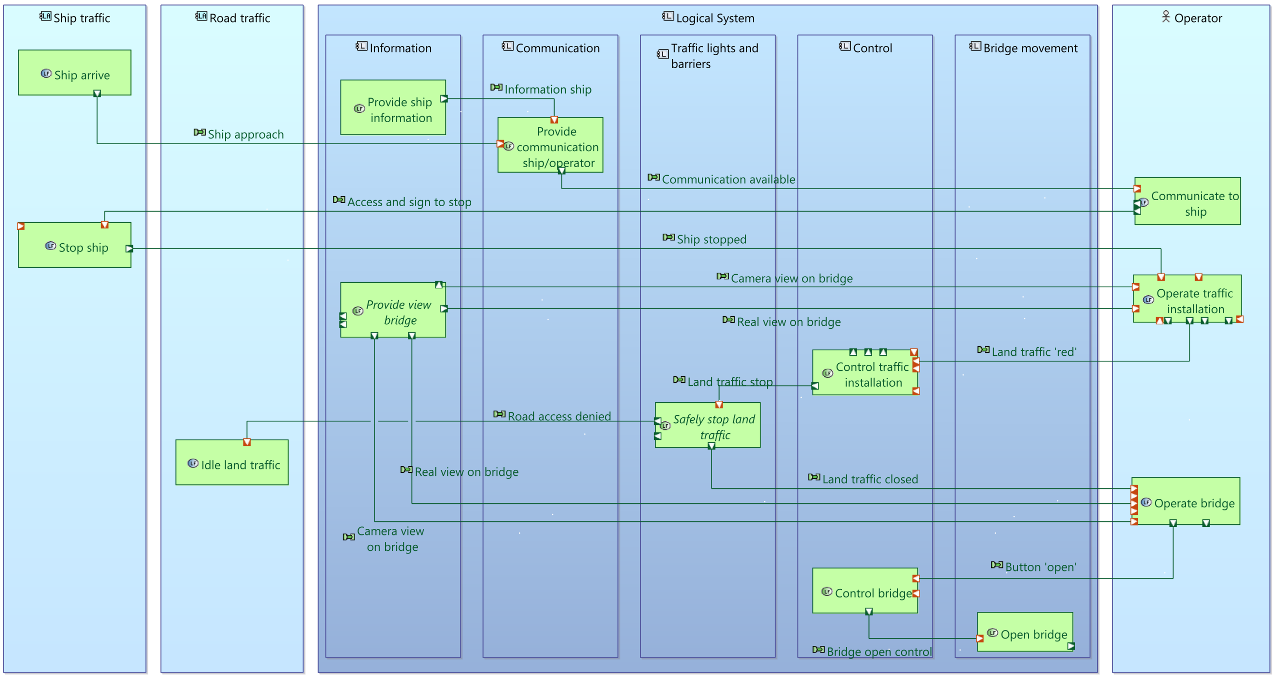

Figure E.15: Logical Architecture Breakdown (LAB) of safely open bridge scenario

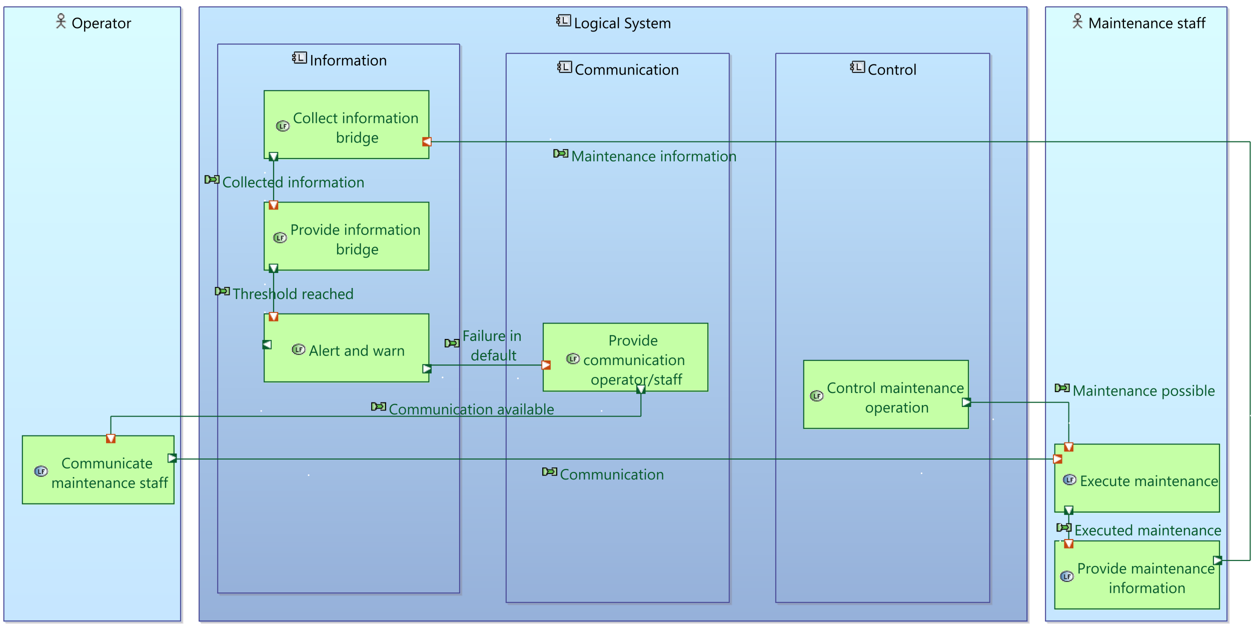

Figure E.16: Logical Architecture Breakdown (LAB) of provide maintenance scenario

Appendix F: Expert session

To improve validity of the expert session, a variety of participants have been selected. The participants vary in role and work experience. A project manager, design manager, and systems engineers were the participants of the expert session, illustrated in Table F.1, including their work experience.

Participant number	Role	Work experience
1	Project manager	20 years
2	Design manager	12 years
3	Systems Engineer	4 years
4	Systems Engineer	9 months

Table F.1: Expert session participants

The responses of the expert session are presented per participant number in Table F.2, Table F.3, Table F.4, and Table F.4 below, organised per question.

Participant number	Clarity of functionalities
1	Yes, I do understand what you can do with it but still have a little difficulty putting it into specific context. But that is also because I have never seen this before and there are many options.
2	Yes, for me it is clear.
3	Yes, clear.
4	Yes, it is obvious what you can do with it.

Table F.2: Answers expert session on clarity of functionalities

Participant number	Advantages
1	For the technical installations discipline, most added value is recognised, as it was not clear at Spooldersluis which functionalities the system must meet. This was the result of no clarity about the desired behaviour of the system and the installation. For example, the traffic barrier installation. Also, several objects, like PLC's and building blocks for the camera and video system of the client, encountered several problems. These objects had interfaces which were not identified but could have been identified clearly with this modelling approach. Another advantage is to complete the verification of requirements. Currently, there is only a verification on the requirement. But this is not traced back to functions and no verification on object-requirement relation is available. With this modelling approach, the verification and validation can be enhanced by checking the fulfilment of each requirement. Another advantage of Capella is the automated transition of elements for each layer, saving much time.
2	For the technical installation discipline, also called Industrial Automation and Electrical Engineering discipline (IA&EE), much added value is recognised as this discipline requires a chain of functions and system architecture. For mechanical engineering discipline also added value is recognised as they also work with functions, but with a lower intensity. Less added value has been identified for the civil discipline, due to a more static type of discipline. This modelling approach can more easily identify interfaces between each discipline. At the current situation, physical interfaces are determined with clash detections and interface sessions with every design manager. For Spooldersluis, each possible civil interface was identified, except for the operation building. The interface list was complete due to high time effort in interface identification. This effort may decrease if this modelling approach will be used. As interfaces are currently only determined by human sessions and clash detections, using this modelling approach will help to complete the entire set of interfaces. If modifications occur, the impact of a change can quickly be analysed. For example, what the impact is on the speed of the bridge by increasing power of the propulsion system. Regarding Spooldersluis, to get notified what the impact is if the IA&EE discipline changes, it would have saved much time.
3	In Relatics, interfaces are recorded using a list of words. This modelling approach helps to complete this list. If a change occurs, Capella helps to determine the effect of this change. So, it improves to connect disciplines. Furthermore, the visual feature helps to easily understand the system early, instead of a list with words about the system in Relatics.
4	At Spooldersluis project, the IA&EE discipline faced several problems, while civil discipline did not experience many problems. However, if projects become more complex than Spooldersluis, certain physical civil interfaces might be overlooked. Lastly, it has potential to improve efficiency in testing phase. Currently, large test protocols must be created in documents which is time intensive. If use cases from the modelling tool can be used to easily create standard test protocols, it can easily be reused for future projects.

Table F.3: Answers expert session on advantages

Participant number	Disadvantages
1	Modelling in an extra MBSE requires extra work and time. On the contrary, it will contribute to efficiency in future projects. The entire model can be reused in future projects with only small project-specific adjustments. Instead of a week, it will cost only two hours for a traffic barrier design.
2	It will require some extra work. But on the contrary, future projects can extremely benefit from this, if such models are created based on standards, like national bridge or tunnelling standards. The only work is to control and check the requirements for each specific project. No more time has to be spend creating a number of documents because they can be generated by the standard model.
3	The disadvantage of Capella is that several add-ons are needed for certain functionalities.
4	In Capella, there are limited information-elements to use. It is mainly the functions, requirements, and objects that can be used. There are no standard elements for rationales or parameters, which may be available in other MBSE tools.

Table F.4: Answers expert session on disadvantages

Participant number	Challenges and solutions
1	Human resistance is a huge challenge. The added value for employees must be clear to mitigate this, as this can arise due to a change of workflow. Furthermore, for the design of the technical installations discipline much added value is identified, but the added value for the other disciplines is not truly clear yet.
2	Control and management of such diagrams or models is a challenge. Responsibility for creating and managing the models must be clearly determined. It seems like a Systems Engineer with a design manager from each discipline could be responsible. Another challenge is the choice of input information for each model and the choice of output regarding documents. To mitigate this, clear guidelines and responsibilities must be established.
3	Integration with current processes can become a challenge. A new integrated process model must be created and tested to mitigate this.
4	Human-related challenges can arise, like the knowledge to model in such a new tool. Trainings and tutorials must be provided to help mitigate such challenges.

Table F.5: Answers expert session on challenges and possible solution