

Feasibility and Viability of MBSE for Complexity Management of Infrastructural Renovation and Replacement Projects

By

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Preface

This thesis is the final result of my graduation project for the Master's programme in Construction Management and Engineering at Delft University of Technology. The research explores how Model-Based Systems Engineering can support improved outcomes for renovation and replacement programmes in the infrastructure sector.

I would like to thank my thesis committee for their guidance, constructive feedback, and thoughtful discussions throughout the process. I also sincerely thank the professionals from various companies and organisations who shared their time and expertise through interviews and validation sessions. Their contributions were essential in shaping the direction and practical relevance of this research.

It is my hope that this work adds value to the development of digital systems approaches in infrastructure and serves as a foundation for further research.

Felix Yorben de Ligt

Executive Summary

The Dutch infrastructure sector is undergoing a major transformation due to the growing complexity of renovating and replacing ageing assets. A central concern is the limited capacity of the replacement and renovation programme to meet increasing demand: while a growing number of assets require renovation or replacement, ongoing maintenance must also be managed within constrained resources. This dual challenge demands a more efficient approach to coordinating maintenance and renovation and replacement efforts. The root of the problem lies on two interconnected levels: the design and management of complex assets through Systems Engineering, and the governance and oversight of the programme as a whole. These layers are often disconnected, resulting in an information management gap that undermines consistent decision-making and long-term coordination. Fragmented communication, static documentation formats that lack machine readability, and weak knowledge retention further exacerbate these inefficiencies. Traditional document-based Systems Engineering approaches are no longer sufficient to manage these interconnected challenges.

Through an exploration of various modelling languages and Systems Engineering tools, this research identified Semantic Linked Data as the core technical enabler capable of addressing the identified challenges. It must therefore be integrated into a structured Model-Based Systems Engineering (MBSE) framework designed to support both asset-level design and management, and programme-level governance. Semantic Linked Data's capacity to express structured, machine-readable relationships across domains makes it especially effective for managing complexity, enhancing Systems Engineering practices, and improving infrastructure programme coordination. Its layered and interconnected structure enables challenges to be addressed at multiple levels, while ensuring consistent alignment between those levels through traceable semantic relationships. Furthermore, it facilitates interoperability between diverse data sources by linking them through a common semantic model and storing them centrally in a Semantic Common Data Environment (CDE).

The adoption of Semantic Linked Data as a core technical component has far-reaching implications for the socio-technical system in which infrastructure programmes operate. As a solution, it primarily introduces a new modelling language and technology. However, realising the benefits of this semantic environment depends on the transformation of the other interdependent aspects of the system.

From the perspective of MBSE, the three foundational pillars (language, methods, and tools) must evolve coherently. While Semantic Linked Data provides a robust modelling language and technological foundation, it also introduces new requirements for the development of an engineering method. These methods must support the incremental and iterative construction and long-term maintenance of semantic models at asset, project, and programme level. In parallel, tools must evolve to support the practical realisation of the Semantic CDE. They must make semantic data accessible and usable across engineering disciplines and throughout different layers of the programme. This includes supporting semantic reasoning to retrieve

relevant data and offering user interfaces that allow domain experts to interact with and visualise information in meaningful ways. While interoperability is largely enabled by the modelling language, it must also be actively supported by tools. Without coherent development of methods, tools, and language, the technical capabilities of Semantic MBSE cannot be effectively applied.

In addition to the MBSE pillars, broader changes are required within the socio-technical system that underpins infrastructure delivery. This system comprises four interrelated domains: technology, people, processes, and organisational structure. The introduction of Semantic Linked Data affects not only digital infrastructure (technology), but also demands new human roles and skills. These include knowledge engineers, ontology developers, semantic model managers, and data engineers. Within project processes, existing practices must be adapted to operate within a model-driven and data-integrated environment. The construction and use of the Semantic CDE becomes central to project execution and can be leveraged across the entire lifecycle of the asset. This requires that teams not only produce and consume data, but also continuously interact with the shared model as a living, evolving source of knowledge.

To realise a Semantic CDE at programme scale, organisational structures must fundamentally evolve. Isolated project teams cannot deliver the consistent modelling and governance required; instead, programme-wide coordination, standardisation, and shared responsibility are essential. This can best be achieved through the formation of a consortium, ideally initiated by a leading asset owner and a small, dedicated project team. A hierarchical implementation approach through such a consortium, steered by asset owners, is necessary to ensure coherence and alignment across the programme, while the system is developed incrementally and iteratively from the project level upward to support higher-level decision-making. By starting with a focused experiment (such as applying the approach across two similar bridge projects) this consortium can develop and test methods, interfaces, and governance structures in a real-world context. Because the required changes span the entire socio-technical system (technology, people, processes, and organisational structure) the approach must evolve incrementally and iteratively. The CDE must be designed from the outset to be scalable and flexible, enabling gradual expansion as organisational maturity increases. Crucially, the consortium must also take responsibility for governance, including model lifecycle management, access rights, quality assurance, and long-term interoperability. Interoperability must be preserved over time to prevent vendor lock-in and to ensure that the semantic environment remains usable and consistent across the asset lifecycle. In this context, MBSE becomes more than a modelling technique, it is part of a broader shift toward data-centric, knowledge-based infrastructure governance. This transition touches all three MBSE pillars (language, methods, tools) and all socio-technical domains, and thus requires substantial strategic investment and cross-disciplinary collaboration. Improvements do not emerge automatically from new technology; they require deep integration across the system.

Furthermore, the current governance model of the Dutch infrastructure renovation programme, shaped by institutional procurement practices, competitive project-based tendering, and limited cross-project learning, often fails to support coordinated, long-term

programme delivery. A particular challenge lies in the public procurement policies that require frequent changes in project teams, making it difficult to retain and transfer knowledge across projects. This undermines the ability to establish a continuous learning curve, even when valuable insights from one project could benefit subsequent ones. Semantic Linked Data can play a pivotal role in overcoming this limitation by enabling the structured capture, sharing, and reuse of knowledge across organisational and contractual boundaries. By embedding engineering knowledge, design rationales, and assumptions into machine-readable models, a Semantic CDE allows programme teams to learn beyond the scope of individual contracts. This often-overlooked but critical dimension of Systems Engineering ensures that modelling and design efforts deliver long-term value beyond their initial use. Utilising MBSE models across the entire asset lifecycle, especially when initiated early in the design phase, provides the highest return on investment. According to MacLeamy's curve, although only 1% of effort is typically spent during design, it directly determines the efficiency of the 25% invested in construction and the 74% spent on maintenance. By front-loading effort into early projects and preserving knowledge semantically, subsequent projects can be delivered more efficiently. By structuring Semantic Linked Data across entire lifecycles and extending its use across multiple bridge projects within the programme, the overall ROI of the programme should theoretically increase. This creates an opportunity to improve programme efficiency and expand its effective capacity to meet the growing demands of the Renovation and Replacement Programme.

Participatory system values such as trust, engagement, and empowerment are largely absent from current practice, yet they are essential starting points for designing a socio-technical system supported by a Semantic CDE. Although competitive, top-down tendering practices will likely remain in place to preserve a functioning market, the Semantic CDE can still support more participatory modes of working by making relevant information visible and usable for all stakeholders. This increased transparency, especially before tendering, supports more open communication about the condition and context of the asset, reducing information discrepancies and enabling better risk assessment by potential contractors. It also mitigates the common issue of incomplete or lost documentation by providing a central, structured repository of asset information. Linked Open Semantic Data thus enables, over time, the possibility of semi-autonomous programme governance, where digital asset twins can be accessed and analysed by participants. Moreover, the Semantic CDE enables project teams to access structured programme knowledge and actively contribute to its development. By making information openly available, it empowers stakeholders to participate more proactively and meaningfully in governance and decision-making processes. In this way, the technical solution proposed in this thesis serves as a catalyst for socio-technical reform, aligning digital infrastructure with the participatory needs of an adaptive and resilient programme system. Its long-term success will depend on how effectively knowledge is captured and reused across project boundaries, and on how this technology serves as the foundation around which people, processes, and organisational structures are aligned and developed in synergy. **For a visualisation of the conceptual solution that answers the main research question, see Chapter 5.2.**

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Chapter 1: Introduction

1.1 General

As the world continues to develop, systems are becoming increasingly complex. One could divide project complexity into technical, organisational and external, with size, variety and context as drivers. These drivers have increased project complexity over the years, mainly manifesting in more complex social-technical organisations with more disciplines and stakeholders, but also by increasing the need for construction, renovation, and replacement projects. Increasing project complexity demands companies' organisational, technical and social improvements for early risk reduction (Institute Project Management, 2021). A significant upcoming assignment for the Dutch infrastructure sector is maintaining, renovating, and replacing infrastructure. Currently, the Netherlands pays 1.5 billion euros per year to renovate infrastructure, which will gradually increase to 3 to 4 billion euros between 2040 and 2050 and reach a peak after 2050 due to many of the bridges built between 1960 and 1980. This research will specifically focus on the renovation of moveable bridges. TNO predicts that, by 400 organisations owned, 8,457 moveable bridges have 4,226 billion euros in replacement costs (TNO, 2021). To realise this significant assignment, the government demands support from the market to guarantee the safety of all those structures in time through a collaborative and innovative programme.

Systems Engineering (SE) is the standard design method for many sectors, and some industries already use Advanced forms of SE. IEEE defines SE as "An interdisciplinary collaborative approach to derive, evolve, and verify a life cycle balanced system solution which satisfies customer expectations and meets public acceptability" (Institute of Electrical and Electronics Engineering, 1994). Furthermore, Fabrycky describes a top-down and interdisciplinary approach, life cycle, and system requirements definition as particular areas of emphasis (Fabrycky, 2011). However, due to its unique nature, the infrastructure industry lags behind SE development and experiences many difficulties with the current (hybrid) Document-Based Systems Engineering approach.

In 2014, the International Council of Systems Engineering (INCOSE) released an article stating that to help SE address the market demands of innovation, productivity, quality and safety to manage the increasing system complexity, one of the main expectations is using models and simulations (Beihoff, et al., 2014). Since then, researchers has explored model-based approaches in different areas throughout the life cycle to help the transition from document-based to model-based approaches. Experts agree that Model-Based Systems Engineering could provide significant ROI and improve document-based methods. Still, the infrastructure sector needs more understanding of applying MBSE. Henderson defines MBSE as a Subset of model-based engineering that deals with SE activities in which models are the central and indispensable artefacts throughout a product's life cycle, encompassing concept, development, deployment, operation and maintenance. Moreover, MBSE is a technical

approach to SE that focuses on creating and exploiting domain models as primary means of information exchange rather than document-based information exchange (Douglass, 2016).

There is potential for MBSE use in the infrastructure sector. The MBSE application lacks compared to other industries, which is the case for the sector's technological development in general. To stimulate the adoption of MBSE in the infrastructure sector, it is essential that organisations understand both the rationale behind MBSE and how it can be effectively applied. While previous research has explored MBSE implementation in various industries, limited attention has been given to its feasibility and viability within the infrastructure domain. This study investigates the conditions under which MBSE can be considered feasible and viable for managing the complexity of infrastructure renovation and replacement projects. By doing so, it aims to provide organisations with the insights needed to determine how MBSE approaches can be developed and implemented in practice. The ultimate goal is to support the structured development of MBSE tailored to the needs and characteristics of the infrastructure sector. Figure 1 provides Inder's & Reay's framework for innovation (Inder & Reay, 2014), showing the intersection of feasibility, viability and desirability, the three main components to assess MBSE in this research.

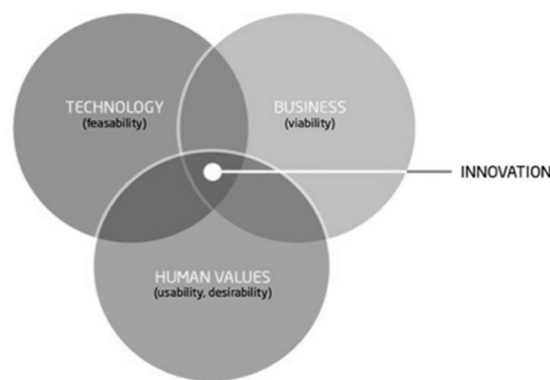


Figure 1 - Inder's & Reay's framework for innovation (Inder & Reay, 2014)

This research investigates whether MBSE is desirable for the infrastructure sector and whether a desire exists to improve the current situation. There is a desire to improve since the approaches are no longer sufficient to manage complexity. However, it is unclear if MBSE resolves this desire for change. There is a growing desire to improve the current situation, but organisations will only be inclined to invest in MBSE development if this study demonstrates that such an approach is both feasible and viable. Grasskamp defines 'feasibility' as the measure of fit between the context of a need or concern and the outcome of the solution (Graaskamp, 1972). Moreover, evaluating viability enables a holistic view of how the technology decisions made early in the design process impact the life cycle affordability of a solution (Sandborn, Herald, Houston, & Singh, 2003).

1.2 Research objectives and questions

1.2.1 Objectives

Several sectors have already made significant progress in developing and benefiting from Model-Based Systems Engineering (MBSE). Professionals from various fields collaborate within international organisations, such as INCOSE, to exchange knowledge and collectively enhance MBSE practices. However, factors influencing successful MBSE adoption differ significantly between sectors, resulting in uneven progress.

In the infrastructure sector specifically, the growing complexity of projects increasingly highlights the limitations of current methods, making MBSE a potentially valuable solution. However, organisations within this sector typically develop MBSE approaches independently, without coherent collaboration or alignment. Furthermore, client organisations currently do not require MBSE explicitly and continue to rely predominantly on traditional document-based approaches throughout the asset lifecycle, which hampers MBSE implementation and limits potential benefits. Additionally, there is no consensus on how MBSE could enhance sector-wide performance effectively.

Therefore, this research aims to clarify the conditions under which MBSE could be feasible and viable for the infrastructure sector. By merging currently dispersed knowledge, the study investigates existing MBSE applications and identifies the requirements needed for successful implementation. If MBSE is assessed as both feasible and viable, the research will illustrate how it could be practically adopted by the infrastructure sector to fulfil its specific needs, providing direction for collective further development.

Ultimately, this research aims to encourage and inspire further studies on MBSE within the infrastructure sector, contributing to broader knowledge development and enhancing sector-wide performance.

1.2.2 Research questions

Main Question:

How can one use MBSE to manage increasing project complexity in renovating and replacing existing infrastructure to improve programme performance in the infrastructure sector?

Sub Questions:

Chapter 2 – Analysis of Challenges and Stakeholders. What are the needs of infrastructure renovation and replacement projects to manage complexity

Chapter 2 – Analysis of Challenges and Stakeholders. Why is MBSE suitable according to theory to solve the problems?

Chapter 3 – Development and Illustration of the MBSE Framework. What MBSE components does the infrastructural sector apply?

Chapter 3 – Development and Illustration of the MBSE Framework. How can infrastructure organisations practically apply MBSE to improve the Renovation and Replacement Programme?

Chapter 4 – Qualitative Evaluation against Needs and Key Quality Metrics. Under what conditions will MBSE be feasible and viable for infrastructure organisations?

Chapter 4 – Qualitative Evaluation against Needs and Key Quality Metrics. What are the weaknesses, strengths, threats, and opportunities in infrastructure replacement and renovation of the new MBSE approach concerning the existing approach?

1.3 Research Methodology

1.3.1 Set-up

This study's main objective is to understand under which conditions, and in what form, the application of MBSE is desirable, feasible, and viable for the infrastructure sector. As mentioned in the introduction, feasibility means the measure of fit between the context of a need and the outcome of the solution. Moreover, viability is long-term sustainability, including a development strategy over time. Thus, this research aims to find the conditions that fit the stakeholders' desires for the solution, resulting in the desired outcome. One has to ensure that the solution through the conditions can sustain and develop in the future. Thus, the main products of this study are the proposed solution and the related conditions to make it successful. Considering the Pyramid of Technology, the goal is to assess whether the technology has the potential to be accepted and vital (Mensvoort, 2013). The desires identified in the problem analysis serve as the starting point for exploring potential solutions. Based on these needs, this study proposes an MBSE-based approach and demonstrates its application through a relevant case study as proof of concept. Finally, verification and validation (V&V) activities are used to evaluate the solution and determine to what extent it meets stakeholder needs. Figure 2 shows the stages of this research, which also structure the chapters, along with their key components. The following paragraphs discuss each stage in more detail.

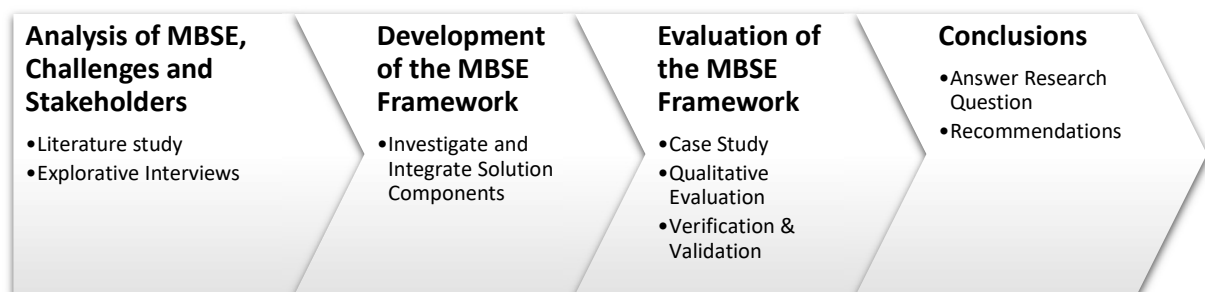


Figure 2 - Research Stages and Key Components

1.3.2 Analysis of Challenges and Stakeholders

The objective of the problem analysis is to understand the broader system context and uncover the underlying challenges and stakeholder desires that an MBSE approach should address. This understanding provides a clear direction for identifying potential solutions that are desirable, feasible, and viable for the infrastructure sector. It is particularly relevant for renovation and replacement programmes, where growing complexity challenges the effectiveness of traditional project approaches.

This research views the infrastructure domain as a layered System of Systems (SoS), ranging from the infrastructure sector, to the programme level, to organisations and individual project teams. These systems are connected through socio-technical structures made up of people, organisations, processes, and technologies. As complexity increases within and between these systems, the need for a more integrated and model-based approach becomes evident. Model-Based Systems Engineering (MBSE) is explored as a potential solution to better manage this complexity and improve collaboration and decision-making.

To support this exploration, the literature study identifies key challenges as well as systemic conditions that influence the effectiveness of MBSE. These findings are complemented by a series of exploratory interviews, which confirm the relevance of these challenges in practice and provide concrete insights into the limitations of current approaches. The interviews also contribute to identifying where MBSE could offer practical improvements and how it might be effectively applied in the Renovation and Replacement Programme.

A stakeholder analysis is conducted to map the concerns of different actors across the lifecycle. These insights together help form a structured understanding of the solution space and reveal the requirements that a proposed MBSE approach must meet.

The chapter concludes with an integrated synthesis of the literature and interview findings. This synthesis combines technical, organisational, and stakeholder perspectives, laying the groundwork for developing a tailored MBSE framework that supports renovation and replacement programme goals while addressing practical realities in the field.

1.3.3 Development of the MBSE Framework

The second stage of the research involves the structured development of a solution concept that responds to the challenges and requirements identified in the previous stage. This phase aims to translate the stakeholder needs, systemic challenges, and enabling conditions into a coherent and applicable MBSE-based approach. The development process is grounded in design-oriented research logic, where iterative reasoning is used to align theoretical insights with practical demands. In this stage, modelling strategies, tool considerations, and organisational factors are progressively defined and refined. The development is guided by the principles of internal consistency, stakeholder relevance, and alignment with programme-level objectives. Rather than starting from a predetermined solution, this stage builds the framework by carefully reasoning from the needs and conditions towards a practical form to improve programme performance, preparing the ground for validation and evaluation in the next research phase.

1.3.4 Evaluation of the MBSE Framework

The third stage of the research methodology focuses on evaluating whether the proposed MBSE framework effectively addresses the identified challenges and stakeholder needs. This qualitative evaluation seeks to assess the framework's relevance, coherence, and practical added value within the context of infrastructure programmes. By grounding the evaluation in the earlier analysis and development phases, the aim is to determine whether the solution aligns with stakeholder expectations and delivers improvement in both technical and organisational dimensions.

Mesly states that a feasibility study aims to find points of vulnerability (Mesly, 2016). In line with this, the evaluation not only highlights the strengths of the MBSE approach but also identifies uncertainties or risks that could affect practical implementation. To ensure a structured assessment, the evaluation incorporates components from McLeod's feasibility framework (McLeod, 2021): capability, acceptability, long-term alignment, technical feasibility, economic impact, sustainability, and timing. This comprehensive approach ensures that the MBSE framework is technically sound and practically suitable for sustainable adoption by infrastructure organisations.

Additionally, the evaluation considers project management principles such as the 'Iron Triangle' – schedule, budget, and quality – as traditional criteria for measuring successful delivery (Basu, 2014). However, Terry Williams argues that relying solely on the Iron Triangle is insufficient and underscores the importance of addressing broader strategic values and long-term contributions (Williams & Samset, 2010). Including divergent MBSE application possibilities, such as the zero option (Williams V. S., 2019), helps mitigate risks and seize opportunities effectively (Samset, 2016). Moreover, this study emphasises the concept of a 'minimum viable product', advocating selection of practical and effective solutions from among multiple alternatives to deliver immediate and lasting value (Project Management Institute, 2017).

The assessment process involves reviewing the MBSE framework against key project and programme needs, considering both short-term and long-term considerations. A SWOT analysis identifies implementation strengths, weaknesses, opportunities, and threats. Verification ensures alignment with systems engineering principles, modelling standards, and identified programme requirements, whereas validation, involving expert interviews and a practical case study, evaluates how effectively the framework integrates into real-world practice. The case study both illustrates the MBSE framework and serves as a means to evaluate its practical application in an infrastructure context.

1.3.5 Conclusions

The final stage of the study draws together the findings from the analysis, framework development, and evaluation phases to formulate conclusions and practical recommendations. This includes answering the research questions by assessing how the proposed MBSE framework is desirable, feasible, and viable for use in infrastructure programmes. The conclusions reflect on how well the framework meets stakeholder needs and addresses systemic challenges. Additionally, the discussion explores broader implications, limitations,

and areas for further research. Finally, the study offers recommendations for both the adoption of MBSE in practice

Chapter 2: Analysis of Challenges and Stakeholders

2.1 Management and Engineering Challenges

2.1.1 Project Complexity

Socio-Technical Systems

The infrastructure sector is a Socio-Technical System (STS) consisting of a multiple-layered System of Systems (SoS). One should focus on Socio-Technical performance-shaping factors, depending on the context, interactions between human beings and the situation and interdependency among influencing factors (Sawaragi, 2020). The socio-technical system's elements are interdependent and interact within the organisation. Element changes in one subsystem will lead to changes in the other subsystem. The system's performance depends on interaction and joint optimisation between social and technology subsystems under external influence. Structure and people are the organisation's social subsystem elements, and technology and process are the technical elements (Bostrom & Heinen, 1977). Carter and Rogers found that organisational sustainability comprises three components: environment, society and economics (Roger, 2008). A sustainable organisation is an organisation that is capable of existence without severance from its niche or alienating itself from future generations' needs (Espinosa, Walker, Grover, & Vachkova, 2023). How well one designs the social and technological systems concerning the demands of the external environment determines how effective the organisation will be (Dougherty, 2001). Social systems must integrate and support the use of the tools, which enhance methods consisting of a logical sequence of tasks, see Fig. 3 (Estefan, 2008).

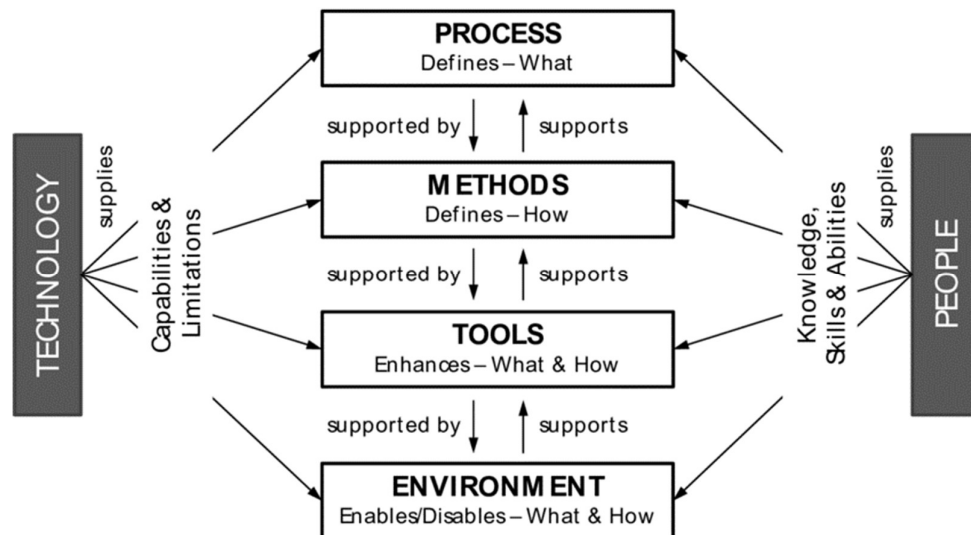


Figure 3 – Estefan's MBSE Diagram (Estefan, 2008)

Complexity

Complexity harms the project performance if one does not adequately manage it (Luo, He, Jaselskis, & Xie, 2017). Complexity drivers are related to project size, variety, interdependence and context factors (Vidal & Marle, 2008). Projects are often underperforming in an increasingly interoperable and interdependent systems environment with many system parts and organisations involved (Locatelli & Mancini, 2010). There is no universal construction industry-accepted definition of project complexity (Luo, He, Jaselskis, & Xie, 2017); however, in the current research, it is broken down into at least technical, organisational and environmental complexity. Table 1 shows the most significant and relevant complexities of Bosch-Rekveltdt's research (Bosch-Rekveltdt, 2011). Brazier describes complex systems as systems that display unexpected, emerging and unpredictable behaviour, and their characteristics as large-scale applications, involvement of many stakeholders, requiring cooperation, and decision-making on uncertain, incomplete, inconsistent information (Brazier, Langen, Lukosch, & Vingerhoeds, 2018). Many authors see a significant interconnectivity between complexity and uncertainty (Suh, 2005). Therefore, one should consider complexity a contributing factor to risk (Andringa, Ökmen, Leijten, & Bosch-Rekveltdt, 2022). There is still insufficient understanding of measuring complexity considering a project's structural, dynamic and interactive elements, project complexity's influencing factors from various stakeholders' perspectives and management of the (life cycle increasing) project complexity for various project types (Luo, He, Jaselskis, & Xie, 2017).

Table 1 – Project Complexities (Bosch-Rekveltdt, 2011)

Technical Complexity	Organisational Complexity	External Complexity
Number of project goals	High project schedule drive	Number of external stakeholders
Non-alignment of project goals	Lack of resources and skills availability	Variety of external stakeholder perspectives
Unclearity of project goals	Lack of Experience with parties involved	Dependencies on external stakeholders
Uncertainties in scope	Lack of trust in the contractor	Lack of experience in the country
Strict quality requirements	Interfaces between different disciplines	Lack of company internal support
Project duration	Number of financial sources	Forced cooperation with local parties
Size in Capital Expenditure	Number of contracts	Company internal strategic pressure
Number of locations	Number of different nationalities	Instability of project environment
Newness of technology	Number of different languages	Level competition
Lack of experience with technology	Organisational risks	Risks from environment
Number of tasks	Involvement of different time zones	
Variety of tasks	Size of project team	
Dependencies between tasks	Incompatibility between different project management methods or tools	
Uncertainty in methods	Lack of trust in the project team	
Involvement of different technical disciplines		
Conflicting norms and standards		
Technical risks		

Systems integration problems

Systems integration makes a system coherent by managing interactions across system elements (Whyte, 2016). The integrated design process is essential for project performance,

and integrating the complex context is crucial to improve results. Systems integration is essential for efficient and effective collaboration. However, Mutual adoption of context is often hard to achieve. In particular, poor interaction between design and construction disciplines causes problems. The integration challenges of civil engineering objects in their increasingly complex context and the integration of a growing number of disciplines dominate today. (Keusters, Bakker, & Houwing, 2022). Senescu found that communication problems in the construction industry increase when complexity increases (Senescu, 2013). For example, project managers provide insufficient time for thorough consideration by all disciplines to ensure an optimum solution (Langley, 2022). Furthermore, current strategies for design error management neglect the role of proper information flow and communication between disciplines (Hattab & Hamzeh, 2015).

Variations

Project variations increase the complexity of projects, which project teams manage to seize opportunities or reduce damage. Variations are design, scope, or method changes different from those specified and agreed upon in the initial contract (Noruwa & Arewa, 2020) that cause an adjustment to the contract price and time (Ibbs, 1994) and are a significant source of delay (Akinsola, Potts, & Ndekugri, 1994) and significantly cause disputes (Perera, Ekanayake, Jayalath, & Jayathilaka, 2019), which are the most significant problems in contract management (Hibberd, 1986). Jones discussed the cumulative disruptive impact of variations whose impact on productivity and cost surpasses the actual cost of the changed work (Jones, 2001). Variation always increases the capital cost of construction projects. They result in a heavy administrative load, requiring reviews, discussion, and tracking (Keane, Sertyesilisik, & Ross, 2010). Thus, minimising variation is one of the prerequisites for keeping the cost within budget and completing the project on time (Chan & Yeong, 1995).

When one addresses or eliminates early major root causes of variations, a significant reduction in the number of variations a construction project will record. Researchers recorded a significant reduction in the number of variations at project completion due to eliminating most project risks, design errors, omissions, rework and effective design coordination and communication (Noruwa & Arewa, 2020) (Love, Edwards, & Smith, 2013). Clients are a significant cause of variations in construction projects. Most variations in projects implementing useful technologies are due to clients' changing needs rather than incorrect designs (Mohammad, Ani, Rakmat, & Yusof, 2010). Ironically, pressure on the variation limitations during projects considerably increases the chance of committing errors (Lopez & Love, Design Error Costs in Construction Projects, 2011).

Design errors

The causes and effects of committing errors are not unidirectional or linear but are reciprocal or looped in their relationships. Understanding how such relationships emerge is necessary for error prevention. The ideal error prevention approach is to view errors as symptoms of underlying problems so they become sources of information to understand how systems work. Table 2 presents major design error cause categories (Lopez, Love, Edwards, & Davis, 2010). A significant problem is the interpretation of requirements since unambiguously writing down requirements is complex, causing a discrepancy between specification and implementation

(Hendriks, 2022). Love and Lopez found that design errors are a symptom of dysfunctional organisational and managerial practices, and one could have prevented many errors by conducting design checks and reviews (Lopez & Love, Design Error Costs in Construction Projects, 2011). Design professionals repeatedly make the same design errors, and determining the most effective error-minimising strategies remains challenging (Love, Edwards, & Smith, 2013).

Table 2 – Causes of Design Error Categories (Lopez, Love, Edwards, & Davis, 2010)

Personal	Organisational	Project
Adverse behaviour	Inadequate training/experience	Unreasonable client and end-user expectations
	Ineffective utilisation	Time constraints
	Inadequate quality assurance	Ineffective design coordination and integration
		Inadequate consideration of constructability

Performance

Variations and underlying problems affecting the project output are the Iron Triangle: schedule budget and quality, in which one defines quality as consistent conformance to stakeholder expectations (Basu, 2014) and fulfilling the stakeholders' needs. Furthermore, the variation and problems should not harm the established long-term values (Williams & Samset, 2010). Table 3 shows Westerveld's proposed clustered project success output criteria (Westerveld, 2013), adding stakeholder appreciation to the Iron Triangle. Additionally, project funders demand a return on investment to realise its strategic benefits. Project success is commonly divided into project management success and investment success, with the latter operationalised in terms of return on investment and the realisation of desired benefits (Key Performance Indicators). Therefore, one should measure project success from different perspectives, such as project efficiency, stakeholder satisfaction, impact, organisational benefits, business success and future preparation (Badewi, 2016).

Table 3 – Project Success Output Criteria (Westerveld, 2013)

Output area	Explanation
Project results: Budget, Schedule, Quality (Iron Triangle).	Almost all projects will have specific scheduling, budget and quality constraints (the original iron triangle of project goals).
Appreciation by the client	The client initiates the project to fulfil a specific need (the aspects and factors the client values in judging the project's success).
Appreciation by project personnel	The project workers will be concerned with reaching their personal goals and an excellent working atmosphere.
Appreciation by users	Users are concerned with their overall influence on the project and the end product's functionality.
Appreciation by contracting partners	Contracting partners try to make a profit on the project. They are also concerned with getting new orders and learning possibilities.
Appreciation by stakeholders	Those parties that are not directly involved in the project but have a considerable influence, for example, environmental groups, citizens and government agencies. These parties manage their specific interest.

2.1.2 Governance, Management and Systems Engineering Complexities

2.1.2.1 Programme governance

The infrastructure Renovation and Replacement Programme (RRP) brings additional complexities within project and programme organisations. Infrastructure is inherently highly complex due to its social, technological and economic aspects. From an economic perspective, there is an undeniable sense of urgency to place reliability high on the political agenda and demand better control through technological innovation and knowledge development (Weijnen & Bouwmans, 2006). From a technological and social perspective, complexity-increasing factors include the increasing number of necessary renovation and replacement projects due to deferred maintenance and changing requirements, creating a capacity shortage due to organisational inefficiency. Organisational inefficiencies demand better programme governance and coordination to align stakeholders' interests and control uncertainties. Other organisational challenges are a lack of trust and high competition within the civil engineering sector (Dorée, 2004), contradicting the need for solid collaboration regarding knowledge and innovation development (Marktvise, 2020). There is a need for adaptable programmes to respond to contextual changes that could harm programme outcomes. Learning and adaptation throughout programmes benefit the programme approach (Van Herk, Rijke, Zevenbergen, & Ashley, 2013) (Rijke, et al., 2014).

To manage the projects, organisations use Systems Engineering for Systems Design and Engineering, and, on the other hand, Rijkswaterstaat (RWS) applies governance, both critical to the success of projects as they have complementary views of the same technical developments. The governance body establishes policies and continuous monitoring, and its primary duty is to enhance the RRP's viability. Governance relies on information about the internal and external context and the systems' life cycle status. Governance encompasses the complete set of policies and monitoring that define an organisation and represent a higher-level structure, defining processes and structures to govern multiple projects and manage strategic objectives (Nielsen, 2010). Correct Governance could enhance performance across multiple project-based organisational layers (Garland, 2009).

In programmes, one must coordinate inter-organisational and project boundaries to make innovations successful (Rutten, Dorée, & Halman, 2019), which is complex since the Dutch Infrastructure sector is a non-hierarchical, polycentric and decentralised system consisting of multiple autonomous, interdependent, collaborating and competing actors (Bletsis A. J., 2020). There is intense competition within the infrastructure sector, which one deems competition crucial for innovation and long-term development. However, collaboration should not suffer due to competition. Due to the construction sector's unique and complex organisational nature, the development and deployment of systems integration and collaboration technologies are behind other sectors (Shen, et al., 2010). Polycentric programme actors want to retain their autonomy yet engage in some form of cooperation (Ménard, 2011). The actors have private social, communication and technical systems, causing additional complexities (Brazier, Langen, Lukosch, & Vingerhoeds, 2018).

The infrastructure industry has a strong project focus since the projects have a unique character, use novel processes and are transient (Turner & Müller, 2003). The projects share few connections with others, complicating cross-project coordination and inter-firm collaboration and hindering long-term productivity, innovation, and learning (Dubois & Gadde, 2002). Thus, if one does not sufficiently stimulate and facilitate innovations and collaboration, for example, through procurement (Edler & Georghiou, 2007), it constrains innovation within the Dutch infrastructure superstructure (Dubois & Gadde, 2002). Because projects are temporary endeavours, much of the knowledge is lost once one completes the project. Being attentive to knowledge transfer serves the organisation by not only the project

delivering value but also allowing the organisation to gain knowledge from the experience of running projects (Institute Project Management, 2021). However, there is a lack of learning instruments to capture, store and disseminate lessons learned (Shabbab Al-Otaibi, 2013).

Rijkswaterstaat Roadmaps

Rijkswaterstaat (RWS), an essential Dutch infrastructure client, created RRP roadmaps through which they want to stimulate innovation to realise specific goals before 2030 (Rijkswaterstaat, 2023). RWS wants to conduct the projects in a future-oriented, cost- and capacity-effective manner through market collaboration, aiming for standardisation, digitalisation, and sustainability innovation. RWS aims for more standardisation, offering repeated design economies through rationalisation and greater use of standard and reusable components. The current customised approach provides flexibility but is inefficient, costing time and money because one has to re-design and reconstruct every object (Hendriks, 2022). However, one should approach standardisation carefully since factors could limit the benefits (Robinson & Gibb, 2012). However, it is crucial to inform designers about the limitations of the re-usability of a design. Designers may distribute their errors and omit to involve others in design decisions, inform others of their assumptions and understand the history of another's problem-solving in a replicated design (Love, Edwards, & Smith, 2013). Another significant and ambitious RWS objective is to work in a circular and climate-natural way in 2030.

Building Blocks

RWS developed system building blocks to prevent inefficiencies (re-design, quality, and integration problems) and design errors due to insufficient knowledge about Industrial Automation components to accelerate the RRP. RWS experiments with 3BB blocks for bridge operation, control and monitoring. However, Adviescollege ICT-Toetsing found shortcomings in the IA-Sourcing Programme (IAS), such as inadequate insight into integrating other technical systems and the impossibility of reusability due to not considering various bridge configurations and design differences. Also, IAS expects one to update the blocks once a year. However, one cannot constantly adapt the objects' maintenance planning to the planning for updates, making the updates infeasible and increasing the different block versions and complexity (Adviescollege ICT-Toetsing, 2021). Furthermore, RWS wants to apply Synthesis-Based Engineering (SBE), a lighter standardisation, for complex systems, such as a bridge-sluice combination, to verify and develop operation, control and monitoring software automatically.

2.1.2.2 Systems Engineering

SE is the leading method for managing complexity. (Stevens, 1998). SE is the discipline developed to deliver successful projects in complex environments through a multi-disciplinary approach considering the whole system life cycle (Bahill & Dean, 1996), ensuring customer satisfaction (Locatelli, Mancini, & Romano, 2014). The multi-disciplinary approach and its principles enable the successful management of complex systems when organisations design individual elements in different phases of the project life cycle (Kossiakoff, 2003). The SE integration process aims to manage internal and external systems interfaces. It ensures that subsystems integrate into one system (Walden, 2010). As the introduction mentions, SE is an interdisciplinary collaborative approach to derive, evolve, and

verify a life cycle-balanced system solution that satisfies customer expectations and meets public acceptability. The main difference between project management and SE is that SE focuses on the SoS, life cycle and technical aspects (Giorgio Locatelli, 2014), while project management focuses on the project aspects (Xue, Baron, Esteban, Zheng, & Jakjoud, 2015).

The Dutch infrastructure sector has a Document-Based Systems Engineering (DBSE) approach combined with hybrid simplistic modelling and (virtual 3D) information models, such as Relatics, conforming to ISO/IEC/IEEE 15288:2023 and BIM.

The most significant problems are the completeness, consistency, and relationships between requirements, design, engineering analysis, and test information, which are challenging to assess and achieve because the project team spreads information (no single source of truth) over different software and documents. Understanding a particular aspect of the system and performing traceability and change impact analysis becomes difficult, leading to poor synchronisation between requirements, system-level design, and lower-level detailed designs (software, electrical and mechanical design). DBSE makes it challenging to maintain or reuse the system requirements and design information for an evolving or variant system design. The progress status of the SE effort depends on the documentation status, which is challenging to maintain and does not adequately reflect the requirements and design quality (Friedenthal, Moore, & Steiner, 2014). Due to the complex interactions and relationships between system elements, traditional analysis and modelling techniques can fail to incorporate the intricate dependencies between system entities and emergent system behaviour (Baudains, et al., 2014).

ISO 15288

ISO/IEC/IEEE 15288:2023 (ISO 15288) provides one of the most fundamental international standards for developing systems according to SE principles. ISO 15288 describes the life cycle as the concept, development, production, utilisation, support and retirement, and support occurs at every stage. More specifically, one could describe the life cycle of the construction industry through the design, manufacturing, construction, maintenance and use, disposal, and recycling phases (Kubler, Buda, Robert, Främling, & Traon, 2017). Table 4 shows ISO 15288's life cycle processes, categorised into four categories, and Fig. 4 shows the complex interrelationship between those processes. The authors developed ISO 15288 for various sectors and applications to ensure SE compliance, providing a general framework; therefore, correct tailoring and adaptation to organisation methodology and tools is essential. Currently, the most applied SE methodology in combination with ISO 15288 is the V-model in the Dutch infrastructure industry, separating requirement development from system verification and validation (Schindel & Dove, 2016).

Table 4 – ISO 15288 Processes

Agreement Process	Organisational Project-Enabling Process	Technical Management Process	Technical Process
Acquisition	Life Cycle Model Management	Project Planning	Business or Mission Analysis

Agreement Process	Organisational Project-Enabling Process	Technical Management Process	Technical Process
Supply	Infrastructure Management	Project Assessment and Control	Stakeholder Needs and Requirements Definition Process
	Portfolio Management	Decision Management	System Requirements Definition
	Human Resource Management	Risk Management	System Architecture Definition
	Quality Management	Configuration Management	Design Definition
	Knowledge Management	Information Management	System Analysis
		Measurement	Implementation
			Integration
			Verification
			Transition
			Validation
			Operation
			Maintenance
			Disposal

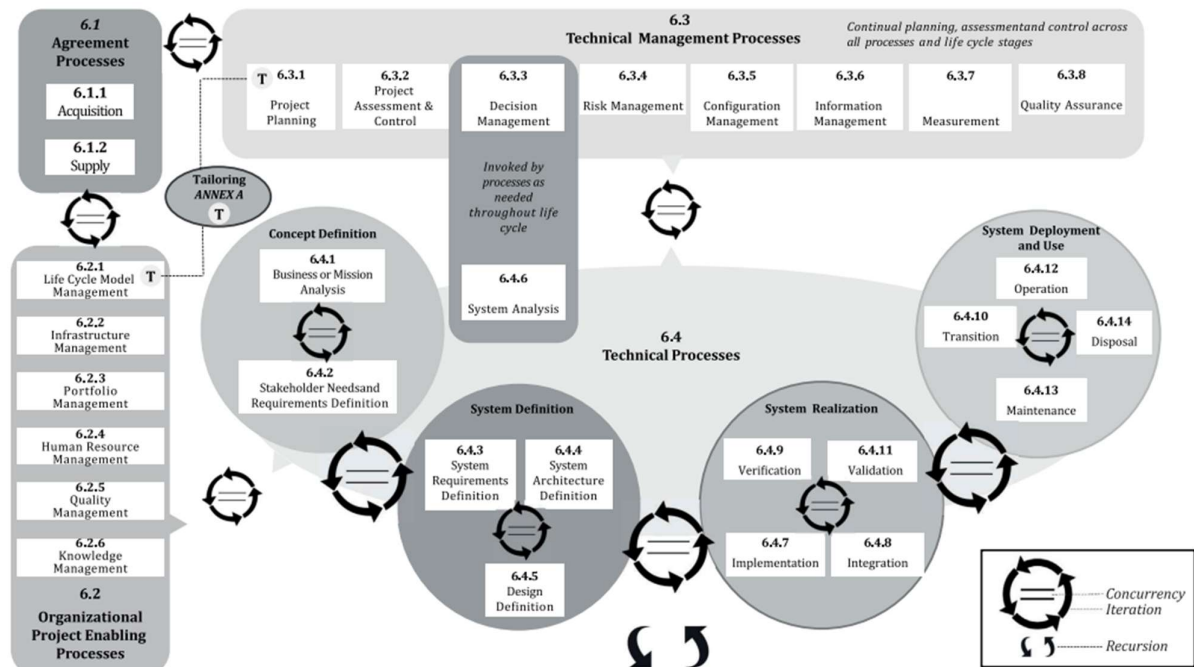


Figure 4 – ISO 15288 Processes

BIM

Building Information Modelling (BIM) supports SE activities in the construction industry. BIM minimises undesirable variations (contract changes) in construction projects by increasing the coordination of designs. BIM allows structure virtual twinning, enhances decision-making and effective change management, and enables various design scenarios to meet clients' needs. Additionally, BIM enhances knowledge retention within the model, provided there is sufficient interoperability between platforms for effective knowledge transfer; without a sufficient level of BIM, significant amounts of valuable information may be lost between project stages (Bokmiller, Whitbread, & Hristov, 2013). However, despite the

emergence of BIM, changes in scope, errors, and omissions are the main contributors to rework costs that still arise (Love, Teo, & Morrison, 2017), leading to unanticipated increases in costs and delays (Meem & Iordanova, 2023). While BIM facilitates the distribution of design information, it can also create issues among engineers, clients, and building contractors due to the quality and expected content accuracy. A common assumption is that all necessary asset information is captured within the BIM model, but this is often not the case and not sensible. This over-reliance on the values and parameters within the model, which may lack crucial details, can lead to a disconnect between what was originally designed and what is actually documented. Omissions of crucial interdisciplinary information and communication, along with the inability to capture and maintain a trackable history of issue resolutions (Roberti & Ferreira, 2021) and design decisions, can exacerbate these problems (Eng, Marfisi, & Aurisicchio, 2011). Additionally, the record of what is actually procured and installed is typically managed in analog formats (spreadsheets and PDFs) rather than as machine-readable data that connects back to the geometric model, which should provide location and system information (Roberti & Ferreira, 2021).

Furthermore, gaps between SE and BIM relate to development phasing, lack of a systemic approach to product and process integration and system management enablers (Chen & Jupp, 2018). BIM primarily focus on physical components, neglecting processes (what the system does), requirements (boundary conditions), and functions (what the system is capable of doing) (Bolshakov, Rakova, Celani, & Badenko, 2023). Team, task and process obstacles regarding the multidisciplinary BIM-based design coordination process significantly affect the defining coordination strategy and generating speciality model stages, having the maximum impact on the project efficiency. The most significant problems are BIM managers not having total control, disciplines' isolated working mentality, resistance to sharing information, no shared data environment to support collaboration, proper BIM collaboration guidelines, and the correct information at the right time (Meem & Iordanova, 2023).

Cloud-based Common Data Environments (CDEs), such as Trimble Connect and BIM Collaborate, are commercial AEC sector BIM collaboration solutions. Despite being developed by different vendors, these tools share many features in common. At the core, they provide centralised cloud storage space for 2D, 3D, point cloud and geospatial files that every authorised user can access. These platforms usually support open data formats for 3D models like STEP and IFC and a few proprietary data formats native to software under each company's ecosystem. The CDEs, as mentioned above, allow users to access the latest information from the "single source of truth" and view/navigate all building information conveyed in the 3D models. However, coordinating designs and resolving conflicts remain manual, making human intervention indispensable for coordinating federated building models (Wang, Ouyang, & Sacks, 2023).

The CDE helps collect data during the design and construction stages in the form of BIM models, drawings, and product data, ideally integrating this information with facility management digital systems. However, data integration is often fragmented, leading to significant data loss and inefficiencies, especially when projects use private servers during the design phase and only transition to CDEs during construction, see Fig. 5. This fragmentation

continues when data moves from CDEs to facility management systems, where further losses can occur if O&M manuals are not fully digital and integrated. This results in critical information gaps, undermining the effectiveness of CDEs and BIM in providing comprehensive project management. The UK Government is attempting to mitigate these issues by implementing COBie as a BIM requirement, but ensuring consistent data management across all stages remains a significant challenge (Roberti & Ferreira, 2021).

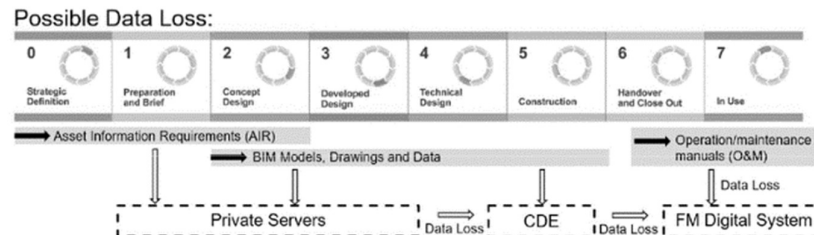


Figure 5 – CDE Data Loss (Roberti & Ferreira, 2021)

Predictive, hybrid, or adaptive design approach

The Project Management Institute describes the three commonly used development approaches at the project level: predictive, hybrid, and adaptive. As Fig. 6 shows, these approaches are often viewed as a spectrum. A predictive approach is practical when the project and product requirements can be defined, collected, and analysed at the start of the project. This is commonly referred to as a waterfall approach. The scope, schedule, cost, resource needs, and risks can be well defined in the early phases of the project life cycle, and they are relatively stable. A hybrid development approach is a combination of a predictive and adaptive approach. This development approach is practical when there is uncertainty or risk around requirements. Hybrid approaches often use an iterative or incremental development approach. An iterative approach helps clarify requirements and investigate various options. An iterative approach may produce a deliverable throughout a series of iterations. Each iteration adds functionality within a predetermined time frame. An iterative approach tries different ideas to clarify scope, approach, and requirements, and an incremental approach progressively develops features and functions. Adaptive approaches are helpful when requirements are subject to high uncertainty and volatility and are likely to change throughout the project. A clear vision is established at the start of the project, after which initial known requirements are refined, detailed, changed, or replaced based on user feedback, environmental factors, or unexpected events. The iterations tend to get shorter on the far side of the adaptive methods, and the product is more likely to evolve based on stakeholder feedback. Agile approaches can be considered adaptive (Institute Project Management, 2021). The V-model is predictive and not agile since it assumes that the requirements are well-defined upfront and that the development process proceeds in a planned and sequential manner.

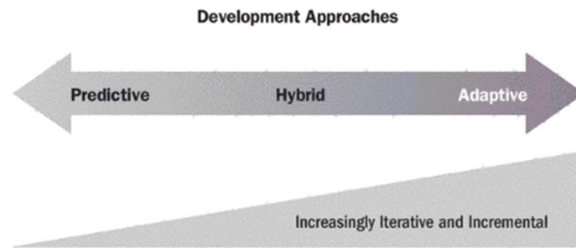


Figure 6 – Predictive and Adaptive Development Approaches Spectrum (Institute Project Management, 2021)

Practical and Case Study Challenges

The practical application of Systems Engineering (SE) within infrastructure organisations faces several significant challenges that have impeded its effective implementation across projects. A key issue is the lack of uniformity in handling SE-related tasks, leading to inconsistent outcomes and hampering the standardisation of processes. This inconsistency highlights the need for standardised approaches, not only for making requirements SMART (Specific, Measurable, Achievable, Relevant, and Time-bound) but for SE practices in general. Implementing such standardisation would provide a reliable framework for project teams, ensuring that SE is applied consistently and effectively.

A major obstacle to the successful application of SE is the prevailing mindset among project teams, who often perceive SE as an unnecessary administrative burden. This perception reduces the effort invested in applying SE principles, which diminishes the potential benefits of SE in project management and quality assurance. To address this, a cultural shift is needed within organisations to highlight the long-term advantages of SE, such as increased project efficiency, risk reduction, and improved outcomes.

Balancing detailed specifications with design freedom is another significant challenge. Over-specification can limit innovation and creativity, while excessive freedom can lead to misinterpretations and inconsistencies in the final product. Striking the right balance is crucial to ensuring that SE facilitates, rather than restricts, the design process.

The management of requirements is another area of concern. Clear and consistent requirements are essential for successful project execution, yet the articulation and management of these requirements are often inadequate. Ambiguities and inconsistencies in requirements can lead to confusion, delays, and even project failure. Therefore, improving the clarity, communication, and management of requirements is critical.

Integration of SE into the design process remains a challenge, as SE is often treated as a separate activity rather than being fully integrated into the project workflow. This separation leads to inefficiencies and missed opportunities for SE to add value throughout the project lifecycle. To overcome this, SE needs to be more deeply embedded in the design process, with clearly defined roles and responsibilities for all team members.

The absence of a cohesive structure for applying SE exacerbates these challenges. Different projects often adopt different approaches, leading to a lack of coherence and coordination.

This issue is further compounded by the absence of a standard overarching method that connects different projects, which often results in dependency on the main contractor's approach. Establishing a cohesive SE structure would ensure that all projects benefit from the systematic application of SE principles.

These conclusions, which are drawn from research conducted by students at a university of applied sciences (Appendix F.1), reflect the practical difficulties faced in applying SE and provide insights that could be valuable for improving SE practices across the infrastructure sector.

In the context of a large-scale movable bridge renovation project in the Netherlands, one engineering consultancy firm experienced key challenges that are particularly relevant to the implementation of Model-Based Systems Engineering (MBSE) and SE within similar organisational settings. These challenges not only reflect specific project issues but also confirm broader trends observed across the infrastructure sector. Addressing these issues is crucial for developing effective solutions and improving future project outcomes.

A significant challenge identified was the tendency for different disciplines to work in isolation. This lack of integration led to inefficiencies, misalignments, and delays, as teams focused on their specific tasks without sufficient coordination with other departments. This issue was exacerbated by the absence of a strong understanding and management of the processes, which resulted in inconsistent approaches across the project.

Another challenge was the delayed or incomplete verification of project requirements. Verification processes were often postponed until the later stages of the project, leading to the late identification of issues that required costly rework and adjustments to the design. The lack of early and continuous verification complicated the overall project execution.

There was also a clear disconnect between contract management and technical design work. This separation made it difficult to ensure that contractual obligations were accurately reflected in the design, leading to inconsistencies and misunderstandings. This disconnect highlights the need for better integration between these critical project components.

The project also faced issues with incomplete and untraceable documentation related to project agreements, progress, and deviations. This lack of reliable documentation complicated the design process and made it difficult to track decisions and changes, potentially impacting the safety and functionality of the final design.

Finally, the project was affected by an uncontrolled expansion of its scope, driven by inconsistent processes and poor management of project boundaries. Without sufficient process management, the project struggled to maintain a coherent approach, leading to increased costs and extended timelines as the project grew beyond its initial scope. In complex projects like this, traditional approaches to process management often proved inadequate in adapting to unforeseen changes. This highlighted a significant problem where the focus on rigid process control hindered the ability to respond flexibly to variations, ultimately affecting the project's resilience and execution.

These challenges underscore the importance of improving integration, verification, traceability, and the overall approach to process management. Addressing these issues is essential for enhancing the effectiveness of SE in future projects, both within similar organisations and across the broader infrastructure sector.

2.1.3 Overview Challenges

The challenges faced in applying systems engineering principles within the infrastructure sector are diverse and interconnected, spanning technical, organisational, and cultural dimensions. Table 5 provides an overview of the key challenges identified in literature and practice. These include issues related to complexity management, fragmented information flows, insufficient collaboration, and limitations in design quality and lifecycle integration, all of which hinder effective project execution and programme coordination.

Table 5 – Overview Challenges

Category	Challenge	Explanation
Project Complexity	Complexity Management	Managing the complexity of large infrastructure projects involves dealing with technical, organisational, and environmental factors. The lack of universal complexity measurement and management standards complicates effective project execution.
Systems Integration	Technical Systems Integration	Integrating multidisciplinary design processes and system functionalities is challenging. BIM often struggles to capture the intricate interactions across system elements, leading to potential gaps in the final product.
Team Collaboration	Insufficient Collaboration and Communication	Effective collaboration across disciplines is often lacking, leading to misinterpretations of requirements and poor interdisciplinary interaction.
Information Distribution	Fragmented Information Flow	The spread of information across multiple platforms and documents complicates traceability and consistency. Without a unified information source, stakeholders may lack access to consistent, accurate data.
Cultural Barriers	Resistance to SE Adoption	There is a prevailing mindset within project teams that SE is an unnecessary administrative burden, reducing the effort to apply SE principles effectively.
Lifecycle Design	Time Constraints for Lifecycle Consideration	Time constraints often limit interdisciplinary lifecycle design considerations, which can lead to oversights and incomplete lifecycle integration.
Design Quality	Insufficient Design Checks and Reviews	Design quality suffers from inadequate checks and reviews, leading to recurring errors and inconsistencies.
Standardisation & Reusability	Challenges in Reusing Requirements and Design Information	A lack of standardisation hampers the ability to reuse requirements and design information, leading to inefficiencies and inconsistencies across projects. Reusing requirements refers to applying the same standards and specifications in multiple projects to ensure consistency and reduce rework.
Governance	Inadequate Error Prevention and Learning Tools	Repeated design errors occur due to the absence of effective learning tools across organisations, leading to recurring issues. (Bletsis A. J., 2020)
Agility & Flexibility	Managing Variations and Changes	Variations in project scope or client requirements can increase error chances due to poor communication and coordination.

2.2 Stakeholder Analysis

Infrastructure sector

As mentioned above, the infrastructure sector is a poly-centric system consisting of the public, governing the programme and private actors, influenced by institutional organisation, initiatives, and associations see Fig 7 (Bletsis A. J., 2020). To illustrate, RWS owns 167 moveable bridges and 215 sluices; the provinces also own bridges and 214 sluices, and ProRail owns 68 moveable bridges (TNO, 2021). Public actors and owners tender work to and select private actors for projects, creating a highly competitive environment and aiming to manage and govern the Renovation and Replacement Programme (RRP) collaboratively. In the case of this research, the work regards renovation and replacement projects of moveable bridges and sluices specifically. Projects often have integrated contracts that incentivise the construction organisation's involvement at an early project phase (Lenferink, Tillema, & Arts, 2013). Commonly, the public and private sector project organisations mirror their project to enhance the exchange of information and effectively monitor and control projects on distance.

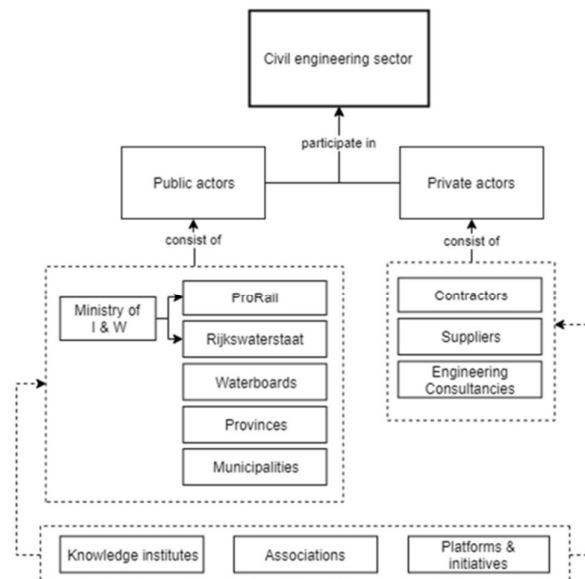


Figure 7 – Infrastructure Organisation Diagram Bletsis (Bletsis A. J., 2020)

The owners, such as RWS, ProRail, provinces, and municipalities, are high-priority stakeholders because of the responsibility for the objects' performance for over 100 years. Currently, the information storage is fully document-oriented. Documentation quality is of significant concern to contractors, who rely on the provided information, which must be accessible to all relevant stakeholders during the life cycle. However, one has identified erroneous design documentation as a significant contributor to rework during the design process (Lopez, Love, Edwards, & Davis, 2010). A significant problem is old, incomplete documentation caused by people not documenting execution and maintenance changes (Hendriks, 2022).

Moveable bridge design

One divides the moveable bridge into civil, mechanical and electrical designs, which are interdependent. There is interdependency between civil engineering and mechanical design, hydraulic machinery, electrical controls and software. Since moveable bridges are machines, one has to consider the moveable bridge's dynamics effect (Langley, 2022). Moreover, RWS states to develop and integrate more intelligent systems within moveable bridge systems, such as sensors and smart cameras, as part of the IA (operation, control and monitoring) (Rijkswaterstaat, Ministerie van Infrastructuur en Waterstaat, 2023).

Different factors influence those interdependent designs, such as main dimensions, loading conditions, foundations, operation time, risk assessment, mechanical- and electrical systems and maintenance costs (Thomsen & Petersen, 2019). Important moveable bridge design considerations are machinery accessibility, failure mode and effects analysis (FMEA), Life Cycle Cost (LCC) analysis, quality assurance, and machinery design regarding robustness, redundancy and failure (Parke & Hewson, 2022). Various authors emphasise the importance of considering operation and maintenance aspects in design and engineering. Decisions early in a project significantly impact performance and LCC. Methods to reduce the LCC include Building Information Modelling (BIM), Risk and RAMS Analyses and Asset Management (Jensen, 2018).

Furthermore, during design and engineering, the project team must intensively involve the moveable bridges' stakeholders – that is, vehicular traffic and shipping port authority (Langley, 2022). The SE (Shenhar, 1994) (Eisner, 2008) (Gräßler, Wiechel, & Pottebaum, 2021) and Project Management (Morris, 2013) disciplines must ensure the integration of the multi-disciplinary team, stakeholder involvement and collaboration during the project. Table 6 summarises the disciplines and related tasks to conduct a multi-disciplinary renovation and replacement project successfully.

Table 6 – Discipline Tasks Moveable Bridge Renovation and Replacement Projects

Discipline	Task
Owner	- Determines contract type and tenders - Project control on distance - Information maintenance, storage and distribution
Project Management	- Project Management (Iron Triangle)
SE	- Ensures technical design integration - SE tasks - BIM
Contract Management	- Managing variations (paragraph 2.1.1) - Contract analysis and design
Asset Management	- Maintenance Specialist
RAMS	- Reliability, accessibility, maintainability and safety assessment - FMEA
Civil Engineering	- Civil Engineering Design
Mechanical Engineering	- Mechanical Design
Electronic Engineering	- Electronic design (including sensors and cameras)
IA Engineering	- (Operation, control and monitor) Software Design
Stakeholder Management	- Obtains stakeholder needs (owner, vehicular traffic, shipping port authority)
Cost	- LLC

2.3 MBSE a Strategic Solution

2.3.1 Introduction MBSE

For better project performance and to manage the increasing complexity, the construction industry could apply Advanced Systems Engineering, more specifically Model-Based Systems Engineering (MBSE), which means using models as artefacts for SE activities (Schmidt & Stark, 2020) and provides an approach for top-down consideration of systems (Whyte, 2016). The Institute of Project Management defines modelling as creating simplified representations of systems, solutions, or deliverables such as prototypes, diagrams, or storyboards. Modelling can facilitate further analysis by identifying gaps in information, areas of miscommunication, or additional requirements (Institute Project Management, 2021). MBSE enhances complexity management; modelling is the principal means of complexity management (Masior, Schneider, Kürümlüoglu, & Riedel, 2020) (Locatelli, Mancini, & Romano, 2014). The MBSE approach, with its centralised system model, serves as a single source of truth and data repository (Riesener, Doelle, Perau, Lossie, & Schuh, 2021).

MBSE is the formalised modelling application to support systems requirements, design, analysis, (formal and automated) verification and validation activities from the conceptual design phase to later life cycle phases. Many expect the MBSE approach to become the standard SE practice and be crucial to supporting an effective collaborative development environment and facilitating SE activities (Ramos, Ferreira, & Barceló, 2011). Madni and Purohit found that the expected gains of MBSE depend primarily on the system's intrinsic characteristics, such as complexity, operational environment and lifespan. Madni and Purohit concluded that the infrastructure sector could benefit significantly from MBSE (Madni & Purohit, Economic Analysis of Model-Based Systems Engineering, 2019).

Model-centric approaches are, in contrast to document-centric methods, capable of formal definition and description of systems, which are necessary for enabling the systems thinking perspective and the automatic processing of interrelationships between system elements as well as the impact assessment of changes (Kunnen, Adamenko, Pluhnau, & Nagarajah, 2019). MBSE simulation is essential for designing multi-disciplinary, closely linked component systems to achieve optimal performance (Sinha, Liang, Paredis, & Khosla, 2001) (Locatelli, Mancini, & Romano, 2014). Analysis, experimentation, modelling, prototyping, evaluation and testing are part of MBSE and ensure that cost and timescale remain controlled (Albers & Lohmeyer, 2012). MBSE is a collaborative tool that facilitates trust and cooperation (Das & Teng, 1998).

Three MBSE Pillars

Delligatti classifies the three most crucial elements of MBSE as a modelling tool, method, and language and names them together as the Three Pillars of MBSE. As a design team member creating an integrated system model, one will use a dedicated *modelling tool* to perform a set of design tasks prescribed by a *modelling method* to add elements and relationships between elements to an integrated system model expressed in a standard *modelling language* (Delligatti, 2013).

A *modelling language* is a semiformal language that defines the kinds of elements one allows put into the model, the allowable relationships between them, and, in the case of a graphical modelling language, the set of notations one can use to display the elements and relationships on diagrams. MBSE practitioners commonly use the Systems Modeling Language (SysML) to construct models of a system's structure, behaviour, requirements, and constraints. Other modelling languages include UML, UPDM, BPMN, MARTE, SoaML, IDEFx, Verilog and Modelica. The key is that each modelling language is a standardised medium for communication; the rules defined in a given language give the elements and relationships unambiguous meaning. A modelling language is a documented set of design tasks that ensure that everyone on the team builds the system model consistently and works toward a common endpoint.

A *modelling method* dictates how and when to use the language to create a model. A modelling method is a documented set of design tasks a modelling team performs to create a systems model. According to Delligatti, every MBSE project requires a plan beginning with a purpose and a scope. The scope determines the modelling method the team will follow. Examples of well-known methods spanning the SE lifecycle stages are OOSEM, SYSMOD and IBM Telelogic Harmony-SE.

Modelling tools are a particular class designed and implemented to comply with the rules of one or more modelling languages, enabling one to construct well-formed models in those languages. Modelling tools are distinct from diagramming tools such as Visio, Schematic, SmartDraw, ProcessOn, and others. With a diagramming tool, one creates merely diagrams. With a modelling tool, one creates a model, a set of elements and relationships between components, and charts that serve as views of the underlying model. The underlying model automatically ensures consistency. When one modifies a part of a diagram within a modelling tool, one changes the element in the underlying model (Delligatti, 2013).

SysML

Different modelling languages exist to design successful models for various applications. The most used MBSE modelling language is Systems Modeling Language (SysML), developed for SE specifically to improve communication among the involved stakeholders (SysML™, 2019). However, SysML models still need to improve in representing complete system life cycle information, flexible reduction regarding present needs, and interdisciplinary integration of models; continuousness and consistency are still the subject matter of research (Albers & Lohmeyer, 2012). Geyer argues that only graphical languages, such as SysML, can fundamentally provide for both system analysis and system synthesis. SysML is a modelling language consisting of a toolbox offering several ways to describe a complex system. SysML is not a method, and the Object Management Group (OMG) does not propose a specific approach (Geyer, 2012).

2.3.2 Governance direction

Governance and Modelling

SE tools and practices foster and enable the managers involved in project governance to deal with uncertainty and complexity by introducing flexibility and higher reliability of project planning and control. Modelling facilitates the open system approach and system integration. One of the main obstacles to system integration is the unexpected stakeholders and system behaviour; modelling is the primary tool used to hedge this risk. Furthermore, efficient systems reuse hedges the risk of delivering projects in complex environments and can cut costs (Giorgio Locatelli, 2014).

Brazier designed an integrated approach to the life cycle management of complex sociotechnical systems, including Governance and Design Process Coordination (DPC). DPC coordinates and manages the design process concerning resource allocation, given process objectives and progress booked, using stakeholder interaction on process requirements, requirements and design on the implications of process requirements for the coordination strategy. DPC provides requirements and design with information on the design strategy and stakeholders with design progress.

Simulation/Experimentation/Implementation (Modelling) is central in Brazier's design model, connecting the life cycle stages with Governance. Modelling assesses the feasibility of a set of requirements and design in practice, in interaction with the Requirements Design, Artefact Design, and DPC. Moreover, Modelling provides a Requirements and Artefact Design assessment and progress assessment (Brazier, Langen, Lukosch, & Vingerhoeds, 2018).

Governance approach

Gorod proposes the Holonic governance approach, which combines hierarchical and network-centric approaches interchangeably, ensuring flexibility and control (Gorod, Hallo, Statsenko, Nguyen, & Chileshe, 2012). Hierarchical management is necessary to exercise the execution of the master plan with rigorous control mechanisms in place to facilitate the harmony, uniformity and consistency of projects (Shehu & Akintoye, 2009), while the network-centric approach is appropriate under complex conditions during which the project pivots in response to emerging challenges or changes in the political and economic environment.

Programmes require central control of projects and have the characteristic of sharing resources from one project to another within a programme since programmes tend to share common resources. There is an indication in the literature that centralising adequate resource management is one of the driving forces of efficient, effective programme management. Thus, providing standard resources (tools and techniques), infrastructure, and equipment is crucial. Actors should share and reuse elements within the programme to maintain quality, ensure a steady workforce supply, and make knowledge management more effective, helping save money and time (Shehu & Akintoye, 2009).

On the other hand, Bletsis proposes to apply a participatory system to improve the RRP results (Bletsis A. J., 2020). Participatory systems are distributed socio-technical systems enabled by ICT wherein the goal is to accomplish some collective mission based on the design values of trust (transparency, security, privacy, identifiability, traceability, accessibility, proportionality, reliability, robustness), engagement (interaction, presence, enactment,

communication, awareness, co-creation) and empowerment (autonomy, self-regulation for human actors and automated systems, self-organisation, emergence, ability to act and take responsibility) (Brazier & Nevejan, Vision for Participatory Systems Design, 2014). Participatory systems demand a certain degree of similarity between the actors' systems such that they are interoperable (Kurapati, et al., 2012).

Learning and Adaptability

Resilience has received increased attention as an ability for risk aversion and crisis control (Sawaragi, 2020). Researchers focus on the adaptive capacity to manage complexity (Luo, He, Jaselskis, & Xie, 2017). A programme must be able to address or anticipate contextual changes (Ritson, Johansen, & Osborne, 2012). These changes are conducted based on the fit between programme and organisational strategies, programme structure flexibility, and adaptability to its context (Shao, Muller, & Turner, 2012). Adaptability and the ability to generate learning effects across projects and organisations are considered essential to programme governance through collaboration, knowledge development, innovation sharing, and cross-project thinking to improve productivity and control (Rijke, et al., 2014). Adaptability and learning manifest in the project execution while maintaining feedback loops within the programme's organisation (Van Herk, Rijke, Zevenbergen, & Ashley, 2013).

Love proposes a systemic learning framework to reduce errors and failures (Lopez & Love, Design Error Costs in Construction Projects, 2011). Error prevention should be viewed as a continuous process rather than the result of isolated activities, involving the investigation and mapping of dependencies and interfaces that influence the error prevention process (Lopez, Love, Edwards, & Davis, 2010). Organisations can prevent many errors by adhering to proper quality, organisational and project management practices and providing an environment for individuals to learn from mistakes and act as learning organisations (Love, Edwards, & Smith, 2013). Organisational learning is the basis for adaptation and developing collective intelligence, and adaptation is the basis for viability and sustainability (Espinosa A. , 2022). Coping with problems, closely related to adaptation, builds the foundation for reflection, learning, and change. Information and knowledge sharing are essential to a resilient organisation (Duchek, 2019).

2.3.3 MBSE project direction

Underlying needs and recommendations

Project teams apply front-end activities to decrease the adverse effects of complexity on project performance (Bosch-Rekveltdt, 2011). To understand and measure the complexity, project teams should have a complexity measurement method to determine the correct management strategies (Luo, He, Jaselskis, & Xie, 2017). Generally, one decomposes the system into known subsystems and determines their relationship, integration, and interaction with surrounding systems to understand complexity better (Akundi, Tseng, Almeraz, Lopez-Terrazas, & Luan, 2021) and to decrease epistemic uncertainty (Menshenin, Moreno, Brovar, & Fortin, 2021).

Suggested approaches to improve integration are early involvement, trust, open communication, learning, knowledge sharing and collaborative working (joint problem-solving and risk management) (Suprpto, 2016). One should enable efficient information exchange to prevent underestimation or poor recognition of complexity in an earlier project, which often causes complexity to increase over time (Bosch-Rekvelde, 2011). Identifying lifecycle complexities and delivering an integrated design requires intense interdisciplinary collaboration (Sacks, Eastman, Lee, & Techolz, 2018). An integrated approach emphasises addressing project lifecycle issues early and allowing information to flow efficiently between disciplines (Halfawy & Froese, 2007). There is a significant need to synthesise knowledge across diverse expertise, roles and responsibilities to integrate interdisciplinary elements (Whyte, 2016).

One should apply strategies holistically to prevent safety problems, rework and disputes. Providing designers adequate time to produce documentation and implementing audits, reviews, and verification is insufficient to mitigate errors. Similarly, project teams that do not coherently apply constructability analysis, BIM, benchmarking, quality management, and risk management prevent errors only partly (Lopez, Love, Edwards, & Davis, 2010). Other strategies for design error reduction are instigating situated learning, computer technology, simplifying and standardising procedures, reducing individuals' reliance on memory, decentralised decision-making, and increasing project team communication (Love, Edwards, & Smith, 2013). To effectively minimise variations in construction projects, a combination of other appropriate emerging technologies with BIM along the construction process is required (Love, Teo, & Morrison, 2017). Nathan Eng proposes rationale mapping to increase communication and resolve problems related to the retrieval of design information (Eng, Marfisi, & Aurisicchio, 2011). As mentioned above, BIM neglects the functional design of objects. Behavioural modelling is one of the four main aspects of MBSE (requirements, system behaviour, system structure and parameters), which ensures the multidisciplinary integration of the desired behaviour of various elements (Morkevicius, Aleksandraviciene, Mazeika, Bisikirskiene, & Strolia, 2017). Moreover, MBSE significantly facilitates the execution of ISO 15288 life cycle processes (ISO - International Organization for Standardization, 2023).

MBSE benefits and requirements

ISO 15288 and Friedenthal list the benefits of executing system life cycle processes in an MBSE environment. Kelly X. Campo researched the benefits of MBSE from 60 academic sources and coded over 2900 claims (Campo, et al., 2022). Table 7 provides the three benefit lists.

Table 7 – MBSE Benefits of ISO 15288, Friedenthal and Kelly X. Campo

ISO 15288	Kelly X. Campo	Friedenthal
A more thorough understanding of the concept and system definition	Better communication	Enhanced communications
Better ability to perform trade-offs	Better analysis capability	Reduced development risk
More effective and efficient measurement	Improved system understanding	Improved quality
Better ability to perform impact analysis	Improved consistency	Increased productivity

ISO 15288	Kelly X. Campo	Friedenthal
Help ensure consistency and completeness of requirements	Reduce time	Leveraging the models during downstream lifecycle phases
Help ensure consistency and completeness of architecture and design	Increased efficiency	Enhanced knowledge transfer
Enable reuse and adaptability.	Better manage complexity	
Surrogate for verification and validation activities	Reduce cost	
Reduction of risk	Reduce errors	
Early detection of integration issues	Increased traceability	
Better understanding and management of dependencies		

Initial modelling of the solution concept helps identify the known unknowns and clusters of known knowns distributed among individuals and across teams. Furthermore, it allows the project team to communicate knowledge more efficiently and faster (Asan, Albrecht, & Bilgen, 2014). An initial model is mainly used to validate critical decisions about the system and mitigate specific technical risks early in the design process (Madni, Madni, & Lucero, Leveraging Digital Twin Technology in Model-Based Systems Engineering, 2019). One should consider that the effectiveness of MBSE increases by applying various activities across the life cycle. Thus, the proposed MBSE approach should consist of all essential SE activities working correctly in synergy (Madni & Purohit, Economic Analysis of Model-Based Systems Engineering, 2019).

Brazier shows that complex Socio-Technical System (STS) design and engineering management require well-established governance and states that it is essential that the project team revise the design requirements at every design stage due to new insights and external changes. Thus, an agile design approach capable of continual adaptation is desirable (Brazier, Langen, Lukosch, & Vingerhoeds, 2018). An agile approach to MBSE can help with stakeholder engagement, continual integration, and dynamic learning and evolution (Hause, 2023). Furthermore, a more agile MBSE approach could contribute to better managing change to project constraints, such as budget, scope and quality, and communication, enhancing satisfaction and results. Key benefits are improved engineering data quality, efficiency, stakeholder satisfaction, increased project control, responsiveness to change and project risk reduction (Douglass, 2016).

MBSE supports reusability and knowledge transfer. Two relevant reuse categories are codified knowledge and design effort reuse. Codified design knowledge refers to architectural concepts, physical principles, and interrelationships. Design effort encompasses the set of value-adding work products of the systems architecting process that capture and record design knowledge, digitised as MBSE system models, metamodels, and patterns. Standardised MBSE work products can be reused if designed correctly. MBSE is a powerful paradigm, and SysML is a powerful tool for developing and implementing a systemic approach to realising reuse benefits (Madni A. E., 2022). A model is considered (codified) knowledge if it formalises a modelling pattern, is reusable and customisable for various purposes, and acts as a container if it includes displays and contextualises data, information, and knowledge relevant to handling, sharing, and tracing (Alaoui, Rabah, Chapurlat, Richet, & Plana, 2022).

Explicit knowledge management utilizes four primary resources: Explicit knowledge repositories; Refineries for accumulating, refining, managing and distributing knowledge; organisation roles to manage the refining process; and information technologies to support explicit knowledge management (Zack, 1999), which are compatible with MBSE models.

Other industries

Moveable bridges are machines; therefore, to obtain insight into complexity management, the comparison is possible with mechatronics, having similar disciplines' designs (mechanical, electronic, software) and multi-disciplinary interactions (Cabrera, et al., 2010) (Faria & Barbalho, *Mechatronics: A Study on Its Scientific Constitution and Association with Innovative Products*, 2023). The mechatronics industry emerged around 1970 and could provide lessons for the infrastructure industry's moveable bridges and sluices. Furthermore, recent researchers compared the Architecture, Engineering and Construction (AEC) and the aerospace industry regarding, for example, multidisciplinary design optimisation (Muthumanickam, Brown, Duarte, & Simpson, 2023) and design management improvement (Eng, Marfisi, & Aurisicchio, 2011).

Biswanath Samantha defines mechatronics as a synergistic interdisciplinary integration of multiple engineering fields – mechanical, electrical and electronics, computer, control systems, and information technology – to design, develop, and test intelligent systems. Furthermore, mechatronics is an ideal field to incorporate systems thinking and data-information-knowledge-wisdom hierarchy through an integrated approach (Samanta, 2023). Cabrera states that model and data sharing is a vital issue to progress towards an overall solution and proposes a high-level function models as a base to a framework to support communication through tool and model integration (Cabrera, et al., 2010). Various researchers propose MBSE approaches to enhance the mechatronics multi-disciplinary design process (Zheng, Hehenberger, Duigou, Bricogne, & Eynard, 2017) (Mhenni, Choley, Penas, Plateaux, & Hammadi, 2014) (Vazquez-Santacruz, Portillo-Velez, Torres-Figueroa, Marin-Urias, & Portilla-Flores, 2023).

Life Cycle Considerations and Digital Twin

MBSE can contribute a variety of system modelling constructs that Digital Twins (DT) can exploit (Madni, Madni, & Lucero, *Leveraging Digital Twin Technology in Model-Based Systems Engineering*, 2019). DT is another upcoming ASE method in the infrastructure sector. There is no consensus yet among researchers and practitioners regarding how DT can support the design and construction of civil engineering constructions (Sacks, Brilakis, Pikas, Xie, & Girolomi, 2020) (Opoku, Perera, Osei-Kyei, & Rashidi, 2021). A DT can serve as a model and central information source within a circular project life cycle (Underwood, Goulding, Kurugolu, & Açikalin, 2009).

Asset Managers have to monitor objects, collect data and maintain constructions. Therefore, the proposed MBSE approach should be beneficial in storing and accessing the data in a model. Although the scope of this research does not include asset management as a significant topic, it is crucial to consider how improved asset management could contribute to better

engineering or design through SE. Moreover, the design model contains all vital information about the designed object. The model information should be accessible to and updateable for asset managers for more than a hundred years. Delligatti recommends selecting an XML Metadata Interchange (XMI) compliant tool (Modelio and Papyrus). XMI standard compliance enables the exchange of model data. This capability will ensure that the team avoids the vendor lock-in trap when it needs to change in the future (Delligatti, 2013). As mentioned above, MBSE provides modelling constructs that DT can exploit, and asset management experiences significant benefits from DT (Macchi, Roda, Negri, & Fumagalli, 2018).

The design of a safety-critical system, such as a movable bridge, requires an adequate prediction of its reliability, availability, maintainability, and safety (RAMS). Often, project teams perform the RAMS analyses once one has defined the product in terms of architecture, components, and materials. The safety assessment, requiring an evaluation, is practical, but it fully integrates safety analysis after completing the trade-off, which is too late, according to several authors. The resulting design synthesis could be ineffective and inefficient because of a lack of information about the system failures. Brusa proposes integrating Model-Based Safety Assessment (MBSA) with MBSE (Brusa, 2021).

Monitoring bridges' exposure conditions and performance could make better assumptions during the plan and design phase. Structural health monitoring systems are crucial for improving our understanding of LCC and the reliability of mechanical components (Catbas, et al., 2012), and systematic identification of LCC facilitates a holistic approach to cost-optimal design (Jensen, 2018). Frangopol and Soliman provide an integrated platform for civil and structural systems, combining different life cycle framework modules to establish optimum life cycle applications (Frangopol & Soliman, 2015). A DT, which uses an adaptive data structure and ontologies, can be applied to automatically produce the cost model from data-mined information throughout a product lifecycle (Farsi, Ariansyaha, Erkoyuncu, & Harrison, 2021). Moreover, DT has significant potential to contribute to circularity (Preut, Kopka, & Clausen, 2021). The product design directly affects the subsequent phases. Hence, developing a proper and accurate DT in the design stage can enhance reuse at the end of the life cycle by selecting the most sustainable and cost-effective solution performing scenario simulations and what-if analyses (Atta, 2023). DT is a data-driven concept, and it is vital to understand that digitalisation and sustainability goals rely on the excellent use and management of data. The ability to improve circularity in the construction industry relies on the capacity to capture the built environment- or construction-related knowledge, and the way to accomplish it is by perceiving and aligning digital data-driven concepts throughout the construction life cycle (Mêda, Calvetti, Hjelseth, & Sousa, 2021).

The interoperation of a physical facility and its digital components, such as digital twins, is called Digital Thread. The aim of the Digital Thread is the creation of a digital lifecycle ecosystem that links together the data generated throughout a product's lifecycle and represents the data, processes and communication platform that supports a product at any instance of time (Margaria, Pesch, & McGibney, Digital Thread in Smart Manufacturing, 2022). Digital Thread connects real things and their twin models, but also the communication

networks, the decision algorithms, and the visualisations needed to work in design, construction, and operation within a mature Industry 4.0 environment (Margaria & Schieweck, The Digital Thread in Industry 4.0, 2019). Having a well-established Digital Thread that holistically considers the entire construction project lifecycle and ecosystem is fundamental for the digital transformation of the industry. The data encompassed in the Digital Thread is essential for all stakeholders and supports short- and long-term decisions and could lead to better project predictability and performance, greater collaboration and transparency between stakeholders, and more standardisation of the industry (Hatoum, Nassereddine, AbdulBaky, & AbouKansour, 2023).

2.4 Findings from Interviews

This chapter presents an analysis of the key findings derived from a series of interviews conducted with industry experts and practitioners in the field of Model-Based Systems Engineering (MBSE), particularly within the context of infrastructure projects. The insights gathered from these interviews provide valuable perspectives on the challenges, opportunities, and future directions of MBSE, as well as their practical applications in complex infrastructure projects.

The summary of the interviews, detailed in Appendix C, were prepared based on discussions with professionals from various organisations. These discussions offer a nuanced understanding of the current state of data standardisation, integration, and the adoption of advanced digital methodologies in the industry.

Throughout this chapter, the findings have been organised into thematic areas that reflect the most critical issues and developments identified during the interviews. These include the complexities of renovation projects compared to new construction, the challenges of data standardisation and integration, the practical application of MBSE, and the cultural and organisational barriers that must be addressed for these methodologies to reach their full potential.

By synthesising the information from these interviews, this chapter aims to provide a comprehensive overview of the current landscape of MBSE in the infrastructure sector, offering insights that are essential for advancing research and practice in this field.

Complexity in Renovation versus New Construction

Increased Complexity in Renovation Projects: Renovation and replacement (R&R) projects present inherent complexities that are not typically encountered in new construction. These challenges primarily revolve around the integration of new systems into aging infrastructure, which is compounded by several key factors:

Incomplete or Inaccurate Documentation: Several interviewees emphasised that older infrastructure often lacks comprehensive and accurate documentation. This deficiency necessitates additional inspections and often forces engineers to make assumptions in design calculations, which increases the risk of errors and potential delays in the project timeline.

Preservation and Integration of Existing Structures: Interviewees also highlighted the challenges of preserving existing structural elements, such as the foundation of bascule bridges, while integrating new mechanical systems. This dual focus on preservation and innovation creates significant design and execution challenges that are unique to renovation projects.

Unforeseen Issues and Increased Risk of Failure Costs: Due to the unpredictability associated with older infrastructure, R&R projects carry a higher risk of encountering unforeseen issues. These issues can lead to increased costs and delays. The necessity to minimise downtime during these projects further intensifies the pressure on project management and execution.

System Optimisation versus Resilience: A crucial trade-off in infrastructure management is between system optimisation and resilience. Highly optimised systems, while efficient, tend to be less resilient, making them more vulnerable to disruptions. In the context of R&R projects, this trade-off is particularly significant. The ability to adapt to unforeseen challenges is essential, as small errors in an optimised system can lead to disproportionately large impacts.

Challenges in Data Standardisation and Integration

Variety of Data Standards: The industry faces significant challenges due to the large number of data standards in use, which has led to confusion and inefficiency. One interviewee explained how the extensive array of existing standards complicates the establishment of a unified approach. Despite ongoing efforts to promote standards and streamline data management, the sheer volume and diversity of standards create difficulties. This situation is particularly pronounced in the Netherlands, where public entities are increasingly adopting Linked Data for managing assets. The varied standards contribute to inefficiencies and make it challenging to integrate data effectively.

Integration of Standards like NEN 2660: The development of standards such as NEN 2660, which focuses on semantic modeling in the built environment, aims to address the fragmentation caused by varying modeling techniques. These standards provide guidelines on applying existing formats and languages for modeling assets, promoting consistency across different sectors. However, the challenge remains in ensuring that these standards are widely adopted and effectively implemented across the industry.

BIM and Linked Data Integration Challenges: The interviewee also discussed the ongoing efforts to integrate Building Information Modeling (BIM) with Linked Data, particularly through the Industry Foundation Classes (IFC) model. While IFC is a widely used standard in the construction industry, particularly for infrastructure projects, its integration with Linked Data faces significant hurdles:

- **Lack of Sufficient Software Support:** A notable challenge is the shortage of developers specialising in integrating IFC with Linked Data. To address this, new standards such as NEN 2660 are being developed to guide this integration and ensure effective use of Linked Data with IFC models. IFC data can be encoded in various formats, including XML and JSON. IFC-XML supports text-based data interchange, making it

compatible with XML-based systems, while IFC-JSON provides a lightweight and human-readable format that facilitates integration with modern web technologies. Despite these developments, the tools and standards are still evolving, and significant progress is needed to bridge the gap between different technologies and approaches.

- **Complexity of Linked Data:** Linked Data, while powerful, is inherently complex. Its effective adoption in the industry requires extensive training and the development of new tools to manage this complexity.

Application of MBSE

Practical Applications and Industry Collaboration: MBSE and Linked Data are increasingly being applied across various infrastructure projects to streamline data management and enhance collaboration among stakeholders, though these practices are still in their early stages. Key applications include:

Proof of Concept for a Public Infrastructure Client: One project involved integrating data from multiple sources into a single system, aiming to unify various data elements related to a major bridge. Although it is in the early stages, the approach focuses on improving asset management by consolidating structured data and documents. It facilitates easier access to essential information through a unified interface, enhancing how data and information are accessed and managed.

PALLAS Reactor Project: Leo van Ruijven (Croonwolt&eros) highlighted the PALLAS reactor replacement as another proof of concept for Linked Data. This project involved the use of a unified data environment aligned with international standards, as shown in Appendix F.2, which includes the presentation by Leo van Ruijven for further information on the specific standards applied. The project ontology developed for this initiative supports MBSE, digital twins, and asset lifecycle management, demonstrating the practical application of Linked Data in a complex, safety-critical infrastructure project.

Role of Relatics and SEm Model: One technology provider has developed the Systems Engineering model (SEm), a standard data model for MBSE designed to facilitate interoperability and adherence to ISO and W3C standards. While Relatics is widely used for data and information storage and requirements management, its role in deep systems integration remains limited. One interviewee emphasised the importance of storing models as graphs to enhance reusability and facilitate communication between different software tools.

SysML in Tunnel Systems: The application of SysML has been notably successful in managing the complexity of tunnel systems in the Netherlands. SysML's capability to model intricate system interactions and behaviours has proven valuable in addressing the challenges inherent in such dynamic and complex infrastructure projects. The use of SysML has facilitated effective system design, simulation, and integration in these projects.

MBSE and BIM Application in a Major Airport Project: One interviewee from a construction company described how MBSE was crucial for managing the complexity of a large airport project. By using digital models, MBSE provided a structured framework that ensured design

agreements were adhered to and any changes were systematically tracked. This approach was vital for managing the performance contract, as it allowed the project team to monitor compliance with performance criteria effectively. The integration of MBSE with BIM facilitated complex system interactions, streamlined lifecycle management, and supported effective design, construction, and maintenance throughout the project.

Use of 3D Models for Verification and Stakeholder Involvement: Another interviewee explained how 3D models played a crucial role in their projects. These models were used for verification and validation by simulating various aspects of the infrastructure, such as the visualisation of camera placements in tunnels and interactions with the operation of sluices. This approach ensured design accuracy and compliance with project requirements. Additionally, 3D models facilitated stakeholder involvement by providing an interactive and detailed representation of the project, which was instrumental in communicating complex design elements and gathering feedback from various stakeholders.

Digital Twins and Their Role

Sophisticated Data Integration through Digital Twins: Digital Twins represent a significant advancement in data integration, offering a sophisticated means of centralising and unifying data from various sources. Projects like the Digital Twin of a major Dutch bridge and the PALLAS reactor replacement, as mentioned by van Ruijven, demonstrate the potential of this technology to enhance asset management and lay the groundwork for more advanced applications in the future.

Challenges in Real-Time Data Integration: While integrating real-time data into Digital Twins (such as strain measurements from sensors) holds promise for dynamic infrastructure management, it is not always necessary or feasible. One interviewee noted that the decision to incorporate real-time data depends on the specific needs of the project, and in many cases, the focus remains on centralising existing data for more efficient management.

Organisational and Cultural Challenges

Cultural Resistance to New Methodologies: The adoption of MBSE, Linked Data, and other advanced digital methods is often met with resistance within organisations and across the broader industry. Several interviewees highlighted the need for a cultural shift to embrace these new approaches. This resistance is particularly evident among asset owners who often prefer traditional document-based methods over more dynamic, model-based approaches.

Need for Industry-Wide Standardisation and Collaboration: The interviews underscore the importance of industry-wide standardisation and collaboration to overcome the challenges of adopting MBSE. There is a pressing need for concerted efforts by clients, consultants, and contractors to work together towards common standards and methodologies, as the lack of a universal Object Type Library (OTL) or common language hinders seamless integration and collaboration across projects.

Collaborations with Industry Players: Research and technology organisations are working closely with public utilities and contractors to develop ontologies (structured frameworks for

organising information). These collaborations are essential to ensure that the models developed meet the diverse needs of various infrastructure projects.

Long-Term Strategic Approach: One consultancy adopts a long-term strategic approach to enhance product development processes, including infrastructure projects. Their strategy emphasises integrating diverse engineering disciplines and improving collaboration across different stages of a project. They advocate for strategic experimentation to continuously refine MBSE practices. This focus on cross-discipline integration and ongoing experimentation underscores the broader cultural shift needed for the successful adoption and implementation of MBSE.

Future Directions and Scalability of Linked Data

Scalability and Performance Issues in Linked Data: Linked Data faces significant challenges in terms of scalability, particularly when handling large or dynamic datasets. While traditional relational databases might offer more efficient performance in some cases, advancements in database technologies are gradually improving the scalability of Linked Data solutions. One interviewee mentioned that new developments in Linked Data technology are enabling it to handle larger datasets more efficiently, suggesting that these scalability issues may be mitigated in the future.

Need for Education and Training: There is a strong need for more education and training in the industry to build the necessary skills and knowledge for effectively implementing MBSE and Linked Data. The same interviewee emphasised the importance of demonstrating the practical benefits of these technologies to encourage broader adoption and overcome scepticism. This is crucial as the industry is still in the early stages of embracing these methodologies. For example, one interviewee described how a project team demonstrated the advantages of working with models to a contractor, which led to the contractor adopting and using this approach to enhance their design processes. Such practical demonstrations help to showcase the tangible benefits of MBSE, facilitating their acceptance and integration into industry practices.

Impact of Contracts and Risk Management

Challenges in DBFM Contracts: DBFM (Design, Build, Finance, and Maintain) contracts offer significant benefits, such as incentivising long-term infrastructure functionality, but also present unique challenges. Interviewees highlighted the difficulties in ensuring that all stakeholders, including designers, contractors, and maintenance teams, are aligned with the overall project goals. Misalignment can lead to increased costs, delays, and inefficiencies, particularly when different tools or methodologies are used by different teams.

Risk Management in Large Infrastructure Projects: The shift towards MBSE is seen as a way to better manage risks in large infrastructure projects. One interviewee explained how MBSE can help reduce ambiguity and misinterpretation by providing a clear, agreed-upon model that captures all requirements and system interactions. However, it was also noted that while MBSE can significantly reduce the scope of undefined elements, it is not a complete solution, as there will always be factors that fall outside the scope of the model.

Software Tools and Methodology Integration

Several interviewees discussed the limitations of current software tools in supporting MBSE and complex infrastructure projects. Modelling languages such as SysML, implemented through platforms like Enterprise Architect, play a crucial role in managing the complexity of dynamic systems by capturing a wide range of system behaviours and relationships. SysML's versatility allows it to be applied across various aspects of system design, from object trees to behavioural models. Notably, SysML's effectiveness has been demonstrated in complex projects, such as tunnel systems, where it has proven valuable in managing complex system interactions.

However, some interviewees emphasised the importance of distinguishing between the modelling language (SysML) and the tools used to implement it. While SysML provides the framework, tools like Enterprise Architect facilitate the creation and manipulation of models. Despite their capabilities, SysML and Enterprise Architect, along with other tools like Relatics and BIM, are not universally optimal. This highlights the need to critically evaluate and select the most appropriate tool based on the specific project requirements and challenges. The integration of tools often requires manual adjustments, which can lead to inefficiencies and potential errors. This underscores the need for more adaptable and robust solutions that can seamlessly integrate various methodologies and technologies across projects. Addressing these challenges involves advancing software integration to enhance the management and execution of complex infrastructure projects, ensuring that the tools used align effectively with project requirements and complexities.

The Role of Standards and Ontologies

Adoption of International Standards: Leo van Ruijven (Croonwouter&dros) emphasised the importance of adopting international standards, such as ISO 15926-11 for industrial data integration and ISO/IEC 81346 for project breakdown structuring. These standards are crucial for establishing a Common Data Environment (CDE), which integrates various breakdown structures into a unified framework, improving data management and communication among stakeholders.

Development of Ontologies for Data Integration: Van Ruijven also discussed the development of project ontologies aligned with ISO 15926-11, which support MBSE, digital twins, and asset lifecycle management. These ontologies, along with technologies like RDF (Resource Description Framework) and SPARQL (SPARQL Protocol and RDF Query Language), are essential for managing the relationships between different data elements and ensuring a coherent and integrated data environment.

SysML's Limitations: Several interviewees noted that while SysML has proven effective in some applications, such as tunnel systems, it has limitations. Specifically, they pointed out challenges related to tracking changes and decisions and reusing models. These issues highlight the need for ongoing development and refinement to address these shortcomings. Due to these limitations, some interviewees expressed a preference for Linked Data over

SysML, as Linked Data offers more robust solutions for managing and integrating complex information.

Future of MBSE and Linked Data in Infrastructure

Potential of Digital Twins and Linked Data: The future of MBSE and Linked Data in the infrastructure sector looks promising, with Digital Twins playing a key role in managing the lifecycle of infrastructure projects. As highlighted by van Ruijven and one interviewee, Digital Twins can provide a detailed and up-to-date view of infrastructure components, supporting real-time monitoring, predictive maintenance, and more efficient asset management.

Overcoming Organisational and Cultural Barriers: For MBSE and Linked Data to reach their full potential, the industry must overcome significant organisational and cultural barriers. This includes not only adopting new technologies but also fostering a mindset of collaboration, continuous learning, and adaptation. Strong leadership and a clear vision for integrating these technologies into existing workflows are essential for driving this transformation.

2.5 Integrated Synthesis: Findings

MBSE is a promising tool to address the sector's complexity challenges and increase the programme capacity. Its implementation must be gradual, evolving toward more advanced applications such as Digital Twins, Digital Threads, and system reusability. Initial improvements should focus on practical, short-term benefits that enhance the current situation, particularly by strengthening integration and communication between disciplines and with clients. This involves improving clarity through abstract and unambiguous language, integrating currently used tools, and reinforcing traceability and structured information distribution.

Simultaneously, MBSE must support knowledge diffusion across the programme, facilitate inter-project collaboration, and enhance governance capabilities. These improvements require a shift in mindset towards programme-based thinking and shared ownership, where clients and organisations work together to build a resilient, learning-focused infrastructure sector. Achieving this also involves creating sector-wide understanding of Linked Data principles and moving through a phased process to ensure the right digital and human resources are in place.

Table 8 provides a concise overview of key Dutch infrastructure Renovation and Replacement Programme challenges and MBSE approaches; a more interpretative analysis is available in Appendix A.6, and the full structured version in Appendix A.7. These challenges not only hinder project performance but also result in structural inefficiencies at the programme level, ultimately affecting the sector's overall capacity to deliver renovation and replacement works on time and within budget. The table systematically aligns each problem with a corresponding MBSE-based solution approach, outlines the conditions required for successful implementation, and describes the anticipated benefits of MBSE. In doing so, it offers a viable pathway toward a more collaborative, data-driven, and resilient infrastructure programme.

The answers to Research Question 1 and Research Question 2 are elaborated in Chapter 5.1.1, directly reflecting the content and findings discussed throughout this chapter.

Table 8 – Infrastructure Sector's MBSE Challenges, Solution Approaches, and Conditions

Category	Problem Statement	Solution Approach	Conditions for Solution
Team Collaboration	Project teams face challenges in effective coordination, leading to misinterpretations and insufficient interaction.	Implement MBSE to establish a culture of collaboration and open communication across disciplines.	Trust-building across organisations, enabled by regular, structured communication.
Lifecycle Design	Time constraints limit interdisciplinary lifecycle design consideration.	Apply a holistic MBSE approach aligned with ISO 15288 and its Three Pillars.	Sufficient time and budget to support lifecycle-wide modelling.
Information Distribution	Stakeholders and disciplines face insufficient information flow.	Use MBSE to enhance communication and knowledge transfer, acting as a single source of truth.	Centralised, consistent information access across disciplines.
Design Quality	Design checks and reviews are insufficient, leading to inadequate quality assurance.	Use MBSE to improve progress tracking and design quality management.	–
Software Utilisation	Underutilisation of existing software alongside MBSE.	Integrate MBSE with tools like BIM, supported by proper training.	Comprehensive training in MBSE and tool interoperability.
Agility	Variations from the client side increase errors due to late-stage communication.	Use MBSE for early validation, simulation, and adaptive design.	–
Governance	Repeated design errors due to lack of organisational learning tools.	Encode knowledge in MBSE models to promote learning and error prevention.	A culture that supports learning and experimentation.
Organisational Collaboration	Limited collaboration due to siloed systems and high competition.	Use MBSE to support shared models and inter-organisational learning.	Trust, balanced competition, and participatory system alignment. (Bletsis A. J., 2020)
Standardisation & Reuse	No structured reuse of requirements or design components.	Implement MBSE modularisation and structured component frameworks.	A clear framework for component reuse and model standardisation.
Technical Systems Integration	BIM fails to capture full system interactions in complex designs.	Combine MBSE with BIM for early, holistic integration of systems.	Integration of MBSE with BIM and early alignment of technical disciplines and functionalities.
Traceability & Impact	Poor traceability and unclear impact relationships between system elements.	Model system relationships in detail using MBSE.	–

Chapter 3: Development and Illustration of the MBSE Framework

3.1 Strategy, Needs and Key Quality Metrics

To assess the viability and feasibility of Model-Based Systems Engineering (MBSE), including its conditions, and to compare it with the current Document-Based Systems Engineering (DBSE) approach, it is necessary to understand the concept of current MBSE applications and how MBSE contributes to future goals and desires. Therefore, this study provides a possible and practical combination of tools within a MBSE framework to enable the assessment. An analysis inventarises the MBSE tools in the infrastructure sector to provide an essential selection tools for this research. The next paragraph clarifies what determines the combination of models preferably integrated and interoperated to enhance consistency and traceability which lacks in the current Document-Based approach. Yet, procedures involving human actions are required, enhanced by the tools (Estefan, 2008), to enhance collaboration and a coherent federated model. One has to consider the pragmatism of integrating models, since mapping across different ontologies is not a trivial task and becomes increasingly complex with the growing number of federated data models (Moretti, Xie, Garcia, & Parlikad, 2023). This research focuses on the selection of tools used in the MBSE framework to establish a coherent and interoperable solution. Additionally, it discusses how other software tools, listed in Appendix B.2, may be integrated to complement the framework or support additional objectives, such as the development of a Digital Twin.

Based on the problem analysis, Table 9 provides the Key Qualitative Metrics (KQM), aligned with the infrastructure sector's needs, used to qualitatively evaluate the MBSE solution. The full extended version of this table is available in Appendix B.2. The study explores how the sector must implement the KQM related conditions required for a feasible and viable MBSE application. Also, the KQM ensure complete SWOT Analysis input as part of the evaluation. A quantitative study was not conducted due to the exploratory and context-specific nature of the research, which focuses on complex organisational and technological transitions that are not yet mature enough to be meaningfully captured through quantifiable indicators. Additionally, the development of measurable working examples in case studies was not feasible within the available timeframe.

Utilising MBSE models over the entire life cycle, constructed at the design phase, provides the largest Return on Investment (ROI) considering that project teams approximately spend to design, construction and maintenance, 1%, 25% and 74% respectively (MacLeamy, 2010). For understanding this research's MBSE development it is important to emphasise again that MBSE means that clients, contractors and other stakeholders utilise integrated models, instead of documents, over the entire life cycle for SE (related) activities. ISO 19650 establishes a framework for the organisation and digital management of lifecycle information, compelling project teams to consistently manage and exchange information throughout the entire lifecycle

of infrastructure projects. During the design phase, specific trigger events often occur at the end of design stages and, at times, during the operational phase, which initiate the exchange of information. Consequently, the integration of the MBSE framework with the Common Data Environment (CDE) becomes essential. This integration ensures the comprehensive coverage and accessibility of all relevant lifecycle information for all stakeholders, streamlining information management practices to enhance both efficiency and effectiveness across the project's lifecycle.

Increased programme capacity can be achieved in various ways, as explained in the problem analysis, including by reducing design mistakes and improving the sustainability and maintainability of infrastructure assets through structured information storage and reuse. This allows programme managers and project teams to query relevant data for programme and project enhancement. The MBSE approach must wholistically facilitate the need for capacity increase to reduce the bridges' down-time. The MBSE models contain the system's life cycle information and must provide the governing organisation with information about the progress, internal and external context on which it can react (Brazier, Langen, Lukosch, & Vingerhoeds, 2018).

The study demonstrates how (environmental) changes, such as specification changes, are managed differently by considering the technical state of the moveable bridge using MBSE. The success of MBSE managing complexity hinges on its ability to provide a comprehensive and integrated view of the entire system through graphical models and systematic abstraction enhancing complexity management. Theoretically, enhanced integrated multi-disciplinary design decisions considering risks reduces problems associated with the operation and performance (Catbas, et al., 2010). Furthermore, engineers must make greater use of the knowledge gained to consider designing for inspection and maintenance on new bridge projects and exchange more information with owners and operators regarding durability, inspection and maintenance (Colford, Beabes, & Bulmer, 2019), supporting the need for enhanced information and knowledge diffusion. Project organisations must share and utilise the models over the infrastructure work's life cycle phases, described as design, manufacture, construction, maintenance and use, disposal, and recycling (Kubler, Buda, Robert, Främling, & Traon, 2017) and between organisations. Therefore, relevant information and data storage in a traceable, integrated, accessible and maintainable manner is crucial. A crucial benefit of using models to exchange information between project and programme organisations is that one reduces the difficulty of forming a mental model of the complex situation. Forming mental models based on textual documents for information exchange often demands significantly more time and effort compared to utilising high-quality MBSE models. Preferably, stakeholders over the entire life cycle have their specific and limited view on model information. Organisations joining the programme must identify relevant information for each stakeholder to support effective information management.

Table 9 - Key Qualitative Metrics (KQM) for Feasibility and Viability Evaluation

KQM	Qualitative Assessment	Need	MBSE Success Condition
Collaboration & Communication	Assess how MBSE improves interdisciplinary collaboration and communication clarity.	Enable seamless collaboration and consistent information flow across disciplines.	Provide an integrated communication environment with real-time data exchange to support systems engineering and governance processes.
Flexibility & Adaptability	Examine MBSE's handling of design changes and evolving requirements.	Capture full lifecycle considerations and allow for requirement changes with follow-up design adjustments.	Implement a dynamic system architecture that enables flexible change management and supports lifecycle-wide model use.
Error Reduction & Accuracy	Evaluate MBSE's potential to reduce errors through integrated modelling.	Improve risk control by aligning statical, functional, and behavioural models.	Ensure consistency and accuracy across models by adopting a Common Data Environment (CDE) and a Reference Data Library (RDL).
Traceability	Investigate how MBSE supports requirement and change traceability.	Provide lifecycle-spanning traceability of decisions, requirements, and system changes.	Enable end-to-end traceability using interoperable tools with structured element interrelationships.
Organisational Readiness	Assess cultural and structural readiness for MBSE adoption.	Stimulate learning and openness across teams and organisations.	Foster an adaptive, experiment-driven culture supported by continuous MBSE training and iterative development.
Management Support	Evaluate leadership commitment to MBSE initiatives.	Ensure adequate resource allocation and long-term support.	Provide strong managerial backing and structural investment in MBSE adoption and tool integration.
Sector Collaboration	Assess the sector's potential for inter-organisational model sharing.	Enable secure, standardised and open exchange of models and knowledge across organisations.	Establish open standards for model and data sharing to ensure interoperability, data protection, and prevent vendor lock-in.
Strategic Alignment	Evaluate alignment of MBSE with strategic goals like innovation, sustainability, and scalability.	Support future-proof infrastructure renewal and reuse of standardised components across projects.	Align MBSE implementation with long-term strategy, using open data and open architectures to prevent vendor lock-in.
User Experience	Explore the impact of MBSE on user and operator satisfaction.	Ensure systems reflect the needs of users, operators and maintenance teams.	Continuously involve end-users and maintenance actors in model development and feedback cycles.
Financial Implications	Estimate qualitative returns in terms of efficiency, design quality, and lifecycle optimisation.	Improve long-term value through reduced errors, improved collaboration, and better lifecycle planning.	Align investment decisions with MBSE's potential for return on investment across the project lifecycle.

3.2 Linked Data Framework: Application and Organisational Considerations

The central goal of this study is to assess the feasibility and viability of MBSE through a holistic qualitative evaluation. By critically examining the limitations of traditional document-based approaches and their inability to meet evolving infrastructure demands, this research investigates the added value of a model-based alternative. At the core of the proposed MBSE solution lies the integration of Semantic Linked Data, which forms the foundation for improved information flow, traceability, and lifecycle collaboration. This study demonstrates how Linked Data technologies, based on RDF and RDFS, serve as the backbone of a Common Data Environment (CDE) that supports both technical and organisational needs within renovation and replacement programmes.

The Semantic Linked Data CDE is positioned as a necessary enabler for improving programme outcomes by addressing fragmentation, supporting continuity, and enhancing governance across project stages, including structured and informed decision-making. Through structured access to lifecycle data, shared standards, and lessons learned, it improves both individual project performance and programme-level coordination.

To support this, the study integrates several complementary tools: SysML for system modelling, Relatics for requirement management, and Autodesk Revit for BIM-based spatial modelling. While these tools are already familiar within the infrastructure sector, their integration into a Linked Data-driven framework allows them to move beyond isolated, document-based use. It is crucial to acknowledge that the flexibility in configuring MBSE tools around the Semantic CDE is essential to accommodate varying project needs and innovation cycles. This flexibility not only enables ongoing experimentation and refinement but also fosters a competitive environment in which companies are encouraged to seek the most effective tool configurations to increase efficiency and performance.

Accordingly, this chapter will first briefly introduce the technical and organisational integration of SysML, Revit, Relatics, and several other complementary tools. However, the primary focus lies on the in-depth development and exploration of the Semantic Linked Data CDE, which is positioned as the crucial integrative component enabling MBSE to meet the interdisciplinary and long-term demands of infrastructure programmes.

3.2.1 Semantic Technologies (Linked Data)

The adoption of semantic technologies – such as the Resource Description Framework (RDF), RDF Schema (RDFS), and supporting standards – forms the core of the MBSE framework by enabling the centralisation of data from diverse sources into a unified, machine-readable structure. This foundational capability ensures semantic interoperability across tools and organisations and supports consistent information handling throughout the lifecycle. By leveraging subject-predicate-object triples (Linked Data), semantic technologies provide a flexible and standardised way to model, query, and reason over data. This not only facilitates

cross-domain integration and automation but also enhances human understanding and decision-making. A triple comprises at least an object called “subject”, a predicate (property) that represents a relationship between a subject and an object or data called “object”. Leo van Ruijven designed and successfully applied a RDFS based semantic Common Data Environment (CDE) for managing of engineering and facility life cycle data of a medical isotope production plant (Van Ruijven, 2023). The ISO 19650 and 15925-11 compliant CDE uses semantic technology to interconnect, integrate and structure multi-disciplinary data, enables the information and data washed exchange between disciplines and aligns the “as required, designed, as is”, ensuring up-to-date and consistent data and information. Also, consortium INTERLINK has researched asset information management for European Roads life-cycle management using Linked Data, including an Object Type Library (OTL), and provided proof-of-concept through different applications (Luiten, Böhms, Alsem, & O’Keeffe, 2019). Leo van Ruijven and the INTERLINK consortium provide proof-of-concept of semantic technologies within project applications, thereby motivating the use of semantic technologies in this research. Rijkswaterstaat (RWS) standardises asset information using an OTL, a practical and up-to-date information model constructed with Linked Data. For each type of object within the RWS area, a clear and consistent description is defined, specifying the necessary characteristics and the relationships between objects. The OTLs are structured according to four key standards: NEN 2660 for data organisation, NEN 2767 for condition assessments, SATO for specific tunnel design aspects, and UTD for uniform technical breakdowns. The approach by RWS ensures a common language, facilitating the easy comparison and integration of data, thereby enabling more effective management and maintenance of assets throughout their entire lifecycle (Rijkswaterstaat Ministerie van Infrastructuur en Waterstaat, 2024).

Fig. 8 illustrates the Semantic Web Technology Stack (SWTS), a conceptual framework delineating the layers or technologies constituting semantic technologies (Krieger & Rösner, 2011). Each layer builds upon the capabilities provided by the layers beneath it, and this hierarchical structure is essential to understand the dependencies and data flow. Infrastructure organisations should prioritise the consideration and implementation of SWTS technologies to ensure a complete and robust application of semantic technology within their MBSE environment.

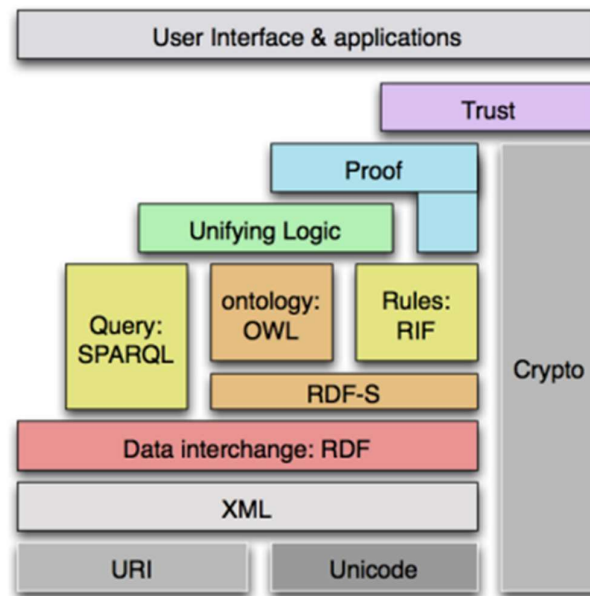


Figure 8 – Semantic Web Technology Stack (Krieger & Rösner, 2011)

URI, Unicode and XML

Uniform Resource Identifier (URI) and Unicode form the foundation because everything else in the stack relies on the ability to uniquely identify resources and represent information in a standardised textual form through Unicode. RDF is the core standard for encoding, exchanging, and linking data through triples (subject, predicate and object) across the web. RDF provides a flexible and extensible way to model data and express relationships between resources. Linked together triples form RDF graphs, where nodes represent resources and edges relationships between them. The graph structure allows for the representation of complex data and semantic relationships, enabling interoperability and integration across diverse datasets and applications. Developers often use Extensible Markup Language (XML) as serialisation format for RDF that can be easily shared, stored, or transmitted between different systems. Serialisation is not limited to XML. There are several serialisation formats available for RDF and the W3C Web Ontology Language (OWL) beyond XML. The choice of format depends on the specific requirements.

RDF, RDFS, SKOS, SHACL and OWL

The ontology layer defines the vocabulary and the structure of the data. RDFS provides basic mechanisms, and OWL adds more expressive power for complex modeling an relationships. RDFS enhances RDF by allowing more structured and semantically rich data modelling. RDFS enriches RDF by offering additional attributes and capabilities. RDFS enables the categorisation of resources into classes and subclasses, introduces constraints on properties, and provides mechanisms for labeling and commenting. RDFS supports property inheritance and facilitates semantically rich data modeling, allowing for the development of ontologies. These features enable not just data storage but also knowledge inference. Since RDF and RDFS inherently support the creation of hierarchies and taxonomies due to their ability to define classes, subclasses, and properties, making them suitable for generating breakdown

structures. Semantic technologies provide a standardised manner to represent, store, retrieve, and reason about data, enabling enhanced interoperability, integration, and knowledge discovery across diverse datasets and applications.

SHACL (Shapes Constraint Language) is a W3C standard used to validate RDF data against a set of conditions or "shapes." SHACL adds an essential layer of data validation to the semantic technology stack, ensuring that RDF data adheres to defined rules and structures. It enables the specification of constraints on the kinds of values that RDF nodes can have, such as types, cardinalities, or patterns. SHACL's ability to enforce data integrity by checking whether data conforms to specified shapes enhances the reliability of the data models and supports robust data governance. Implementing SHACL within an MBSE framework ensures that the complex relationships and constraints modeled in OWL or RDFS are consistently maintained across different data sets, promoting data quality and reducing errors during data exchange.

Implementing a Reference Data Library (RDL) in infrastructure projects profoundly enhances asset management and project efficiency. Utilising RDF and RDFS, the RDL fosters an interoperable, semantically rich data framework crucial for consistent data interpretation and management across projects. Serving as a central repository, it contains standardised definitions and classifications that streamline communication, ensure documentation accuracy, and facilitate industry standard compliance. Crucially, the RDL standardises the implementation of semantic technologies, promoting a shared understanding among stakeholders regarding object names and attributes, which is vital for maintaining a common language and framework.

OWL builds on the foundation provided by RDF and RDFS (RDF Schema) to offer a more expressive framework for semantic modeling. While RDF and RDFS lay the groundwork for creating structured, linked data on the web by defining basic elements like resources, properties, and classes, OWL introduces a richer set of modeling features designed to capture more complex relationships and constraints among data. This enhanced expressivity is particularly advantageous for the renovation and replacement programme within a Model-Based Systems Engineering (MBSE) framework.

The Simple Knowledge Organization System (SKOS) significantly extends the foundational capabilities of RDF and RDFS, providing a more nuanced approach for representing knowledge structures and facilitating the capture of complex, associative relationships between concepts, particularly crucial in environments where the interconnectivity of data play a vital role. SKOS introduces a layer of flexibility and expressiveness that surpasses the hierarchical and structured data modeling constraints of RDF and RDFS, enabling the depiction of richer, multidimensional relationships. By leveraging its relational properties and enriched metadata capabilities, SKOS enhances semantic interoperability and the discovery of linked information, enabling a deeper and more structured articulation of knowledge. SKOS supports multilingual labeling and facilitates interoperability across diverse datasets with properties.

SPARQL, RIF and SWRL

Integrating OWL (Web Ontology Language) within a Semantic Common Data Environment (CDE) significantly advances the efficiency of Systems Engineering (SE) practices by facilitating integration and automatic reasoning of requirements throughout the asset lifecycle. This dynamic assessment capability ensures real-time evaluation of system compliance with stakeholder expectations, enabling proactive decision-making to address discrepancies or enhance operational performance.

The Semantic CDE, underpinned by the structured semantic foundation of the Reference Data Library (RDL), supports efficient planning and lifecycle management of infrastructure assets. The Semantic CDE ensures data related to standardised bridge components, maintenance protocols, and operational metrics are uniformly defined and accessible. Crucially, the RDL's semantic foundation not only enhances decision-making and operational efficiency through advanced analytics and predictive maintenance but also ensures the standardised application of semantic technologies across the sector.

The integration of rule-based systems, such as SWRL (Semantic Web Rule Language) and RIF (Rule Interchange Format), at the governance level, plays a vital role in improving asset management practices. By embedding these systems within the governance framework, organisations can automate and refine decision-making processes, ensuring that asset management strategies are both effective and aligned with overarching objectives. This approach enables the proactive identification of maintenance needs and enhances the allocation of resources, thereby increasing the program's capacity. Automated decision-making and knowledge inference from predefined rules ensure that maintenance and SE practices are both proactive and informed by comprehensive data analysis. This approach is critical for effective decision-making and prioritisation, thus enhancing the overall efficiency and effectiveness of infrastructure management.

SWRL is a powerful language used to express rules that can be combined with OWL ontologies, significantly extending the semantic modeling capabilities. And RIF, as a W3C-recommended standard, is designed to enable the interoperability of rules across different systems, enhancing the Semantic Web's infrastructure. The main idea behind rule exchange through RIF is that the different systems will provide syntactic mappings from their native languages to appropriate RIF dialects and back. These mappings are required to be semantics-preserving and thus rule sets and data could be communicated by one system to another provided that the systems can talk through a suitable dialect, which they both support (Kifer, 2018).

In assessing the adoption of OWL for project and governance frameworks, program managers must weigh the need for OWL's semantic sophistication and advanced reasoning capabilities against its complexity, particularly for teams new to semantic modeling. OWL, offering a semantically richer language with enhanced reasoning capabilities beyond RDFS, presents a more complex framework that may pose challenges for project teams lacking experience in semantic modeling. At the governance level, however, the application of OWL could yield significant advantages. The complexity inherent in managing the lifecycle of multiple assets, along with the necessity for intricate relational definitions and reasoned decision-making,

aligns well with OWL's strengths. Given that OWL is built upon RDFS, project teams have the flexibility to evolve their RDFS models into more complex OWL-based models as their familiarity and requirements grow. The semantic technology's scalability allows for a tailored approach to semantic modeling, accommodating both immediate needs regarding MBSE and future expansions.

OWL's precise semantic modeling capabilities ensure data consistency and support governance frameworks by maintaining standardised data definitions across projects. The reliability of this data underpins effective governance, enabling program managers to gain a comprehensive overview of the assets' current state. Furthermore, the application of SPARQL enhances project execution and governance by enabling targeted data queries, which support monitoring compliance, assessing asset performance, and ensuring adherence to maintenance schedules. Furthermore, SPARQL (SPARQL Protocol and RDF Query Language) empowers project teams to leverage information and data from similar projects, facilitating the improvement of their own projects through the strategic use of collective knowledge. By querying stored information in semantic models, teams can identify best practices, lessons learned, and innovative solutions that have been effective elsewhere. This not only accelerates project development by avoiding common pitfalls but also fosters a culture of continuous improvement and knowledge sharing within and across organisations.

Unifying Logic

The Semantic Web Technology Stack's Unifying Logic layer is the backbone for ensuring that different systems can apply logic consistently. It achieves this through standards like Rule Interchange Format (RIF) and Semantic Web Rule Language (SWRL), which allow for the expression and exchange of rules across diverse ontologies. The inclusion of a Reference Data Library (RDL) within this layer further unifies logic by providing a set of standard definitions and classifications, ensuring that the logic applied is based on a shared understanding of terms and structures across different projects. Together, these components facilitate interoperability and sophisticated reasoning across the web of data, crucial for the governance and asset management.

To ensure the effective integration of rule-based systems within the MBSE framework, focus on the alignment of ontologies and rules, data quality management, expert crafting of rules, and the use of clear logic constructs. Ensuring consistency in definitions across ontologies and employing a shared vocabulary are crucial for accurate rule application. Expert involvement in rule development guarantees completeness, relevance and precision, while maintaining data integrity enhances rule engine performance. Validating and cleansing the data regularly helps maintain high-quality inputs for the rule engine, reducing the risk of incorrect inferences.

Proof and Trust

Integrating the Proof and Trust layers into the Semantic Web framework significantly enhances the system's capacity to manage and interpret complex data with high levels of integrity and security. These layers, each serving a distinct yet complementary function,

employ a variety of strategies and technologies to achieve their objectives, ensuring that the information processed and shared is both reliable and trustworthy.

The Proof layer, foundational to the Semantic Web, utilises formal mathematical proofs to verify the logical consistency and validate the data derived through inference engines. The Proof layer plays a crucial role in guaranteeing that conclusions derived from semantic data are consistent with predefined ontologies, thus confirming the data's accuracy and reliability. To achieve this, the Proof layer utilises reasoning engines that analyse complex ontologies to automatically verify data relationships and inferences. These engines are essential not just for verifying data consistency but also for validating the emergence of new relationships, facts, and classifications, significantly enhancing the system's knowledge base. The employment of OWL is critical in this layer, as OWL's comprehensive vocabulary and expressive capability facilitate the detailed modeling of domain knowledge, crucial for effective reasoning and verification processes. Workflows embedded in these reasoning engines continuously verify and validate information, ensuring the data remains accurate and reliable. This process of checking and confirming data's consistency and relevance is crucial in areas like critical infrastructure management, where the integrity and dependability of data are essential.

Conversely, while the Proof layer focuses on ensuring logical consistency and validating data relationships, the Trust layer emphasises the authenticity and credibility of data sources within semantic technologies. The Trust layer empowers users and applications to evaluate the trustworthiness of data by considering its origin, historical lineage, and the reputation of its providers. Achieving a robust Trust layer involves the deployment of cryptographic techniques, including digital signatures and encryption, to secure data transactions and authenticate the identity of data contributors. Furthermore, even when employing blockchain technology (Cano-Benito, Cimmino, & García-Castro, 2019), which offers a permanent and transparent ledger for recording data transactions, it's important to note that access to the content of these transactions can be restricted to authorised individuals or entities only, especially for private and sensitive data or information. Blockchain technology's ability to provide a trustworthy and traceable record, thereby facilitating credibility, makes it an essential element in semantic technologies for creating a Digital Thread (Zhang, Liu, & Chen, 2024). Blockchain facilitates the traceable flow of information through all phases of a project or an asset's lifecycle, ensuring that every piece of data can be precisely tracked and verified. Moreover, the Trust layer emphasises the importance of creating and enforcing comprehensive data governance policies and access control mechanisms. Data governance policies dictate how data is accessed, shared, and utilised, ensuring that sensitive information is adequately protected and that data exchanges are conducted in a secure, regulated manner. Implementing such data governance policies requires a collaborative effort across all stakeholders involved, underpinned by a thorough understanding of the data's sensitivity and the potential risks.

Crypto

The incorporation of the Crypto Layer into the semantic technology CDE within the MBSE framework is crucial. The Crypto Layer integrates a comprehensive security framework

across the semantic architecture, ensuring the foundation of the Trust layer. This integration is crucial, serving as a fundamental element that secures and ensures the reliability of critical data throughout the system.

The Crypto Layer manages data confidentiality through advanced encryption techniques, thereby controlling access to sensitive information and protecting it against unauthorised disclosure. Cryptography serves as a safeguard, ensuring that only authorised individuals can access crucial data and information. The ability to safeguard data confidentiality mitigates the risks associated with potential data breaches and exposure, maintaining the privacy and security of vital information.

Data Integrity is strictly maintained through cryptographic hash functions, serving as robust protectors against unauthorised changes to data. These hash functions create unique identifiers for data sets, allowing the system to quickly identify any modifications. Careful monitoring builds trust among stakeholders, ensuring that the data supporting critical decision-making processes remains clean and reliable.

Moreover, the layer enhances authentication and proof of origin through the use of digital signatures. This mechanism not only verifies the identity of data contributors, ensuring that the data originates from a credible source but also binds them to the data they provide. Consequently, it becomes nearly impossible for contributors to deny their involvement, thereby reinforcing accountability and trust within the system.

The integration of Blockchain Technology within the Crypto Layer elevates these security measures by providing a transparent and unchangable ledger for transaction records. This not only advances data traceability and accountability but also facilitates the creation of a Digital Thread. This thread records every interaction and modification related to the infrastructure asset, embedding principles of circularity by enabling the systematic tracking, standardisation, and reuse of materials across the bridge's lifecycle. A detailed and verifiable record is vital for promoting sustainability, as it guides the strategic recycling and reuse of bridge components in alignment with circular economy principles.

User Interface & Applications

The integration of the Model-View-Controller (MVC) architecture (Wikipedia, 2025), as Fig. 9 shows, into the User Interface & Applications (UIA) layer significantly enhances management systems within the renovation and replacement program context, leveraging semantic technology for improved efficiency and decision-making. This approach notably enriches user interactions, making complex data more accessible and actionable for stakeholders.

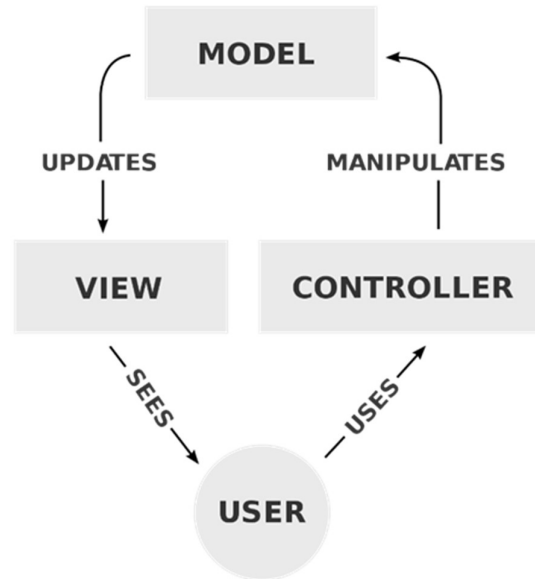


Figure 9 – Model-View-Controller Architecture (Wikipedia, 2025)

The UIA layer serves as the primary point of interaction between the system and its users, facilitating access to complex semantic data through user-friendly interfaces and applications. The UIA layer is where the complexity of semantic technologies is translated into actionable and comprehensible visualisations and controls. For engineers, bridge operators, and maintenance personnel, this layer provides the tools to interact with the system, whether it's querying bridge data, visualising structural health, or planning maintenance schedules. The performance of the UIA layer is crucial as it shapes how effortlessly and effectively users can interact with the extensive semantic data they need to access.

Supporting this user-centric layer is the MVC architecture, which separates the application into three interconnected components: Model, View, and Controller. The server hosted Model component ensures accessibility from various locations and by different organisations, is responsible for managing the semantic data and logic of the system, utilising RDF for data representation, OWL for ontology definitions, and SPARQL for data queries. The semantic setup ensures the data model is both robust. The View component, through front-end web technologies like HTML, CSS, and JavaScript frameworks, along with visualisation libraries, crafts intuitive displays that allow users to interact dynamically with the system's data. The architecture inherently supports the development of customisable user interfaces, enabling tailored views that control data access based on each stakeholder's role, further enhancing data security and personalised interaction. The Controller acts as an intermediary, processing user inputs, managing application logic, and determining the views to render. Server-side frameworks and web services enable communication between the user interface and the server, where application logic and data processing occur, ensuring efficient operation and user engagement.

The MVC architecture's compartmentalised structure plays a pivotal role in enhancing the system's agility and responsiveness. This architecture divides the application into three

distinct, interconnected component (Model, View, and Controller) each of which can be developed and maintained independently. This separation allows for focused improvements and updates without the need for extensive changes across the entire system, thereby facilitating easier maintenance and faster iteration.

In parallel, adopting a modular approach within each MVC component, especially the Model which handles the semantic data and business logic, further amplifies these benefits. For example, organising the Model's semantic data into distinct, interoperable modules – such as structural components, maintenance records, and operational status – enables targeted updates and modifications. Modularization within the MVC framework crucially increases the system's flexibility, enabling evolution and robust performance in response to the changing needs of infrastructure management.

In semantic technology applications, the success of the MVC architecture mainly depends on standardisation, modular design, and testing. Adhering to best practices enhances system maintainability and scalability, while a modular approach to the semantic model promotes adaptability and resilience. For example, organising the semantic model into distinct, interoperable modules (such as structural components, maintenance records, operational status and environmental conditions) allows for targeted updates and minimises disruption, crucial for the changing demands of infrastructure management.

Moreover, the organisation provided by the MVC architecture ensure that complex semantic data is both accessible and actionable for users. Accessibility is essential in within the renovation and replacement programme, where rapid and informed decision-making can significantly impact outcomes. By facilitating a more intuitive interaction with the system, users can quickly understand and act upon critical data, thereby improving response times to needs or emerging issues.

In conclusion, the strategic implementation of MVC within the UIA layer, coupled with a focus on standardisation, modular design, and rigorous testing, not only simplifies the complexity inherent in semantic web technologies but also strengthens the foundation for data management and user interaction. This synergy between semantic technologies and a user-centered design significantly enhances the capacity for undertaking renovation and replacement projects, providing a comprehensive and coherent overview of vital data and information.

Strategic Implementation

The integration of Semantic Web technologies within a MBSE framework marks a significant advancement in infrastructure management, particularly in the areas of maintenance, renovation, and replacement. This approach harnesses the full capabilities of digital models and Linked Data to facilitate a seamless flow of information across the entire lifecycle of an asset, moving beyond the constraints of traditional data silos to enable a dynamic, holistic view of assets through the application of semantic technologies and knowledge graphs. This results in a significant enhancement in operational efficiency and decision-making processes.

Central to this paradigm shift is the role of Linked Data, which serves as a crucial bridge connecting disparate data sets, ensuring that information is not only accessible and interoperable but also actionable. This addresses the longstanding issue of data fragmentation and ensures stakeholders have access to up-to-date, comprehensive models, streamlining workflows in renovation and replacement projects by providing a consistent and shared information environment. Furthermore, Linked Data plays a key role in maintaining dependencies between system elements, enhancing traceability, and facilitating accurate impact analyses, thus reinforcing its importance within the MBSE framework.

The synergy of digital twins and digital threads within this integrated framework exemplifies the benefits of a cohesive semantic ecosystem. By incorporating blockchain-like technology into the digital thread, an additional layer of integrity and traceability is added, creating an unalterable record of the asset's lifecycle changes. Concurrently, digital twins, augmented with real-time sensor data and performance analytics, offer a living, detailed view of the asset's state, significantly improving predictive maintenance strategies and supporting informed decision-making and strategic planning. This digital thread not only records every interaction and modification related to the infrastructure asset but also embeds principles of circularity, enabling the systematic tracking, standardisation, and reuse of materials across the asset's lifecycle. The detailed and verifiable record is vital for promoting sustainability by guiding the strategic recycling and reuse of components in alignment with circular economy principles. Moreover, the digital thread ensures that historical data, encompassing all events, maintenance records, and performance analytics, is perpetually accessible and retrievable, enriching the depth of possible analysis and providing a comprehensive archive of the asset's history.

A noteworthy aspect of adopting this semantic MBSE methodology is its capability to generate traditional documentation as needed, facilitating a gradual transition for stakeholders towards a model-based paradigm without disregarding established documentation practices.

Additionally, the deployment of semantic technologies facilitates the efficient organisation and retrieval of extensive information on projects and assets throughout their lifecycle. The creation of a Semantic CDE establishes a centralised repository for knowledge, fostering enhanced collaboration and knowledge sharing among project participants and programme managers. This collective intelligence approach accelerates the pace of renovation and replacement projects by drawing upon a vast pool of shared data and information. A crucial requirement for realising a cross-project Semantic CDE is the development of a Reference Data Library (RDL), Object Type Library (OTL), and shared ontologies, including taxonomies, to ensure semantic consistency, interoperability, and reusability of data and models across projects.

The holistic implementation of the Semantic CDE within the MBSE framework promotes adaptive asset management and governance, enabling programme managers to adjust management strategies based on (real-time) insights and comprehensive data analytics. The semantic CDE, structured as a comprehensive knowledge graph, serves as the backbone of the infrastructure management ecosystem, offering a dynamic, interconnected data architecture.

The semantic CDE ensures that governance models are continually updated with the latest knowledge and insights. Furthermore, the knowledge graphs facilitate effective sharing and application of knowledge across projects, significantly enhancing the program's capacity.

The strategic integration of semantic technologies with machine learning enriches the infrastructure management ecosystem with advanced analytical capabilities and predictive modeling. The machine-readability of semantic technologies facilitates the application of machine learning algorithms, enabling the extraction of patterns and insights from structured, interconnected data (Mountantonakis & Tzitzikas, 2017). The synergy between semantic technologies and machine learning significantly enhances maintenance strategies, predictive analytics, and decision-making processes. Successful machine learning integration relies on establishing a comprehensive semantic web infrastructure and rigorous data validation to ensure the accuracy and reliability of the data. For successful machine learning applications, ensuring high data quality and establishing a comprehensive semantic infrastructure are essential prerequisites. The capabilities of Semantic Web technologies, particularly through ontologies, SHACL, and SPARQL queries, provide robust mechanisms for conducting data quality checks and ensuring data integrity.

3.2.2 Modelling Language (SysML)

Within the MBSE framework, SysML offers an expansive language capable of modeling the complex interactions across varied engineering disciplines. SysML can depict both the structural integrity and dynamic behaviours of systems, enabling comprehensive simulation and analysis of operational scenarios. This advanced representation allows for an in-depth exploration of the system's response to diverse conditions. Furthermore, SysML contributes to the framework's efficiency and adaptability through the reusability of its models. This feature allows for the creation of modular, reusable model components, enhancing design efficiency across similar projects.

SysML's graphical visualisation contributes to better readability and understandability of multi-disciplinary complex systems. The visual nature of SysML diagrams facilitates a more intuitive understanding of the system structure, dynamics, and interrelationships among various components, making it easier for stakeholders from different disciplines to grasp complex concepts and scenarios. Its power also lies in its ability to serve as an interface between, for example, a complex Linked Data model and the user, translating structured semantic information into accessible visual representations. In this sense, SysML builds directly on top of the Semantic CDE, which forms the foundational layer of the MBSE framework. The Semantic CDE provides consistent, structured, and interoperable data that SysML can reference and represent visually, ensuring that the models remain coherent, aligned, and traceable across disciplines and tools.

SysML enhances maintainability by offering a clear visual representation of the system's architecture and behaviour. This advantage persists from the design phase through the entire maintenance lifecycle, facilitating a comprehensive understanding of the system for all stakeholders involved. The integration of SysML with tools like Relatics for requirements management, Revit for detailed visualisation, and Semantic technologies for agile data

management and interoperability ensures a cohesive and comprehensive approach. The Linked Data model serves as the underlying model for data structuring, whereas SysML, Relatics, and Revit primarily act as user-facing interfaces through which different stakeholders access, manipulate, and enrich the structured information.

SysML is a key enabler of MBSE because it provides a standardised modelling language (ISO/IEC 19514) for expressing complex systems in a graphical (and textual) form. A significant advantage of SysML is that implementation is done at an abstract level, allowing for the involvement of stakeholders with less technical understanding (Wagner, Portenlänger, & Zuccaro, 2023). The expression the Four Pillars of SysML refers to the four essential diagrams of SysML: Requirement, Activity, Block, and Parametric diagrams. Figure 9 shows SysML's diagram hierarchy the Four Pillars, enabling a comprehensive, unambiguous and integrated representation of the entire system. SysML allows the model to exchange information and data with other models of other tools supporting consistency.

SysML can be effectively utilised to create a digital thread and digital twins, offering capabilities for simulating, testing, monitoring, and maintaining systems, while establishing traceability across requirements, design, analysis, and testing (Pessoa, Pires, & Wu, 2022) (Wagner, Portenlänger, & Zuccaro, 2023). However, creating overly large models can lead to an unwieldy clutter of graphical entities, making it time-consuming to develop and challenging for humans to keep track of the model (Jilissen, Dieleman, & Groote, 2024). For this, formal verification tools such as mCRL2 could be more appropriate. Instead, focusing on high-level abstractions ensures that the SysML diagrams serve as powerful tools for visualisation and communication across various teams and projects.

Linked Data acts as the foundational framework for data and information exchange and storage within the MBSE approach. Additionally, SysML diagrams can be transformed into XML or JSON format (Bone, et al., 2018), a step that is crucial for their integration with semantic technologies. However, utilising standardised methodologies for this transformation and interoperability is crucial, ensuring accurate mapping between SysML elements and semantic data models. Furthermore, it is critical to adopt a standardized approach to SysML modeling to ensure that the graphical representations maintain their clarity and universality across interdisciplinary project teams within the programme. For optimal interoperability and parallel use with semantic technologies, the SysML ontology should align closely with or be readily translatable to the semantic ontologies, facilitating seamless data integration and ensuring that models are interoperable within the broader semantic framework. Hence, while Linked Data facilitates the interconnection of models and continuous data flow, SysML affords a precise and standardised graphical depiction of the system, which interdisciplinary teams leverage for collaborative development (Wilking, Sauer, Schleich, & Wartzack, 2022), ensuring the system's operational efficacy. Standard practices in SysML modeling and its XML or JSON conversion are critical to uphold the models' integrity and functionality across the system's lifecycle. Teams utilise the SysML model as a collective agreement on the system's design, such as specifying locations and types of sensors required to actualise a digital twin.

The rationale for incorporating the Semi-Formal Language SysML into this study lies in its role as an extension of the Unified Modeling Language (UML), specifically tailored for Systems Engineering (SE) to address the distinctive requirements and challenges inherent in SE practices (Saqui-Sannes, Vingerhoeds, Garion, & Thirioux, 2022). The fundamental concept shared with other modeling languages is the provision of tools to articulate various facets of intricate systems in a structured and standardised manner. Noteworthy distinctions among modeling languages encompass their emphasis on specific facets of system development, the level of abstraction they employ, and the categories of systems they are designed to represent. Certain projects may leverage multiple modeling languages to effectively tackle diverse aspects of a complex system. However, the determination of the optimal combination of modeling languages for infrastructure projects falls beyond the scope of this research and may constitute a valuable subject for subsequent investigations. Specifically, the applicability of SysML requires experimentation, expertise, and domain experience to determine whether it offers added value for particular disciplines involved in engineering the system. Its usefulness may vary depending on the nature of the engineered object and the specific modelling requirements, information exchange needs, or analytical perspectives of each discipline.

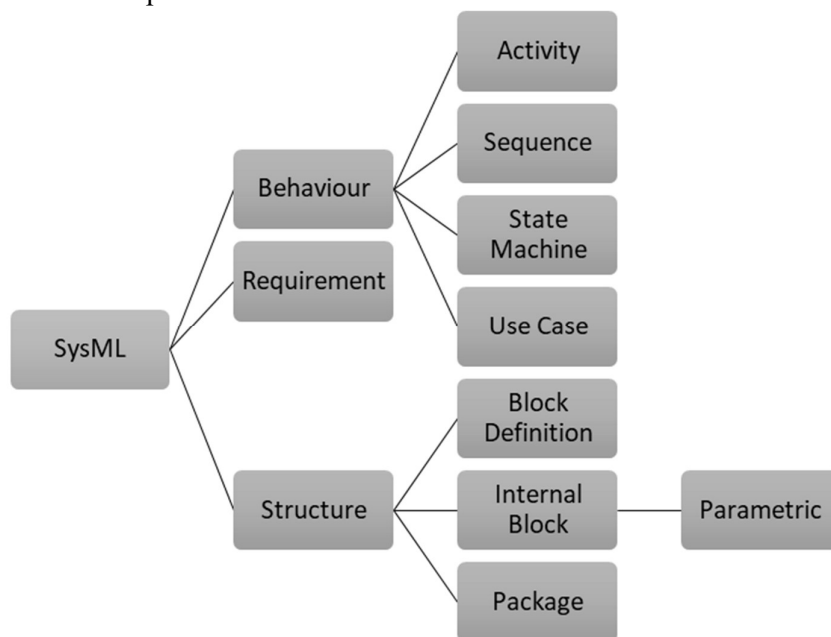


Figure 10 - SysML Diagram Hierarchy

3.2.3 Requirements Management (Relatics)

Incorporating Relatics into a MBSE framework represents a strategic approach to enhancing requirements management in Dutch infrastructure projects. Recognised for its efficacy in the sector, Relatics is a robust, web-based platform that excels in SE and information management. This integration provides a structured environment for managing project data, documents, and processes, enabling users to connect requirements with system elements, functionalities, and risks. The platform supports the creation of clear and traceable project structures, including Object, Function, Work, and Organisation Breakdown Structures,

through its intuitive interface, positioning Relatics as a valuable requirement management tool for managing the complexities inherent in infrastructure projects.

Despite Relatics' strengths in requirements and document management, Relatics functions primarily as a structured database rather than an advanced modelling tool. However, it works well as an interface for structuring, managing, and tracing requirements in a systematic and user-friendly way. Relatics is reliant on manual document verification and a document-driven approach to changes in requirements, necessitating direct communication among project stakeholders to ensure mutual awareness and implementation of changes.

The integration of Relatics with complementary tools is crucial within the MBSE framework to enhance the potential of systems engineering. The Semantic CDE is crucial, serving as a versatile platform that centralises and manages data from Relatics and various other software applications, facilitating interoperability and efficient data utilisation. Key to the integration is ensuring interoperability between Relatics and the Semantic CDE, which would facilitate the direct connection of data from Relatics to the outputs of other tools. The interoperability of Relatics with other tools promotes automatic compliance checks against project requirements, significantly streamlining the process and reducing the manual effort needed to verify document compliance.

This incorporation of Relatics within the MBSE framework leads to earlier verification of requirements, minimising the instances where project teams verify requirements too late in the project lifecycle. The Semantic CDE enhances this process by enabling the checking and verification of data, requirements, and relationships, which is a capability beyond the reach of Relatics alone. By applying semantic rules, the CDE ensures a more precise and structured management of project requirements and relationships, overcoming the limitations of Relatics in guaranteeing consistent data quality and relationships due to the absence of integrated checks.

The collaboration between Relatics and the Semantic CDE enhances data analysis and interpretation, enabling projects to benefit from advanced analytics and the visualisation of interconnected information. The synergy of Relatics with the CDE simplifies change management processes, ensuring requirements are dynamically updated across platforms, and supports standardisation and compliance efforts by aligning requirements with industry standards. Furthermore, it enhances collaboration by providing a unified view of project data, requirements, and progress.

Incorporating systems modeling languages like SysML complements the MBSE approach by offering more visual representations of the information and interactions within the system. SysML's ability to graphically represent complex systems helps in visualising the relationships and dependencies between different system components, which, when integrated with the detailed requirement management provided by Relatics and governed through the Semantic CDE, leads to a more efficient, coherent, and collaborative project management environment.

The integration further ensures that the hierarchical structures within Relatics are aligned with the taxonomy and object type library defined in the Semantic CDE, allowing for the automated generation of breakdown structures in Relatics, ensuring consistency and coherence across the CDE's hierarchical framework. The MBSE integration elevates the capabilities of Relatics and marks a significant advancement toward a more cohesive, interoperable, collaborative and effective project management ecosystem.

3.2.4 Building Information Modelling (BIM: Autodesk Revit and 360)

Integrating Autodesk BIM tools, particularly Revit and BIM 360, into infrastructure projects significantly enhances the digital management and execution of engineering and construction initiatives. BIM applications provide a robust environment for the visualisation, planning, and management of infrastructure projects, leveraging detailed 3D modeling and real-time collaboration. Revit is particularly notable for its multi-disciplinary design and documentation capabilities, which allow for an accurate representation of a project's physical aspects. Complementarily, BIM 360 extends these capabilities by offering a CDE that facilitates comprehensive project management, documentation, stakeholder collaboration, and risk management throughout the construction lifecycle.

However, Autodesk BIM tools focus primarily on the geometric and physical dimensions of projects, which, within the broader MBSE framework, introduces limitations. Despite their proficiency in managing information and facilitating collaboration within individual projects, these tools do not inherently support the aggregation, analysis, and leverage of data across multiple projects effectively, hindering the potential for generating insightful cross-project analyses and advancing collective knowledge. Moreover, BIM technologies primarily focus on physical components, neglecting processes (what the system does), requirements (boundary conditions), and functions (what the system is capable of doing). To address the gaps, the inclusion of the MBSE approach is essential (Bolshakov, Rakova, Celani, & Badenko, 2023). The adoption of NEN-EN 17632 facilitates interoperability among BIM, GIS, and other data models, through semantic technologies, enhancing the 'FAIRness' (Findable, Accessible, Interoperable and Reusable) of project information across the built environment within a MBSE approach.

Semantic Technologies enable the creation of comprehensive knowledge graphs that depict complex data relationships and dependencies, offering an interconnected view of information that spans across projects. The semantic approach allows for sophisticated queries and insights, identifying patterns that are not immediately apparent within isolated project databases. The adoption of standards such as RDF, RDFS, and OWL ensures data remains accessible and interpretable over time, preventing vendor lock-in and fostering a more flexible and enduring software ecosystem.

Moreover, while the Autodesk environment allows for the analysis of certain aspects of the system, the incorporation of a Semantic CDE and related technologies enables a more comprehensive analysis. The Semantic CDE acts as a hub, integrating and aggregating outputs from various analysis tools. This semantic integration facilitates the holistic examination of data from disparate sources within the MBSE framework, enhancing the

capacity for detailed system analysis beyond the scope of individual tools. A synergistic approach enables the extraction of nuanced insights from the collective data, significantly enriching systems engineering and programme governance. The integration of semantic technologies with BIM and other software tools fosters an advanced MBSE environment.

SysML complements BIM tools by providing a visual representation of system structures, behaviors, and requirements in an abstract manner. The focus on behavior and abstract functional structure contrasts with the role of BIM models, which offer concrete three-dimensional information models of the project's physical elements (Ammon & Paech, 2018). The graphical representation, distinct from the physical models produced by Revit, highlights potential operational scenarios and risks by illustrating system interactions and dependencies. Crucially, SysML enables traceability from these scenario and behavior graphical representations back to the specific requirements managed within Relatics. SysML's traceability capabilities are vital for ensuring consistency and completeness throughout the system's lifecycle. By explicitly linking requirements, design elements, and verification procedures, SysML supports the evaluation of system performance under various conditions and facilitates well-informed decision-making during development and lifecycle management.

Relatics plays an essential role in the MBSE framework by offering a detailed breakdown overview of the BIM model through its powerful breakdown structures, including Object, Function, Work, and Organization Breakdown Structures. This ensures a clear, traceable project structure, effectively bridging the gap between SysML's abstract system models and BIM's concrete physical models. Primarily focused on requirements management, Relatics increases coherence and efficiency by systematically aligning requirements across various models. The integration of Relatics with Semantic Technology leverages the strengths of Autodesk BIM tools and addresses their inherent limitations, facilitating a more holistic approach to systems engineering, achieved by providing a comprehensive, decomposed, and structured overview of project components.

The need to integrate BIM with MBSE and Systems Engineering arises from the demand for an all-encompassing project understanding, one that goes beyond physical and geometric features. MBSE contributes the decomposition, formalisation, and digitisation of requirements, functions, components, processes, and relationships, facilitating a systemic integration that BIM environments alone cannot achieve, necessitating the inclusion of diverse tools within the BIM software ecosystem to fully realise the benefits of a systems engineering approach.

3.3 Integrating Other MBSE Tools: Organisational Aspects and Integration Strategies

Model-Based Systems Engineering (MBSE) combines different models integrated with Systems Engineering practices. Therefore, to gain understanding about a possible infrastructure MBSE framework configurations and applications this study inventorises software tools within the infrastructure sector. Appendix B.2 lists software tools that create or support models used in the MBSE framework. Currently, those tools provide output in the

form of alphanumeric documentation, which one must translate and re-model during life cycle phases. This paragraph examines the integration of various tools within the research's MBSE framework, taking into account both current software applications and future objectives. Moreover, the specific utilisation of MBSE components within the Semantic CDE framework may necessitate certain conditions to ensure successful implementation. It is crucial to understand how to realise an interconnected model using currently available tools and how it enhances life cycle activities compared to a Document-Based approach. As one can see the tools have many different outputs, which might impact one another. Therefore establishing interrelationships, traceability and providing information in a clear and structured manner are requirements to efficiently and effectively manage complexity to improve the performance of the programme. This paragraph conducts a study based on the information presented in the Appendix B.2 table to determine how tool implementation within the selected MBSE framework may be possible to meet the specified needs, considering configurations and conditions. The analysis is structured around the different tool categories, which reflect distinct functional roles and integration within the MBSE environment.

3.3.1 Analysis and Simulation

Incorporating analysis and simulation tools into a MBSE framework, underpinned by a Semantic CDE, marks a paradigm shift from traditional document-centric project management to a dynamic, data-driven approach, which emphasises leveraging direct software tool inputs into the CDE, thereby streamlining the verification of standards and compliance with requirements, among other advantages that surpass traditional document-reliant methods. McKinsey&Company states that infrastructure asset owners lag behind other sectors and have been applying advanced analytics approaches to generate deeper insights and value on infrastructure life cycles, maintenance versus replacement decisions, and asset-longevity trends. Taking advantage of data-driven methods when making decisions could help asset owners free up capital, according to McKinsey&Company 5 to 15 percent portfolio savings (Levene, Litman, Schillinger, & Toomey, 2018).

Design

Structural, mechanical, and geotechnical design tools, such as Scia Engineer and Ansys, deliver essential data on a bridge's structural integrity and stability, fundamental to meeting safety and performance standards. Once this data is integrated into the Semantic CDE, it enables automatic compliance verification against project requirements and standards, obviating the need for manual document checks and significantly mitigating error risks.

Predictive analysis

Predictive analysis tools, like IBM Watson, facilitate forecasting and decision-making based on trends and metrics. Incorporating this predictive data directly into the CDE allows for the automated adjustment of project or programme parameters in alignment with forecasted conditions, thereby enhancing proactive management. Machine Learning is a component of predictive analysis tools and there is a rapid growth in interest to Semantic Web Machine Learning (SWeML), which are systems using semantic data structures as input and

intermediary and are used in a wide range of domains, as well as for solving a variety of tasks. However, the maturity of SWeML systems is relatively low, therefore the implementation of these systems provide opportunities for organisations (Breit, et al., 2023). Project teams could also use the output of analysis tools as input for the semantic web, putting it into context and enable sequential analysis and actions.

Predictive analysis tools, such as IBM Watson, play a pivotal role in forecasting and informed decision-making by analysing trends and performance metrics. By integrating predictive data directly into the Semantic CDE, it becomes possible to automatically adjust parameters in line with forecasted trends, fostering a proactive approach to project and program management. Within this context, Machine Learning emerges as a critical component of predictive analysis, with an increasing interest in Semantic Web Machine Learning (SWeML). SWeML systems leverage semantic data structures for input and processing, applicable across diverse domains and tasks. However, the current developmental stage of SWeML systems is relatively novel, presenting both challenges and opportunities for advancement in organizational application (Breit, et al., 2023). Furthermore, leveraging analysis tool outputs as inputs for the Semantic Web enriches semantic data, facilitating deeper analysis and informed action. The analytical tool integration not only enhances the Semantic CDE's analytical capabilities but also underscores the importance of a robust, data-informed MBSE framework in managing complex infrastructure projects effectively.

Design visualisation and environmental analysis

Design visualisation and environmental analysis tools, such as Autodesk Revit and ESRI ArcGIS, play a pivotal role in enriching stakeholder engagement by offering immersive, interactive experiences through detailed 3D models and environmental impact assessments. These visualisation tools empower a broad spectrum of stakeholders to virtually explore and interact with project designs, enhancing understanding and facilitating comprehensive training. The model's capability allows stakeholders to provide valuable feedback during the design phase and quickly grasp the structure and design implications without the need to sift through extensive documentation. Interactive visualisation fosters deeper collaborative efforts, enabling disciplines to work together more effectively, identify potential design clashes, and refine operational workflows. The synergy between technical precision and practical application ensures that infrastructure projects progress with a unified vision, aligning detailed engineering insights with broader project goals.

Separately, the quantitative data and reports generated by these tools offer invaluable insights for project management. Material quantity reports, when integrated with cost data within the Semantic CDE, enable precise financial planning and budgeting. This ensures a direct association between project financials, design elements, and environmental assessments, leading to accurate cost estimations and effective resource allocation. Furthermore, lighting and energy analysis outputs provide critical information on sustainability and energy efficiency, essential for evaluating the project's environmental impact, contributing to comprehensive planning and coordination by offering detailed insights into the project's context and the integration of essential services. The flexibility of the MBSE framework

ensures regulatory compliance and accommodates specific stakeholder preferences by allowing the generation of traditional documents when necessary, while simultaneously providing the benefits of the MBSE approach.

RAMS

The integration of SysML, the Semantic CDE and RAMS analysis tools represents a transformative enhancement to traditional project and asset management, transcending conventional document-based approaches, facilitating a deeper, more dynamic engagement with project data and requirements. SysML contributes through visual modelling and, where applicable, simulation, offering an interactive means of exploring system complexity and interactions – though its use for simulation depends on the specific context and level of model detail. The Semantic CDE ensures seamless data structuring, interoperability and aggregation, enabling holistic and informed decision-making. Meanwhile, RAMS tools excel in assessing and ensuring operational safety and efficiency, providing critical insights into achieving desired outcomes. The technologies collectively form a comprehensive framework elevating RAMS standards, illustrating the practical benefits of applying advanced systems engineering principles through a synergistic combination and configuration of tools. While SysML serves as a valuable addition for visual modelling and potentially simulation the Semantic CDE constitutes the core of the MBSE framework, providing the foundational infrastructure for coherent data management and information accessibility across the system.

SysML serves as an additional layer within the integrated MBSE framework, building upon the foundational data infrastructure provided by the Semantic CDE. It offers a structured, graphical representation of the system's architecture, behaviour, and requirements, enabling engineers to visualise complex interactions and dependencies within the design, and to depict operational scenarios and their potential impacts on structural integrity and functionality. The visual nature of SysML diagrams, combined with its ability to model abstract concepts, makes it an invaluable tool for conceptualising the system in a clear and accessible manner. Furthermore, SysML's capability for tracing requirements throughout the system enhances the ability to make RAMS requirements explicitly traceable, verifiable, and evaluable, ensuring that every aspect of the system's design and operation aligns with the defined RAMS criteria. This facilitates a thorough and systematic approach to maintaining safety, reliability, availability, and maintainability standards throughout the lifecycle.

The Semantic CDE acts as the central hub in this MBSE framework, integrating and standardising data from diverse sources, including outputs from SysML simulations and RAMS analysis. By leveraging Semantic Web technologies, the CDE ensures that all project data is interoperable, findable, accessible, and reusable (FAIR), regardless of its origin, breaking down silos between different project phases and disciplines and enabling advanced data querying and analysis capabilities. The Semantic CDE facilitates a shared understanding of the project among all stakeholders, providing a unified view.

RAMS analysis tools specifically target the assessment of the bridge's reliability, availability, maintainability, and safety features. By drawing on the structured data repository contained within the Semantic CDE, RAMS tools can conduct in-depth evaluations of

potential failure modes, maintenance requirements, and safety risks. The RAMS analysis is critical for identifying vulnerabilities in the design and operational strategies, ensuring that the bridge meets all regulatory standards and performance criteria.

The interoperability between SysML, the Semantic CDE, and RAMS tools fosters a cycle of continuous improvement. SysML simulations, including recent operational data, can uncover potential issues or stress points in the asset's design, triggering targeted RAMS analyses to evaluate the implications of these findings. The outcomes of these analyses feed back into the Semantic CDE, enriching the project's data pool and informing subsequent design iterations or maintenance strategies. The iterative process, supported by the data exchange and integration capabilities of the Semantic CDE, ensures that the asset design and operational plans remain aligned with safety standards and performance expectations.

In summary, the integration of SysML, Semantic CDE, and RAMS tools within an MBSE framework represents a paradigm shift towards a more interconnected, data-driven approach to infrastructure management. The synergy among various tools within the Model-Based Systems Engineering (MBSE) framework significantly enhances our understanding of current conditions, facilitating faster and more informed decision-making processes. Establishing an MBSE environment requires a deep understanding of the unique strengths of different tools, highlighting how their combined synergy can create an optimal MBSE landscape. Specifically, SysML is invaluable for operational analysis and ensuring the traceability of requirements. The Semantic CDE plays a crucial role in structuring and providing data, while specialised tools for RAMS analysis offer new insights that feed back into both the Semantic CDE and the SysML model, fostering a cycle of continuous improvement through a feedback loop that informs subsequent design and operational strategies. Adopting an integrative approach underlines the importance of selecting tools not only for their individual capabilities but also for their collective potential to enhance the efficiency and effectiveness of the MBSE framework in managing complex projects, emphasising the value of adopting a holistic, systems-oriented perspective in engineering projects, where the interplay between different tools and methodologies can uncover insights and opportunities that would otherwise remain hidden. However, MBSE specialists should remain cautious not to overcomplicate the tool landscape; only the minimum necessary set of tools should be deployed to effectively achieve the project and programme objectives.

3.3.2 Requirements and Systems Engineering: Bridge Controlling Software and Synthesis-Based Engineering

Technical Introduction of Synthesis-Based Engineering

Rijkswaterstaat (RWS) has taken a significant step forward in infrastructure management with the development of a Synthesis-Based Engineering (SBE) approach for creating control software, representing a nuanced form of standardisation aimed at producing reusable building blocks for assets, thereby enhancing operational efficiency and ensuring safety. The SBE methodology is crafted to address the complex nature of infrastructure control systems, encompassing a wide range of elements such as lock-bridge combinations, lock doors, traffic

barriers, traffic lights, and control panels, requiring sophisticated control and operation software capable of managing their interactive behaviors safely and efficiently.

The complexity of these control systems, highlighted by the potential for thousands of combined operational scenarios, underscores the need for a robust and thorough development process. For example, with just ten sensors, there are already 1024 combined situations possible. The amount of situations increases if one also considers the possibility of defective sensors. SBE responds to complexity by automating the design of control software, supported by rigorous model-based engineering (MBE) practices, facilitating the establishment of control software through detailed models developed and utilised across the system's entire lifecycle. The SBE model generates controlling software code and automatically and formally verifies and validates the code through Model-Based testing and simulation.

Key to SBE's methodology are two foundational models: the plant model, often modelled as a state machine, describing the system's potential behavior, relationships between sensors and actuators, and events without control inputs, and the requirements model, outlining the necessary unambiguous control specifications. Together, these models enable the synthesis of a supervisory controller that adheres to critical supervisory control theory principles, such as safety, controllability, non-blocking operation, and maximal permissiveness. Hendriks points out the lifecycle benefits of SBE, including early identification of software issues and streamlined management of updates. Furthermore, SBE Configuration-Based development through providing parameters, enables re-use these produced models, enhancing efficiency and quality and reducing needed expert knowledge (Hendriks, 2022).

Fig. 11 shows an often-used architecture for supervisory controllers at a relatively low abstraction level, Table 10 outlines the components of these controllers along with the potential roles of the integrated MBSE framework. Abstraction simplifies aspects but sufficiently detailed to develop the controlling software. Integrating SBE controlling software design within a MBSE framework offers substantial opportunities to enhance the software improvement process, demonstrating a progressive strategy for ensuring the efficient operation and safety of critical assets

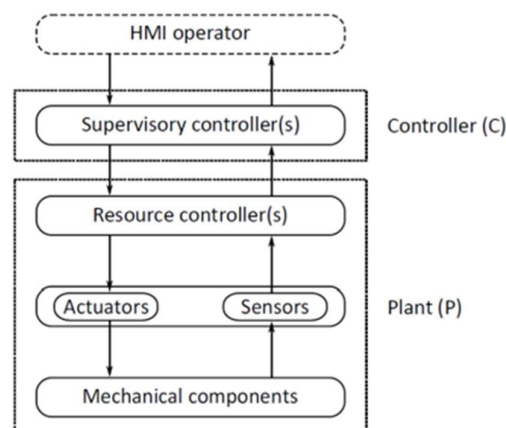


Figure 11 - Supervisory Controllers Architecture

Table 10 - Component Roles in the Integrated MBSE Framework

Component	Description	Potential Role in MBSE Framework
Human Machine Interface Operator	The interface through which operators interact with the system's operational dashboard, providing a user-friendly visualisation of real-time data.	Monitors real-time data and manages bridge operations through operational dashboards connected to the SBE model. Capable of inputting important operational data and comments into the Semantic CDE, enhancing the data pool for continuous improvement.
Supervisory Controller	A software entity that dictates the overall control strategy, ensuring the system operates within defined parameters.	Interprets high-level control logic from SBE and aligns it with operational consistency requirements, as defined in SysML.
Plant: Resource Controller	Executes specific control actions within the system as dictated by the supervisory controller.	Carries out detailed control actions based on SBE logic; these actions and their outcomes are monitored and analysed through SysML simulations for critical scenario analysis.
Actuators & Sensors	Physical devices within the system, where actuators perform actions and sensors provide feedback on various conditions.	Supply real-time operational data to the Semantic CDE, serving as foundational elements for the feedback loop and supporting SysML scenario analysis and SBE refinement.
Mechanical Components	The structural and operational parts of the bridge, including the mechanisms that enable movement and functionality.	Contribute operational and status data to the Semantic CDE, which is used for planning maintenance and software upgrades. SysML models simulate these components to reflect real-world behaviors and inform the development of SBE control logic.

Enhancing Asset Operations through SBE and MBSE Integration

Building upon the foundation laid by SBE, its incorporation into the MBSE framework creates a unified strategy for improving the assets' operational systems. The strategic MBSE integration is essential for refining control software, prevent risks, and boosting operational efficiency across the network of assets.

Within the MBSE framework, SysML is potentially instrumental in modelling the complex operational processes and the dynamic interplay between a bridge's physical structure and its control mechanisms. By focusing on high-risk scenarios – such as sudden emergency stops and the potential for component malfunctions – SysML offers a systematic approach for comprehensive analysis and simulation, supporting the resilience of the SBE-crafted controlling software and preparing it to handle a wide range of operational challenges. The application of SysML, combining the controlling system and physical structure for scenario analyses, has the potential to substantially reinforce the safety and reliability of assets, making it a promising element within the MBSE framework.

At the core of the integration is the Semantic CDE, which functions as the central hub for extensive data management, operating as a comprehensive repository, enabling the efficient storage, access, and analysis of operational data in conjunction with recorded software anomalies. The CDE facilitates feedback loops, which are essential for the continuous and cyclic refinement of control software. By exploring the rich data collected from the bridges'

operational systems, the Semantic CDE supports the identification of recurring patterns and systemic issues, enabling early adjustments and informing strategies for maintenance and software improvements. The fusion of RAMS tools into the MBSE environment elevates the process by delivering precise assessments of operational software data, fostering software modifications that are truly reflective of empirical performance data.

Another benefit of the MBSE framework with integrated controlling system is the synchronisation of maintenance schedules across the asset network, ensuring swift implementation of software updates and thereby preventing operational and software inconsistencies. With the Semantic CDE's analytical capabilities and access to operational data, program managers are well-equipped to thoughtfully orchestrate upgrades and make necessary adaptations within the network. Updating software in alignment with scheduled maintenance not only streamlines resource allocation but also decreases downtimes.

Process Overview: Enhancing the SBE Controlling Software through MBSE Integration

Integrating SBE within the MBSE framework establishes a strategic approach for refining control software in movable bridge operations. This integration leverages the combined strengths of SBE, optionally SysML, the Semantic CDE, and RAMS tools to foster a robust, efficient, and adaptable operational system. It emphasises resilience and adaptability through a coherent iterative process, supported by critical feedback loops that enable continuous improvement. By detailing the phase-by-phase development and highlighting the synergistic interaction between tools, it's evident how each component contributes to a comprehensive and resilient management strategy, enhancing the SBE model and demonstrating the importance of complementary tools within the MBSE framework, ensuring the operational systems are well-equipped to meet current and future challenges cohesively and efficiently.

Phase 1: Design and Synthesis

In the initial phase, the focus is on leveraging SBE's capabilities to develop the foundational control logic crucial for the bridge's operations, involving synthesising a supervisory controller from detailed plant and requirement models. The essence of this phase is to tackle the inherent complexity of the control systems, considering the numerous potential operational scenarios, including sensor malfunctions or unexpected interactions between system components.

Phase 2 (Optional): Modeling and Validation

Utilising SysML, this phase transitions into system modeling, where the previously developed SBE control logic is validated against the system requirements. SysML facilitates the graphical visualisation of the system's architecture, behavior, and interactions, enabling a detailed examination of critical, high-risk scenarios (Hecht, Chuidian, Tanaka, & Raymond, 2020). The validation process ensures that the control software is adequately robust to withstand operational difficulties and adheres to the specified requirements.

Phase 3: Data Integration and Analysis

The Semantic CDE becomes the focal point in this phase, serving as the repository and analytical engine for operational data collected from the bridge's sensors and actuators to support a continuous loop of system evaluation and refinement. Through the analysis of CDE data, patterns and anomalies indicative of potential system issues or areas for improvement are identified, enabling proactive adjustments to the control software and informing maintenance strategies.

Phase 4: RAMS Evaluation

Incorporating RAMS tools at this stage facilitates a comprehensive evaluation of the system's reliability, availability, maintainability, and safety, leveraging operational data stored in the Semantic CDE and insights from scenario analyses, aiming to identify and address vulnerabilities in the control system, ensuring it meets all defined system requirements, including those for safety, reliability, and performance. Findings from the RAMS evaluation lead to specific changes in the optional SysML model, which in this case serves as the visual, graphical representation of the operational system. These changes address maintenance requirements and potential structural modifications, ensuring that the system design is informed by empirical data and complies with safety and reliability standards.

Phase 5: Synchronised Maintenance and Upgrades

This phase involves strategically coordinating software updates with the bridge's maintenance schedules to enhance operational efficiency. Insights from the Semantic CDE, combined with the RAMS evaluations, are critical in planning software updates and maintenance activities. By synchronising maintenance activities and software upgrades across the bridge network, based on programme manager insights from Semantic CDE data, this phase seeks to ensure uniformity in software versions, optimise resource allocation, and reduce operational disruptions, thus improving the overall operational efficiency of the infrastructure.

3.3.3 Data Integration and Interoperability

To construct a comprehensive MBSE framework within the Dutch infrastructure sector, focusing on the renovation and replacement programme, it's crucial to embrace a multifaceted approach towards data integration and interoperability. The integration approach hinges on the strategic unification of advanced technologies, the adoption of evolving standards, and collaborative initiatives. A key element of the approach involves deploying a server-based architecture that hosts the Semantic CDE, incorporating essential semantic technologies, ensuring scalability, reliability, and centralised access to data, enabling real-time collaboration and informed decision-making across projects. While a server-based architecture offers these benefits, integrating cloud servers can further enhance scalability, dynamically allocate computing resources based on demand, and offer advanced security features. Cloud servers are known for their high levels of security, including data encryption, security audits, disaster recovery, and compliance with international standards, which can be particularly advantageous. However, cloud-server consideration should be balanced with factors such as regulatory compliance, data sovereignty, and specific security protocols, which may influence the choice between cloud-based solutions and on-premises servers.

The server infrastructure acts as the foundation, accommodating the Semantic CDE and supporting the semantic layer that enables data harmonisation and interoperability. This configuration allows for the seamless integration and interpretation of data from various MBSE tools, further enhanced by the use of RESTful web services. RESTful web services provide a stateless and lightweight approach to tool integration, significantly improving the MBSE framework's flexibility. They are critical for automating interactions and ensuring efficient communication between the Semantic CDE and diverse MBSE tools, thereby creating a responsive and interconnected ecosystem. Moreover, the server's architectural design ensures scalability and remote accessibility, enabling a centralised environment that supports real-time collaboration and informed decision-making across the programme.

Adhering to open standards such as NEN 2660 plays an essential role in the development of uniform information models, crucial for avoiding data fragmentation and ensuring coherent data exchange throughout the program. Application Programming Interface (API), including those designed following RESTful principles (a subset of APIs), further streamline the integration process by enabling the transformation of data formats (e.g., from IFC to Semantic OWL) and ensuring standardised communication across the MBSE framework's components.

While RESTful web services significantly boost the MBSE framework's flexibility and interoperability, enabling efficient communication across diverse systems, the relevance of Open Services for Lifecycle Collaboration (OSLC) standards is more nuanced. Although OSLC primarily targets a different set of applications, its methodologies and approach to tool integration offer valuable insights. Consequently, there's potential in observing OSLC's evolution and exploring synergies, particularly in enhancing NEN 2660's compatibility with OSLC standards, which could pave the way for broader international collaboration and adherence to global standards.

Middleware and integration platforms like MuleSoft and Dell Boomi excel at managing multiple data translations and protocol conversions simultaneously, allowing for seamless interoperability among diverse systems and tools. The ability to handle conversions is crucial for ensuring that all components of the MBSE framework can communicate effectively, regardless of differing data formats or communication protocols. Middleware platforms often offer built-in APIs or the ability to create custom APIs, further enhancing their integration capabilities, which is vital for facilitating flexible and scalable interactions between software applications, making middleware and integration platforms a central hub for orchestrating data flow throughout the MBSE environment. When developing an MBSE framework, it's important to assess the potential of these platforms to contribute to the overall system's coherence and efficiency, ensuring that they align with the integration and interoperability goals.

3.3.4 Digital Twin and Thread

Within Dutch infrastructure sector the integration of MBSE, digital twins, and digital threads represents a significant step towards a more interconnected, data-centric approach in asset lifecycle management, emphasising a paradigm shift towards enhanced interoperability and real-time, data-driven decision-making.

A digital twin dynamic digital representation of the physical system across its life cycle, using real-time data to mirror the physical state, including its structure, context and behavior. The primary purpose of a digital twin is to provide a detailed simulation environment that can predict performance, optimise operations, and improve decision-making by analysing the past, monitoring the present, and predicting the future states of physical assets. A digital thread refers to the communication framework that provides a connected data flow and integrated view of an asset's data throughout its lifecycle, from initial design through construction, operation, and decommissioning. A digital thread encompasses the entire lifecycle of a product or system, integrating information from various sources, including digital twins, to provide a continuous and up-to-date data stream. Thus, a digital thread is a longitudinal record of the project's data and information, ensuring traceability and accountability, the digital twin is a tool for operational insights, leveraging the data from the digital thread to simulate, predict, and inform actions. MBSE facilitates the understanding, simulation, and validation of the system's behavior before physical implementation and aims to improve the quality and efficiency of systems engineering by leveraging models throughout the project lifecycle. The integration of MBSE with digital twins and digital threads revolutionises the programme governance and asset management for the renovation and replacement programme of movable bridges, see Fig. 12, ensuring data flow, information storage and actionable insights across a bridge's lifecycle, enhancing decision-making, predictive maintenance, and operational efficiency. For the renovation and replacement programme, it is crucial to develop a standardised MBSE framework with the foresight to incorporate digital twins and digital threads, as this integration significantly enhances the MBSE process.

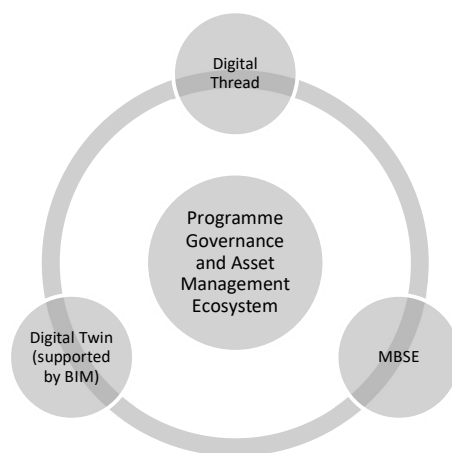


Figure 12 – Programme Governance and Asset Management Programme Governance Ecosystem

The digital thread serves as a vital conduit linking MBSE processes and digital twin models, enabling consistent data flow and traceability throughout the asset lifecycle. It facilitates seamless interaction between the physical and virtual realms, effectively capturing the evolving state of the asset, see Fig. 13 (Jiang, et al., 2023). The integration of the digital thread ensures the real-time evolution of digital twin models and amplifies MBSE processes by aligning data, information, and models from various sources into a unified overview. The alignment facilitates enhanced collaboration across different project stages and strengthens

real-time capabilities, establishing the digital thread as a single source of truth for stakeholders. The centralisation of data through the digital thread considerably improves the consistency of data and information among all interconnected systems and tools, minimising discrepancies and ensuring stakeholders have access to the latest data (Zhang, Liu, & Chen, 2024). Incorporating the Semantic CDE, which may include blockchain technology, as a central and crucial component of the digital thread, is essential for standardising data inputs and outputs across the MBSE framework, fostering flexibility and innovation while ensuring interoperability and efficient information exchange.

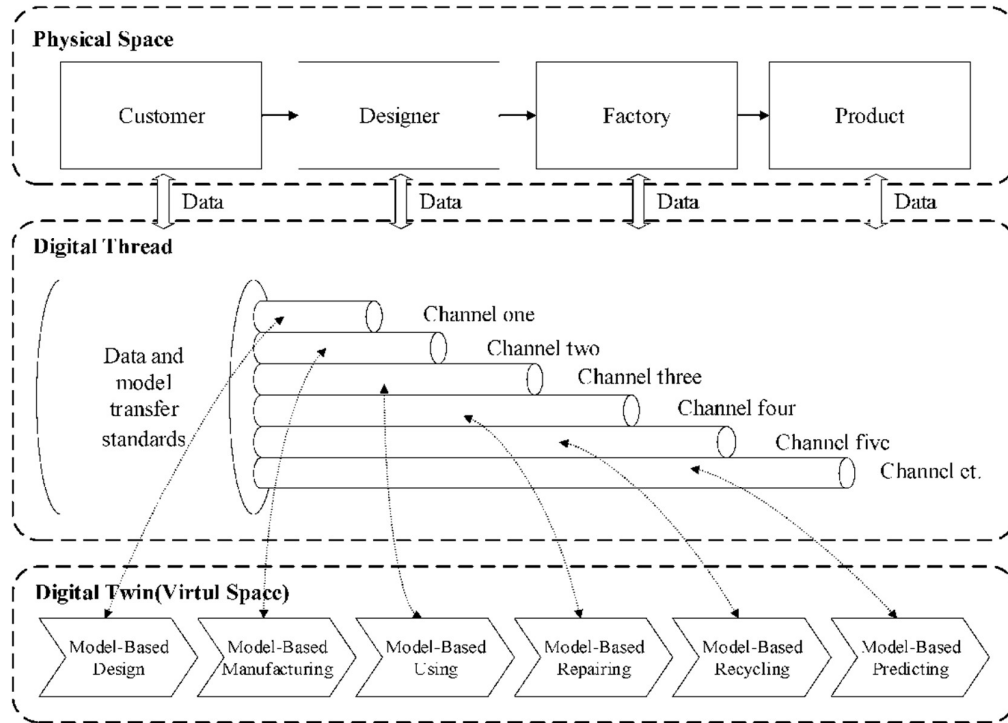


Figure 13 – Digital Thread (Jiang, et al., 2023)

The digital thread, as a method linking all systems, processes, virtual data, and physical data, serves to eliminate “data silos” over the life cycle (Zhang, Liu, & Chen, 2024). The Semantic CDE, enhanced by blockchain, plays a pivotal role in the digital thread ecosystem by offering a secure, immutable, and scalable platform for data management, ensuring that data from various phases of a project can be synchronised and aligned, providing a unified and up-to-date view of the project's status and asset performance. Blockchain technology within the Semantic CDE brings an additional layer of security and traceability, making it possible to track data origin and changes over time, which is essential for maintaining the integrity and reliability of the data within the digital thread.

At the core of realising the full potential of the digital thread and digital twin within the MBSE framework is the Semantic CDE. Acting as the intermediary between the physical world and its digital reflection, the Semantic CDE establishes standardised inputs across the programme, ensuring interoperability and coherence throughout various projects. While project teams are afforded the flexibility to select their tools and configurations, such

selections must align with the standardised inputs to maintain the Semantic CDE's integrity, safeguarding against vendor lock-in, ensuring that organisations are not bound to specific vendors and can innovate within the framework's guidelines.

Contracts and project tenders are instrumental in defining the delivery mechanisms for virtual environments, ensuring that the integration of MBSE, digital twins, and digital threads adheres to the programme's overarching objectives, promoting a standardised yet adaptable approach to managing infrastructure, allowing for project-specific adjustments while adhering to the programme-wide standards.

Furthermore, the diversity of software tools available for developing digital twins and threads, often encapsulated within isolated software environments such as Bentley Systems' iTwin, presents both challenges and opportunities. The Semantic CDE, by establishing a standardised form of digital twins and threads foundation across the program, aims to foster cross-project and program-level information exchange to enhance project and programme improvements. The Semantic CDE ensures interoperability and coherence by integrating the digital twin and thread ecosystem comprehensively, merging with other tools to form a complete, unified system. The semantic technological strategy prevents vendor lock-in, encourages tool flexibility, and supports varied project requirements and team workflows. As a result, the Semantic CDE enhances innovation and improvements across the infrastructure sector, accommodating a broad spectrum of technological solutions and methodologies to meet the industry's evolving needs.

The digital thread facilitates communication and information transfer among different digital twins (Zhang, Liu, & Chen, 2024). The integration of digital twins and threads across distinct projects within a programme enables a comprehensive, programme-level digital thread, facilitating data and information exchange between various assets. Asset interconnectedness, enabling knowledge reuse and sharing, not only improves the outcomes of individual projects but also amplifies the overall programme's effectiveness and capacity, allowing for informed strategic decisions based on a holistic understanding of the asset portfolio.

3.4 Organisational Considerations

Integrating MBSE with semantic technologies represents a transformative approach within the infrastructure sector, notably in renovation and replacement programs, aiming to enhance asset management capabilities. The semantic integration capitalises on the extensive use of digital models throughout the asset lifecycle, significantly empowered by open-source semantic technologies. Open source semantic technologies are essential for ensuring interoperability and fostering collaboration across organisations. They are crucial for maintaining the long-term accessibility and usability of data, while also preventing vendor lock-in. This is foundational for the successful creation and maintenance of a Semantic CDE, which is open and standardised to ensure compatibility with evolving technologies and methodologies, thereby ensuring the system's long-term adaptability.

The formation of a Semantic Technology Consortium (STC) represents a critical strategic initiative aimed at establishing a sector-shared, standardised Common Data Environment

(CDE). This initiative aligns with the first stage of change management models by fostering a shared sense of urgency, establishing a guiding coalition, creating a unified vision for transformation, and empowering broad-based action (Errida & Lotfi, 2021). By uniting government bodies, asset owners, technology developers, and contractors, the STC creates a collaborative platform to drive innovation, standardisation, and the effective integration of MBSE principles across infrastructure programmes.

In the Netherlands, the national initiative digiGO (digiGo, 2025) already provides a concrete structure to support such developments. Through digiGO, organisations and companies can establish a shared DigiDeal to realise a Semantic CDE, supported by sector-wide commitment. digiGO facilitates strategic alignment and collaborative innovation by engaging with stakeholders, initiating pilot projects, and structuring new digitalisation programmes. It offers critical support such as network-building, knowledge sharing, and co-funding opportunities, and helps ensure results can be scaled up effectively across the sector. This makes digiGO a practical enabler for launching and sustaining an STC. The success of the Digital Twin Consortium (DTC) demonstrates the potential of a consortium-based approach (Digital Twin Consortium, 2025). Similar to the DTC, the STC ensures collaboration between diverse stakeholders, prevents fragmented development, and drives innovation.

While the STC focuses on strategy and standards, asset owners are responsible for implementing these strategies within the Renovation and Replacement Programme (RRP). Asset owners must embed CDE requirements into project tenders and contracts, ensuring alignment with the programme's goals. To enable experimentation and foster innovation, asset owners should allocate sufficient resources within projects to test and refine new approaches. Additionally, they should seek increased financial support from governmental bodies to realise the consortium's strategic vision. This additional funding would ensure that infrastructure management and maintenance are equipped to meet future challenges.

To translate the STC's strategies into actionable workflows, asset owners, organised through the STC, can collaboratively establish dedicated Public-Private Partnerships (PPPs) to ensure the effective implementation of the Semantic CDE and MBSE principles within the programme. These partnerships combine public oversight with private sector innovation, ensuring that projects are executed efficiently while adhering to the standards and frameworks developed by the STC. Private partners, as both implementers and members of the STC, play a dual role: contributing to the consortium's development of strategies and applying these strategies in practice.

The STC's primary role is to develop shared strategies, standards, and best practices for designing, implementing, and utilising the CDE and semantic technologies. This includes creating resources like the Reference Data Library (RDL) and Object Type Library (OTL) and shared ontologies, including taxonomies, to ensure semantic consistency, interoperability, and reusability of data and models across projects. The infrastructure sector's push for standardisation (Knippenberg, 2023) finds resonance in the RDL's importance, promoting the adoption of uniform standards across projects.

NEN 2660's conceptual model provides a formal ontology specifically designed for the built environment, detailing core concepts, entities, and their interrelations. It aligns with semantic web languages, which are essential for effective data management and interoperability in infrastructure projects. By adopting and extending this model, the STC can develop an extendable and robust ontology in line with established industry standards. The adoption of NEN 2660 forms the foundation for enhanced communication, data sharing, and integration across projects, ensuring consistent and interoperable data management throughout the programme. Furthermore, recognising how MBSE, digital twins, and digital threads mutually reinforce one another within a holistic model, the development of a unified standard is recommended. This standard should integrate these methodologies and build upon existing frameworks such as ISO/IEC 30141 (IoT) and ISO/IEC 30173 (Digital Twin). Semantic technology emerges as a crucial component for integrating digital twins, including IoT and digital threads, within a comprehensive MBSE framework, facilitating a unified approach to managing the complex interrelations and data flows inherent in these systems. The inherent overlap between IoT, digital twins, and digital threads highlights the necessity of their integration into a single standard as crucial for advancing an MBSE framework. Specifically, the IoT's role in generating big data underscores the need for this data to be effectively processed and structured within the framework to fully realise the benefits of interoperability and integration (Qi & Tao, 2018) (Rathore, Shah, Shukla, Bakiras, & Bentafat, 2021). Given the absence of specific standards for digital threads, collaboration with the Digital Twin Consortium alongside the STC could be essential in developing comprehensive standards that include digital twin and thread concepts.

The STC must aim to create a scalable and adaptable CDE that accommodates the varied requirements of different stakeholders. Asset owners, as initiators of the consortium, play a crucial role in promoting the benefits of improved asset management and systems engineering to foster broad participation. The consortium encourages contractor participation by highlighting the benefits of improved design and maintenance processes, as well as reduced project risks, and fostering a shift from document-centric workflows toward a more efficient, model-driven approach. Semantic technology developers are attracted by opportunities for research, practical application of their technologies, and potential economic benefits, underscoring the consortium's role as a catalyst for innovation and collaboration within the infrastructure sector. The inclusion of Public-Private Partnerships (PPPs) significantly enhances the consortium's capabilities, not just by merging public oversight with private sector innovation but also by injecting critical financial investments and expertise into the consortium.

To ensure success, the STC must be aligned with participatory principles that facilitate comprehensive stakeholder engagement. This includes setting clear requirements for participation, such as maintaining open communication channels, enabling collaborative decision-making, ensuring transparency in project developments, and promoting the equitable sharing of benefits and responsibilities. By embedding these principles into its structure, the consortium creates an inclusive environment in which all members, regardless of role, can

contribute to shaping the development of the Common Data Environment, ensuring alignment with the collective goals and evolving needs of the infrastructure sector.

Moreover, it is critical within programmes to establish clear agreements on which data should be shared, focusing on increasing the programme's capacity and fostering collective knowledge development. This involves determining the types of data that can significantly contribute to the programme's objectives and ensuring that all participants understand the value of shared data in enhancing overall efficiency, innovation, and problem-solving capabilities. In this context, the STC plays an essential role by guiding the integration of specific data into the CDE, while also ensuring appropriate measures are in place to protect sensitive information. Establishing robust data governance frameworks and access control mechanisms is necessary to balance openness with security, thereby building trust among stakeholders and supporting responsible data sharing. This involves creating secure data exchange protocols, implementing robust data encryption methods, and establishing clear guidelines for data access and privacy.

Asset owners play a crucial role in specifying the development requirements of the CDE within project contracts. By clearly defining how the CDE should be developed and integrated into the MBSE framework, clients ensure that these specifications become an integral part of the tendering process. To support this, it is essential that organisations and companies allocate additional resources, including time and funding, to effectively meet the CDE requirements and facilitate experimentation. In line with change management principles, it is also important to generate short-term wins and visible results early in the implementation process. These wins help to build momentum, create cultural alignment, and demonstrate the practical value of the CDE (Errida & Lotfi, 2021).

The STC serves as a central repository of resources and expertise. By consolidating the capabilities, skills, and knowledge of its member organisations, it is well-positioned to allocate these assets efficiently across projects within the programme. The resource aggregation ensures that each project has access to the necessary tools, technologies, and expertise to develop and implement the CDE according to the established requirements. Furthermore, despite the inherently competitive nature of the market, the consortium fosters a collaborative character among its members, ensuring they work towards a unified goal while maintaining healthy market dynamics. At this stage, governance is primarily exercised through hierarchical oversight and structure, as this remains the most effective approach to achieving large-scale change. However, once the data structures are established, the CDE can support decentralised self-governance through a participatory system, enabling autonomy, dynamic interaction, and collaborative decision-making among programme participants. Additionally, the STC establishes a feedback loop, where insights and experiences from individual projects are shared back into the consortium. This continuous exchange of knowledge enhances the consortium's collective expertise, allowing participants to benefit from lessons learned and best practices, thereby improving future project execution and the ongoing development of the CDE. To further enrich this knowledge base, the STC should actively engage with INCOSE, leveraging it as a platform for the exchange of knowledge and best practices in systems engineering. While INCOSE itself does not bear direct responsibility

for developing specific solutions or technologies, its role in facilitating dialogue and sharing best practices can significantly benefit the STC. By fostering knowledge exchange and strategic alignment, INCOSE can support the initial stage of change management by helping to establish a sense of urgency, build a guiding coalition, and shape a shared vision for transformation.

ISO 19650 offers a comprehensive framework for managing information throughout the lifecycle of assets, highlighting the critical role of a CDE as the centralised source for project information. This standard facilitates accurate and efficient data sharing among stakeholders by establishing clear information agreements. Through a dynamic and iterative process, including planning, executing, and assessing these agreements within a feedback loop, ISO 19650 significantly improves the efficiency and effectiveness of information management.

Every organisation involved in the program must establish a dedicated department or team focused on data management. This is crucial for a robust data washing and cleaning process (Van Ruijven, 2023), which prepares data for sharing and collaboration. Such teams are responsible for ensuring the accuracy and consistency of the data integrated into the CDE. Their work is essential not only for the integrity of the data but also for the overall success of collaborative efforts, ensuring that all data shared and utilised across the programme meets quality standards.

Additionally, while the CDE is developed as an open-source platform to prevent vendor lock-in and ensure information permanence, surrounding models in the MBSE framework need not be open-source but must be interoperable with the semantic CDE. The open-standard nature ensures that data remains accessible and usable over the long term, regardless of the specific tools or systems in use. The STC must guarantee long-term, agile and independent utilisation of the semantic technological CDE through the utilisation of open source semantic technology software. The consortium plays a crucial role in facilitating this interoperability with other software providers. Leveraging the consortium's size and collective influence, the STC can negotiate and ensure enhanced interoperability between the semantic CDE and other key software tools.

The STC plays a crucial role in ensuring seamless interoperability and the effective integration of various tools and platforms within the MBSE framework. By establishing the Semantic CDE and aligning it with standards like NEN 2660, the STC lays the foundation for a scalable and standardised engineering ecosystem. In response to the rapid pace of technological advancements, the consortium must continually refine interoperability standards and the framework to maintain its adaptability. Incorporating middleware platform specialists into the consortium is crucial, as their extensive expertise in data exchange and system integration can significantly enhance the framework's coherence.

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and the framework to maintain its adaptability. To support this, it is essential that the STC not only defines standard configurations for tool integration but also allows flexibility for organisations to adapt these to their specific project needs. This balance between standardisation and configurability ensures a robust yet adaptable MBSE environment. Incorporating middleware platform specialists into the consortium is also crucial, as their expertise in data exchange and system integration can significantly enhance the framework's coherence and support flexible tool interoperability.

Chapter 4: Qualitative Evaluation of MBSE Framework

The successful implementation of MBSE requires a structured evaluation to determine its effectiveness across technical, organisational, and strategic dimensions. This chapter provides a qualitative assessment of the MBSE framework against key project and programme needs, focusing on essential quality metrics that determine its impact. The case study is also included in this chapter, as it evaluates the practical application of semantic Linked Data within the MBSE framework. Additionally, the chapter includes a Strategic SWOT Analysis to highlight strengths, weaknesses, opportunities, and threats in the MBSE implementation and concludes with Verification and Validation, ensuring the framework meets its intended objectives.

4.1 Case Study: Demonstrating MBSE in Practical Application

4.1.1 Introduction Case Study

The swing bridges at a key location along the historic Afsluitdijk causeway (see Fig. 14) are undergoing a comprehensive renovation and replacement project to ensure their sustainability and reliability until 2050 and beyond. Managed by a private engineering consultancy in close collaboration with the national road authority, this pivotal endeavour is part of a broader national Renovation and Replacement Programme. The project targets the upgrade of the bridges' structural, mechanical, and control systems, addressing the critical needs imposed by aging infrastructure, evolving technical standards, and increased operational demands. Constructed in 1973 as part of a sluice complex, the bridges were originally designed with defence considerations, necessitating movable structures to accommodate crossing traffic and ensure maritime passage between two major Dutch water bodies. This highlights their strategic and functional importance and underscores the necessity of their renovation for both vehicular and maritime traffic.

The project's inherently multidisciplinary nature demands the cohesive integration of Structural Engineering, Mechanical Engineering, and Electrical and Control Engineering disciplines to address interdisciplinary challenges. Each area contributes unique, interconnected elements of engineering and design, showcasing the project's complexity and emphasising the critical need for effective communication and management strategies among various stakeholder groups and engineering fields.

This research employs the Den Oever swing bridges as a case study to demonstrate the practical value and functioning of MBSE in infrastructure projects. By integrating semantic technologies, the framework enables the development of digital twins and threads, allowing for real-time monitoring, analysis, and adaptive maintenance across the asset lifecycle. This approach enhances operational efficiency and supports long-term programme improvement. MBSE's structured methodology not only enhances the exchange of data and information among project teams, stakeholders, and programme managers, but also improves system

insight by systematically storing critical information and linking it to specific system objects, thereby enabling traceability and informed decision-making.

This case study aims to illustrate how the Semantic MBSE framework, focused on interdisciplinarity, can effectively address the challenges posed by such complex infrastructure projects. By offering simplified examples within the case study, the research underscores the framework's capacity to foster stronger collaboration and enhancing programme outcomes, marking a significant advancement over traditional document-based approaches.

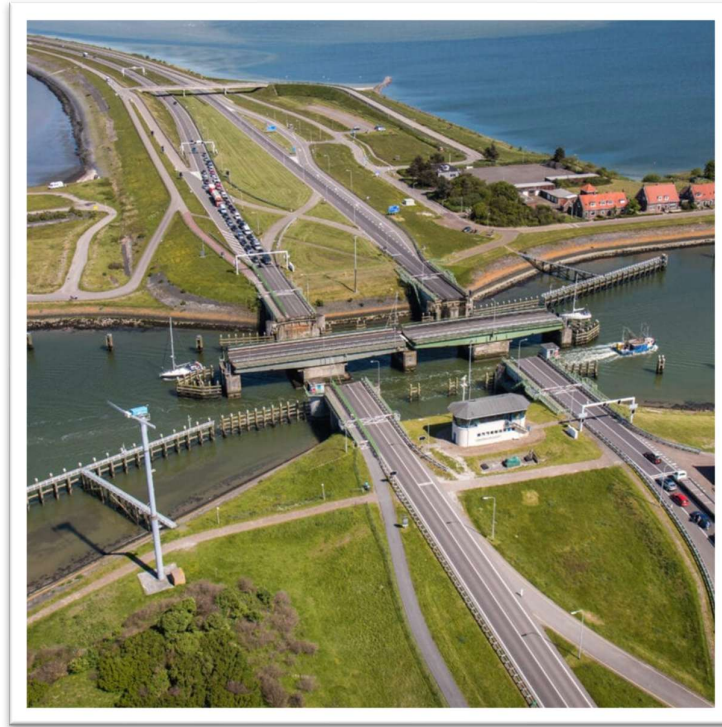


Figure 14 - The Den Oever swing bridges

4.1.2 Semantic Technology

This section presents the semantic foundation of the MBSE framework, demonstrating how ontology elements including a taxonomy (Object Type Library), Reference Data Library (RDL), and defined namespaces enable structured data modelling, traceability, and interoperability across the lifecycle. Using RDF and RDFS, the model supports consistent classification and integration of programme, project, and asset data. Through practical examples of classes, properties, and instances, this section demonstrates how semantic technologies support informed decision-making, enable cross-project knowledge sharing, and operationalise digital twins and requirement management.

4.1.2.1 Taxonomy (Object Type Library)

To effectively structure and manage information across different levels of the infrastructure programme, the semantic model is organised into a taxonomy divided into three main

domains: programme, project, and asset. These taxonomic structures not only reflect the hierarchical organisation of infrastructure activities but also serve as foundational classes within the ontology. When constructing these taxonomies, a degree of separation between different disciplines can be useful to clarify domain-specific perspectives, while recognising that these disciplines remain inherently interconnected. Below is an example of how these three taxonomies are structured and related.

Programme Taxonomy

- Programme Management
 - Asset Prioritisation
 - Prioritisation Criteria
 - Asset Evaluation and Scoring
 - Prioritised Asset List
 - Learning and Continuous Programme Improvement
 - Tranche Evaluation
 - Tranche Lessons Learned
 - Programme Improvement Initiatives
 - Programme Requirement Management
 - Programme Risk Management
 - Tranche Management
 - Tranche 1
 - Project type: Sluice
 - Project type: Bridge
 - Project 1 (Swing Bridge Renovation: SB-R1)
 - Contractors
 - Project Manager
 - ExperienceProfile
 - Budget
 - Timeline
 - Risk Management
 - Performance Indicators
 - Completion Percentage
 - Cost Variance
 - Schedule Variance
 - Stakeholder Satisfaction
 - Project Identifier (SB-R1)
 - ImpactingAssets: SwingBridge (SB-001)
 - Project 2
 - Tranche 2

Project Taxonomy

- Project management
 - SB-R1: Swing Bridge Renovation

- Overall Project Management Attributes
 - Total Budget
 - Project Timeline
 - Overall Completion Percentage
 - Total Cost Variance
 - Cumulative Risk Management Overview
 - Global Resource Allocation
 - Learning and Continuous Project Improvement
 - Project Evaluation
 - Project Lessons Learned
 - Project Improvement Initiatives
- Design phase
 - Project Management Attributes
 - Start Date
 - End Data
 - Budget
 - Resource Allocation
 - Organisation
 - Project Manager
 - Contractors
 - Stakeholders
 - Disciplines
 - Performance Indicators
 - Completion Percentage
 - Cost Variance
 - Schedule Variance
 - Stakeholder Satisfaction
 - Etc.
 - Technical Systems Engineering Aspects (ISO 15288)
 - Associated Asset (SB-001 Technical Specification
Subset of Asset Ontology reflecting the specific aspects of the bridge relevant to the project)
 - Technical Process
 - Stakeholder Management
 - Requirement Management
 - Technical Management Process
 - Project Planning
 - Breakdown Structures
 - Decision Management
 - Risk Management
 - Etc.
- Construction phase
 - Same set-up as design phase

Asset Taxonomy

- Infrastructure Assets
 - Bridge
 - SwingBridge
 - Asset Identifier: SB-001
 - Asset Management
 - Organisation
 - Requirement Management
 - Standards and Compliance
 - Risk Management
 - Performance Monitoring
 - Data Collection and Feedback Integration
 - Sensor Data Collection
 - Maintenance Report Insights
 - Operational Performance Evaluation
 - Performance Analysis
 - Performance Benchmark Updating
 - Maintenance and Renovation Needs Assessment
 - Maintenance and Project Needs Assessment
 - Maintenance
 - Routine Maintenance
 - Routine Maintenance Protocols
 - Routine Maintenance Schedules
 - Routine Maintenance History
 - Project Maintenance
 - Project Maintenance Planning
 - Project Maintenance History
 - Learning and Continuous Asset and Maintenance Improvement
 - Maintenance Feedback Collection
 - Maintenance and Asset Improvement Initiatives
 - Technical Specifications (SysML & Other Tools)
 - SysML Diagrams
 - Behavior Diagram
 - Activity
 - Sequence
 - State Machine
 - Use Case
 - Structure Diagram
 - Block Definition (BDD)

- Internal Block (IBD)
 - Parametric
 - Package
- Object Breakdown Structure
 - MovementSystems
 - PivotMechanism
 - Motor
 - Properties: MotorType, RotationSpeed.
 - Gear Assembly
 - Properties: Torque, GearType.
 - Pivot Joint
 - Properties: PivotType.
 - ControlAndMonitoringSystem
 - ControlSystem
 - Data Collection System
 - SensorSystem
 - Properties: SensorTypes, DataResolution, NumberOfSensors, etc.
 - Safety System
 - Safety Mechanism
 - Barriers
 - Control Module
 - StructuralComponents
 - BridgeDeck
 - Bridge Deck
 - Properties: MaterialType, LoadCapacity, DeckLength, etc.
 - Support Structures
- Functional Breakdown Structure
 - Traffic Management
 - Monitor Bridge Safety
 - Maintenance Operations
- Supplementary Tools and Models
 - Visualisation
 - Revit (BIM)
 - Model Identifier: Revit-001
 - Simulation and Analysis
 - Requirement Management
 - Relatics

- Tunnel
- Sluice
- Viaduct

4.1.2.2 Ontology and Reference Data Library

The Reference Data Library (RDL) is a foundational element of the bridge renovation and replacement programme, designed to systematically organise and manage data across various project dimensions. Utilising semantic web technologies such as RDF and RDFS, the RDL structures data into logical sections through carefully defined namespaces, corresponding to distinct aspects of the programme such as Programme Management, Project Management, and Asset Management. This organisation facilitates efficient data retrieval and management, ensuring that all data remains consistent, relevant, and aligned with the programme's strategic objectives.

The underlying ontology provides the conceptual foundation of this semantic structure, defining the classes, relationships, and properties needed to represent data consistently. The RDL builds upon this ontology by standardising and grouping these definitions into reusable elements that promote semantic consistency and interoperability. Instances are created as realisations of the classes defined in the ontology and RDL, representing operational data used throughout the programme.

Namespaces

Namespaces play a critical role in organising the ontology and taxonomy for the programme. By dividing the model into logical sections, namespaces ensure clarity and facilitate the retrieval, management, and effective use of data by various stakeholders.

Programme Management (prog:): This namespace encapsulates crucial data for overseeing the programme, including risk assessments and strategies for asset prioritisation, enabling high-level decision-making and strategic planning by ensuring data is stored efficiently and readily accessible for analysis, thus supporting timely decisions for prioritising new projects. Additionally, the systematic storage and analysis of data foster continuous learning capabilities, allowing the programme to adapt and evolve based on historical insights, enhancing future planning and the effectiveness of strategic initiatives. @prefix prog: <http://renovationandreplacement.org/programme#.

Project Management (proj:): Focused on the granular aspects of project oversight, this namespace covers management and systems engineering crucial for integrating technical components. It ensures project data is both manageable and actionable, facilitating cross-project querying to boost knowledge sharing and project performance. The insights gathered provide invaluable feedback to programme management regarding project status and impact. @prefix proj: <http://renovationandreplacement.org/project#.

Asset Management (asset:): Concentrating on the physical and operational characteristics of assets such as bridges and sensors, this namespace aids in detailed tracking and proactive maintenance activities. The real-time data from sensors help inform broader strategic

decisions on maintenance and operations within the programme. @prefix asset:
<<http://renovationandreplacement.org/asset#>.

RDF and RDFS (rdf: and rdfs:): RDF and RDFS namespaces provide the foundational structure for semantic technologies. RDF defines the basic data model using subject–predicate–object triples, while RDFS extends this by enabling class hierarchies and relationships, supporting the organisation of the programme’s ontology and taxonomy. @prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> and @prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#>.

RDF (Resource Description Framework) utilises a simple yet effective structure of subject-predicate-object to articulate statements about resources, forming a graph of interconnected data. Properties, such as `rdf:label` and `rdf:type`, are used to establish relationships or attribute values to these resources. These properties act as predicates in RDF triples, clearly defining the relationships between objects in a consistent and semantically rich manner. For example, `rdf:type` is employed to categorise resources under specific classes, thereby enhancing the semantic structure of the data. Additionally, RDF supports linking digital documents to resources, crucial for comprehensive data integration. A property such as `ex:hasDocument` can be used to link a project to related documents, effectively enhancing the data graph with accessible information.

RDFS extends the capabilities of RDF by providing tools for more complex class definitions and relationships. One significant feature is the `rdfs:subClassOf` property, which enables the creation of detailed class hierarchies. This capability allows properties and characteristics to be inherited, providing a more structured taxonomy that enhances the expressiveness and utility of the data model. Additionally, RDFS introduces `rdfs:domain` and `rdfs:range` to further refine property definitions. These properties specify the applicable resource types for each property and the nature of the values these properties can hold. This level of detail ensures that relationships are clearly defined and consistently applied across similar types of data, aiding in systematic data validation and integrity.

Classes

RDF and RDFS classes and subclasses form the backbone of a semantic data model, categorising and interlinking various aspects of program, project, and asset data. This structured approach facilitates consistency and communication across different activities and systems, enabling advanced management and precise compliance tracking. RDF serves as the foundation for the data model, representing basic data structures in the form of subject-predicate-object triples. While RDF effectively describes relationships and resources, it lacks inherent support for complex hierarchies or class definitions.

RDFS extends RDF by introducing additional vocabulary for more detailed descriptions of classes and properties. This extension includes mechanisms to define class hierarchies through subclassing, allowing for the inheritance of properties and behaviors from parent classes to subclasses. The following examples demonstrate how these classes and subclasses are used to model key entities within the programme.

```

# Base class for all assets

asset:Asset a rdfs:Class;

    rdfs:label "Asset";

    rdfs:comment "Represents any physical or digital asset."


proj:Requirement a rdfs:Class;

    rdfs:label "Requirement";

    rdfs:comment "Defines specific requirements within a project."


# Movement systems as a subclass of assets

asset:MovementSystem a rdfs:Class;

    rdfs:subClassOf asset:Asset;

    rdfs:label "Movement System";

    rdfs:comment "Encompasses all systems that enable controlled movement."


# Specific types of movement systems

asset:PivotMechanism a rdfs:Class;

    rdfs:subClassOf asset:MovementSystem;

    rdfs:label "Pivot Mechanism";

    rdfs:comment "A specialised movement system designed for pivotal functions of a swing bridge."

    # Properties defined here are inherited by all subclasses

    asset:maxLengthCapacity "1000 kg";


# Electric pivot mechanisms as a subclass of pivot mechanisms

asset:ElectricPivotMechanism a rdfs:Class;

    rdfs:subClassOf asset:PivotMechanism;

    rdfs:label "Electric Pivot Mechanism";

    rdfs:comment "A pivot mechanism that utilises electric power."

```

Additional properties specific to electric mechanisms

asset: electricPowerRating "200 kW"

Instances and Properties

In the Reference Data Library (RDL) for the bridge renovation and replacement programme, instances and properties play pivotal roles in bringing the theoretical framework of classes and subclasses into real-world application. These elements serve as the actual data points and connections that bring context to the semantic data model.

Properties in RDF and RDFS define the relationships between instances or between instances and their attributes. They specify how various entities within the library interact and depend on each other. These properties establish the practical rules for data interaction within the RDL.

It is important to note that while instances represent the practical implementation of the RDL's framework, they are not components of the RDL itself. Rather, instances are the tangible manifestations of the classes defined by the RDL. For example, if the RDL defines a class called 'Asset', an instance could be a specific bridge or sensor actually deployed within the project. These instances apply the properties and adhere to the relationships outlined in the RDL to ensure data is organised and utilised consistently across the project's operational systems.

The distinction between the RDL as a conceptual framework and the instances as realisations of that framework clarifies the RDL's role in defining data standards and structures. This distinction helps stakeholders understand how the RDL serves as a structural blueprint for data management, while instances represent its application in concrete, operational terms.

Instance of Electric Pivot Mechanism

asset:electricPivotMechExample a asset:ElectricPivotMechanism.

Property: Requires Wear Tolerance

proj:requiresWearTolerance a rdf:Property;

 rdfs:domain proj:Requirement;

 rdfs:range xsd:decimal;

 rdfs:label "Requires Wear Tolerance";

 rdfs:comment "Specifies the wear tolerance requirement in millimeters for an asset."

Property: Applies To

proj:appliesTo a rdf:Property;

```

    rdfs:domain proj:Requirement;

    rdfs:range asset:Asset;

    rdfs:label "Applies To";

    rdfs:comment "Indicates which asset a particular requirement applies to."

# Instance of Requirement
proj:R2 a proj:Requirement;

    proj:requiresWearTolerance "0.5" xsd:decimal;

    proj:appliesTo asset:electricPivotMechExample;

    proj:measuredBy sensor: wearSensor;

    rdfs:comment "Compliance Check through SPARQL and Python to evaluate actual
    sensor outputs against requirements"

# Requirement Management Class
proj:RequirementManagement a rdfs:Class;

    rdfs:label "Requirement Management";

    rdfs:comment "Manages the requirements of a project phase or technical process."

# Property: Contains
proj:contains a rdf:Property;

    rdfs:domain proj:RequirementManagement;

    rdfs:range proj:Requirement;

    rdfs:label "Contains";

    rdfs:comment "Indicates that Requirement Management includes one or more
    requirements."

# Instance of Requirement Management
proj:reqManagementDesign a proj:RequirementManagement;

    rdfs:label "Design Phase Requirement Management";

    proj:contains proj:R2. # Linking requirement R2 as part of Requirement Management

```

Instance of Wear Tolerance Sensor

sensor:wearSensorExample a sensor:WearToleranceSensor;

 sensor:measuresFor proj: R2; # Linking the sensor to R2

 sensor:output "0.7" xsd:decimal; # Example sensor output

 rdfs:label "Wear Tolerance Measurement";

 rdfs:comment "Sensor output that specifies higher wear tolerance based on real-time measurements."

4.1.3 Requirement Management – Relatics

In the context of the MBSE conceptual framework, a requirement management tool such as Relatics is valuable due to its user-friendly interface, making it suitable for structured data entry and management within infrastructure projects. While such tools can effectively serve as input platforms for the Semantic CDE, they do not inherently enforce standardised object breakdown structures or taxonomies. To ensure consistent and interoperable data across the renovation and replacement programme, it is essential that users apply the programme's predefined standards when configuring and using these tools. This alignment ensures that all information entered supports the broader semantic framework and contributes to a coherent, programme-wide data structure.

The integration of a Semantic CDE, utilising RDF and RDFS, complements tools such as Relatics by providing the necessary semantic framework to standardise relationships and data structures in both human-readable and machine-readable formats. This structured approach is vital for enhancing data interoperability and ensuring that all project data remains consistent. However, the current reliance on manual data exchange methods in tools such as Relatics, including the use of Excel imports and exports, limits the timeliness and integration of data. To enable effective interoperability, these tools must evolve to support automated and standardised data exchange with the Semantic CDE. This capability is crucial for supporting dynamic data interactions that enhance decision-making, operational, and design efficiency.

For example, the requirement "The bridge deck must support a distributed load of up to 500 kg/m²" is ideally suited for machine readability within the Semantic CDE. Being quantifiable and specific, it can be encoded into the CDE and subsequently shared with other software tools such as analysis and simulation applications for automated validations. Conversely, a requirement like "The aesthetic design of the bridge must align with the historical architecture of the surrounding area" is more qualitative and benefits from human interpretation, involving judgment and an understanding of cultural contexts which are best evaluated by designers through consultations and reviews. Tools like Building Information Modeling (BIM) are better suited for this task, providing visual tools that help ensure the design meets stakeholder expectations. The use of BIM facilitates the verification or validation process by visually demonstrating how the final construction will look relative to the historical context. The The

Semantic CDE can play a supportive role in this scenario by storing specific characteristics related to these requirement types, such as building materials or design motifs. By making this information easily accessible and reusable, the CDE enables faster execution of similar future projects and ensures that key aesthetic considerations are consistently understood and applied across different contexts.

Moreover, integrating Relatics with the Semantic CDE significantly enhances change management capabilities. By translating requirements into semantically linked data within the CDE, even minor adjustments in project parameters can be swiftly identified and modified. For example, if the requirement "The bridge deck must support a distributed load of up to 500 kg/m²" is updated to "700 kg/m²", the change is immediately converted into a machine-readable format and processed through the CDE. It is also automatically timestamped and cryptographically attributed to the responsible individual using hashing, ensuring full traceability and accountability. This update is automatically propagated across all connected tools, ensuring that analyses, simulations, and related outputs reflect the revised specification. The machine-readable nature of these changes ensures that every adjustment is not only documented but also actionable, allowing for updates and consistent application across various platforms, thereby enhancing system agility and responsiveness.

The textual requirements managed in Relatics can be translated into structured data forms that support verification and validation through simulations and analytical tools. However, to ensure correct transition between Relatics and these modelling environments, a well-defined strategy is essential. This strategy should clearly outline how requirements data is converted, integrated, and applied across platforms to maintain consistency. Automating this process workflows not only improves the efficiency of systems engineering tasks but also ensures adherence to standards throughout the programme.

Programme managers play a critical role in overseeing this integration, ensuring that operational data handling aligns with strategic programme goals. It is essential for each party involved to understand and communicate how they implement and utilise each tool within the MBSE framework. For example, programme managers might utilise machine-readable data of projects and assets at the programme level to inform broader strategic decisions. Conversely, project managers may opt for a combination of human-readable and machine-readable data, depending on the specific requirements and contexts of individual projects. This flexibility allows for the composition of different tools as building blocks of the MBSE framework to be optimally configured to meet the varying needs.

4.1.4 Modelling Language – SysML

In the domain of complex infrastructure projects, the application of SysML within the MBSE framework serves as a valuable tool for supporting specific systems engineering tasks. SysML is an open standard that provides a structured graphical language to visualise, specify, analyse, and document system architectures. While Linked Data forms the underlying data model of the Semantic CDE, particularly effective for traceability and ontology development, SysML can complement it by offering high-level abstractions that improve system understanding. Nonetheless, maintaining alignment with the Semantic CDE is essential to ensure semantic

consistency and interoperability across the programme. At the programme level, SysML's value is limited due to the risk of excessive complexity in diagrams, but it could be particularly useful at the project level for modelling control systems, sensors, and other technical subsystems. In those teams equipped with the required modelling skills, SysML can help develop subsystem specifications, provided that its outputs are well-integrated with the underlying semantic data model.

SysML serves as an abstract modelling language that bridges various disciplinary boundaries, enabling a unified understanding of system functionalities and operational strategies among diverse project teams. This abstract approach proves particularly advantageous when standardising sensor configurations and operational scenarios across multiple projects. By defining a universal sensor setup and data collection methodology using SysML diagrams, project participants can adhere to a consistent programme-wide data protocol. Furthermore, when organisations adopt SysML to model specific subsystems of an infrastructure asset, such as a bridge or control system, they can align those elements with the programme's standardised approach. The strength of SysML lies in its high level of abstraction, which should be a primary goal when using this tool. This abstraction facilitates enhanced cooperation between disciplines and at different system levels. By maintaining this high level of abstraction, users can avoid the temptation to delve too deeply into details, which can diminish the tool's effectiveness.

A detailed application of SysML for the Den Oever swing bridge case study is provided in Appendix D, demonstrating how SysML diagrams can be used to model complex systems within the MBSE framework. This includes use case, block definition, internal block, state machine, sequence, activity, requirement, and parametric diagrams. These diagrams collectively illustrate how subsystem behaviour, operational processes, and data interactions can be structured and understood across project phases. The use of SysML enhances interdisciplinary collaboration, scenario analysis, and control system visualisation, especially when modelling sensor integration, maintenance processes, and operational responses. Although SysML is not the core of the MBSE framework, it proves valuable for abstract modelling of subsystems and high-risk scenarios, complementing the Semantic CDE by enhancing system insight, supporting requirement verification, and aligning stakeholder understanding across engineering and operational domains.

4.1.5 Computer-Aided Design – Revit

Revit, a Building Information Modeling (BIM) software, plays a crucial role in the renovation and replacement programme for movable bridges by providing a comprehensive platform for design, documentation, and collaboration. The Revit model serves as a central repository for detailed information about the bridge, including materials, dimensions, structural elements, and location. This data-rich model enhances the accuracy and efficiency of the design process, facilitates collaboration among various disciplines, and provides 3D visualisation. Additionally, it enables verification and validation within a systems engineering context. Fig. 15 provides a Revit model visualisation of a moveable bridge.

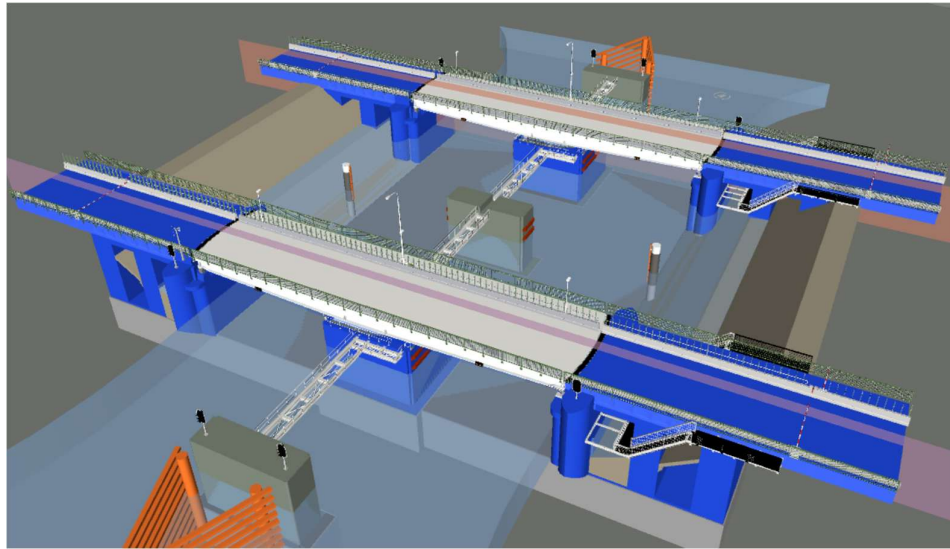


Figure 15 – Revit model of a moveable bridge

The Revit model is an advanced digital representation of the physical and functional characteristics of the bridge. It includes detailed specifications of construction materials, precise measurements of all structural components, comprehensive details of beams, columns, decks, and other critical elements, as well as geospatial information that situates the bridge within its environmental and geographic context. The model also has the capability to visualise the movement and operation of bridge components, such as the opening and closing of the bridge, using Autodesk Inventor, though this visualisation remains limited in complexity. Additionally, Revit allows for verification through various analyses, such as daylight studies, energy usage simulations, and material takeoffs. These elements are thoroughly documented in the Revit model, providing a comprehensive and detailed database accessible to all project stakeholders.

However, while Revit serves as a comprehensive database, it is not inherently a single source of truth. The information in the Revit model must be continuously checked and validated through the Common Data Environment (CDE), which acts as the central hub for managing, storing, and sharing all project-related data. The synergy between Revit and the CDE ensures that the Revit model is up-to-date and accurate, enabling real-time collaboration and informed decision-making (Nöldgen, 2022).

The integration of Revit with the CDE allows for interaction with data from other sources, ensuring consistency and traceability across the project lifecycle. Information from the Revit model, such as material specifications and structural dimensions, can be stored in the CDE, while updates or new requirements from the CDE can inform and update the Revit model. However, this interconnected data ecosystem, which enhances collaboration and accountability among project stakeholders, still needs to be fully established. Once in place, the CDE will track all changes made to the Revit model, providing a central and accessible history of modifications and updates.

In practice, the Revit model can demonstrate how data from various sources informs design and maintenance processes, linking material specifications and structural dimensions to performance requirements and ensuring that the design remains aligned with evolving project needs. While tools like ANSYS are often used for specific engineering simulations, such as load, stress, and dynamic analysis, Revit's primary role is to serve as a comprehensive design and documentation platform. The effort required to integrate Revit with more specialised tools like ANSYS highlights the need for a robust CDE to ensure that all data remains consistent and traceable throughout the project.

In a BIM-based workflow, the team can create 3D parametric models that serve as the foundation for generating necessary documents, such as plans, sections, elevations, schedules, and perspectives. This approach shifts focus from producing textual and 2D documents to investing more time in refining the design models, as these documents can be easily extracted from the model when needed. Additionally, the 3D geometry allows for effective verification and validation through analyses like daylighting studies, energy usage simulations, and material takeoffs (Autodesk, 2024).

As the industry continues to develop processes around the technology behind BIM, its potential continues to grow. Many applications are possible using building information modelling. As more benefits are achievable through BIM, teams find new uses to explore and develop. BIM uses can be organised into five basic activities: gather, generate, analyse, communicate, and realise (Kreider & Messner, 2013). Gathering involves collecting and managing building information. Generating focuses on creating information about the building. Analysing examines aspects or components of the building to make better decisions about how to plan, design, construct, or operate it. Communicating involves collaboratively sharing information about a building. Realising entails building or managing a physical element using building data.

Understanding how benefits are derived from these uses will help focus the team's efforts in planning, managing, and governing BIM processes. For example, during the early design phases of a building, quantities may be generally estimated but become more certain as the contract documents are created and construction processes proceed. All along, the stored information becomes more and more accurate with respect to design intent.

4.1.6 MBSE Framework in Action Introduction

To understand how the MBSE framework operates in practice, it is important to examine how different types of models interact across the system's lifecycle. ISO 15288 outlines four distinct types of models: prescriptive, descriptive, verification, and cognitive models. In the context of a renovation and replacement MBSE framework, the process starts with an informal and semi-formal **prescriptive model** that outlines the system's design to ensure it meets the expected needs and requirements. Once the system is constructed or renovated, it is partially verified against this prescriptive model using a formal **verification model**. This verification model remains active throughout the system's lifecycle, allowing for ongoing assessment as requirements evolve. Any changes in requirements should prompt updates to the system, potentially requiring maintenance or further renovation. Following successful

verification, the system is documented as an as-built descriptive model, which is essential for ongoing maintenance, renovation, and replacement activities. Over time, these **descriptive models** contribute to forming a **cognitive model**, representing the system's current state and supporting decision-making by providing a comprehensive view of the system's status and operational context. This approach ensures that the system evolves to meet operational needs while maintaining traceability throughout its lifecycle.

SysML plays a critical role within this framework by serving multiple functions. Initially, it acts as a prescriptive model for communication between clients and various disciplines, focusing on high-level requirements and scenarios. It facilitates early-stage visual communication through diagrams by capturing constraints, design choices, and interrelationships. As the project progresses, SysML also serves as a verification model to ensure that the system meets the defined requirements. Furthermore, SysML contributes to creating descriptive models that document the current state of the system, which is essential for ongoing maintenance and operational activities. These models are crucial for developing a comprehensive understanding of the system, supporting effective management throughout its lifecycle.

Revit, as a Building Information Modeling (BIM) tool, complements this by offering a detailed 3D digital representation of the physical structure. This becomes vital in developing the prescriptive, verification, and descriptive models within the MBSE framework. Revit allows for the detailed documentation of the "as-built" condition of the asset, ensuring that the descriptive models created in SysML and other tools are aligned with the actual physical attributes of the infrastructure. It also supports the prescriptive models by helping define and visualise the design requirements, as well as the verification models by offering a platform for assessing how the physical structure meets the defined requirements. Although Revit plays a crucial role in managing prescriptive, verification, and descriptive models, the cognitive model is realised through other tools that capture the system's evolving operational context and decision-making processes.

Linked Data is indispensable in managing descriptive models and realising a cognitive model. It enables seamless integration, retrieval, and updating of information across different systems and projects, including the data originating from Revit's 3D models and SysML. This interconnected view of information enhances the effectiveness of information management and configuration management, as outlined in ISO 15288. Traditional software tools often face challenges in integration and updating, which can complicate achieving a complete systems engineering approach. Linked Data's ability to provide a cohesive and integrated view of information supports a comprehensive and consistent approach to systems engineering, particularly across multiple projects, and when working with tools like Revit. Information Management is a critical component of systems engineering, as it involves the systematic handling of data and information throughout the system's lifecycle. ISO 15288 emphasises the importance of managing information to ensure it is accurate, accessible, and up-to-date. Linked Data supports this by providing a framework that allows for the effective storage, retrieval, and integration of information. This capability is particularly valuable in

complex systems engineering environments where managing vast amounts of data from multiple sources is essential for maintaining system integrity and achieving project goals.

The risk management process systematically addresses uncertainty by identifying, analysing, treating, and monitoring risks throughout the system's lifecycle. It involves defining a risk management strategy, identifying potential risks, assessing their likelihood and impact, and implementing appropriate treatments. Linked Data is crucial in this context as it facilitates the storage and management of risk information across different projects. By maintaining a comprehensive risk profile within a Linked Data model, organisations can more effectively identify and manage risks in future projects. This integration allows for easier identification of recurring issues and the application of lessons learned, thereby enhancing the overall risk management process.

Configuration Management is essential for managing system and system element configurations over their lifecycle. This process involves establishing and maintaining consistency, integrity, and traceability of configurations. It includes defining baselines, managing configuration changes, and performing configuration audits. Linked Data supports configuration management by providing a unified framework for storing and managing configuration information. This integration ensures that configuration changes are controlled, the current configuration status is accurately recorded, and information is readily available for decision-making.

The decision management process provides a structured, analytical framework for objectively identifying, characterising, and evaluating alternatives at any point in the lifecycle. It includes defining a decision management strategy, assessing alternatives against criteria, and selecting the most beneficial course of action. Linked Data enhances decision management by providing a comprehensive dataset of historical and current information about alternatives. This allows for better-informed decision-making through the effective comparison of alternatives based on detailed, machine-readable data. The ability to track and analyse past decisions helps in understanding the rationale behind choices and supports future decision-making.

Portfolio Management involves identifying and prioritising strategic ventures, allocating resources and budgets, and managing project performance. Linked Data improves portfolio management by offering a comprehensive, machine-readable dataset that helps in evaluating and prioritising projects based on real-time information. By integrating data from various projects, organisations can more effectively identify which renovation and replacement projects are critical, ensuring that resources are allocated efficiently and strategic goals are met.

Knowledge Management encompasses the creation, organisation, and sharing of knowledge assets. Linked Data plays a crucial role by providing a unified framework for managing and integrating knowledge across projects. Examples of knowledge assets include design specifications, system models, lessons learned, and technical documentation. Linked Data facilitates the effective use of these assets by ensuring they are accessible and up-to-date.

By leveraging Linked Data, the MBSE framework achieves a holistic integration of all key processes as defined by ISO 15288, including risk management, configuration control, decision management, and portfolio management. It also ensures that knowledge and information are retained and made accessible across all lifecycle stages. In the Den Oever swing bridges case study, Linked Data serves as the cornerstone that connects these processes, enabling information flow across the various stages of the project. The integration of Linked Data across models and lifecycle phases, from initial design to long-term maintenance, demonstrates its critical role in keeping both projects and the overarching programme adaptive, informed, and resilient. In addition to supporting daily operations, it reinforces strategic programme governance by enabling long-term asset sustainability. Through its semantic structure, Linked Data interconnects the system at different levels of the programme. This allows information to flow consistently across disciplines and management layers. In doing so, it also enables a participatory system in which actors can self-organise, respond to emerging needs, and collaborate on shared objectives. Trust, empowerment, and engagement are fostered by making data transparent, machine-readable, and traceable, allowing for decentralised interaction and responsible decision-making through an accessible tool interface.

In essence, Linked Data realises the full potential of the MBSE framework by ensuring that all data and processes are interconnected and transparent, enabling informed decision-making across all levels of the system. This supports both the governance of the overarching programme and the effective systems engineering of complex infrastructure projects like the Den Oever swing bridges. In such complex systems, accurate and accessible and structured data is essential for making the right decisions. The following sections provide applied examples that demonstrate the operational integration and functionality of the Semantic CDE.

4.1.7 Semantic CDE in Action Examples

To illustrate the practical application of the Semantic CDE in infrastructure programmes, Table 11 provides an overview of key examples. These examples demonstrate the integration of semantic technologies like RDF, RDFS, OWL, SWRL, and SHACL, alongside tools such as BIM, SysML, and Relatics. By addressing diverse use cases, the examples highlight how the Semantic CDE enables knowledge sharing, interdisciplinary collaboration, impact analysis, and decision-making. RDFS provides the foundational structure for organising data, while OWL and SWRL enable advanced reasoning, such as automated rule-based alerts. Together, these technologies showcase the potential of semantic integration to transform data into actionable insights, supporting effective systems engineering and programme governance.

Table 11 – Semantic CDE Examples Overview

No.	Example	Integrated Concepts	Outcome
1	Integration Between Different Tools Such as BIM, SysML, Ansys, and Relatics	Structural data, such as deck and pivot mechanism specifications, are linked to operational attributes within the Semantic CDE. BIM models (IFC format) are converted into OWL for integration, ensuring consistency and traceability across physical (BIM), semantic (OWL), and functional (SysML) models.	Streamlined collaboration enables design verification and validation, operational insights, and improved interdisciplinary consistency.

No.	Example	Integrated Concepts	Outcome
	Through the Semantic CDE	Analytical results (Ansys) are automatically verified against input from requirement management tools (Relatics), ensuring alignment with design and functional specifications.	
2	Interdisciplinary Collaboration and Knowledge Exchange Through Programme-Level Queries in the Semantic CDE	A structural engineer designs a steel beam, adding its properties into the CDE, which is then shared with electrical engineers for control system integration. SKOS enriches RDF/RDFS by organising taxonomies for components and maintenance categories. Queries can be conducted at different levels: Programme ("Which bridges need maintenance in 6 months?"), Cross-Project ("What lessons learned from sluice renovations apply to the swing bridge?"), and Interdisciplinary ("Which components are critical for multiple disciplines?"). Access control ensures that only authorised personnel can access or modify information, and cryptographic authentication verifies users before changes are made. Cryptographic hashes provide data integrity protection, ensuring no unauthorised alterations occur within the shared environment.	Facilitates enhanced collaboration via shared semantic-linked data, enabling structured knowledge representation and retrieval. SKOS improves query efficiency by adding intuitive labels, synonyms, and relationships, supporting better decision-making and cross-disciplinary knowledge sharing across the programme while ensuring secure data handling and access control.
3	Requirement Change, Impact Analysis, and Traceability	When a requirement change occurs, such as an update in the bridge deck's load capacity, the Semantic CDE enables impact analysis by querying linked models' data, including SysML diagrams, BIM data, and Relatics requirements. The flow and immutable storage of data and information across the asset lifecycle realise a Digital Thread, ensuring end-to-end traceability. Blockchain and cryptographic hashes provide an audit trail, tracking who accessed or modified information, what was changed, how and why it was changed, and when it occurred. Through cryptographic methods, accountability is facilitated by identifying the individuals responsible for changes, while audit trails provide comprehensive insights into the rationale and consequences of design changes, enabling traceability of engineering decisions over time.	Immutable records facilitating accountability and enabling traceability.
4	Digital Twin and Rule-Based Reasoning (SHACL, SWRL, RIF)	Real-time sensor data (e.g., load and wear tolerance) are integrated into the Semantic CDE for automated monitoring and decision-making. SHACL validates compliance with requirements, ensuring data consistency with OWL models. SWRL triggers maintenance or renovation actions when thresholds are exceeded, while RIF ensures rule interoperability across systems. A centralised Performance Dashboard aggregates data from multiple Digital Twins for programme-level insights.	Enhanced operational efficiency through automated monitoring, predictive maintenance, and strategic planning at the programme level, leading to improved resource allocation and asset lifecycle management.
5	Self-Organising Contractor Collaboration in the Semantic CDE (Participatory System)	Asset owners publish a shared pool of bridges requiring renovation into the Semantic CDE. Contractors connect to the CDE, publishing their capacity, specialisation, and past project performance as Linked Data. Through SHACL-based rules, the system matches bridge assignments to contractors based on eligibility criteria (e.g., certification, availability, price, past	Demonstrates participatory interaction and decentralised coordination through a Semantic CDE. Supports trust (transparent matching and logging), engagement (shared visibility and interaction), and

No.	Example	Integrated Concepts	Outcome
		quality scores). Contractors can transparently view assignments, propose work reallocation among themselves, or initiate joint execution of complex projects. All actions are recorded with provenance (who, when, what, and why) and validated against governance rules.	empowerment (self-organisation and negotiated responsibility). Accelerates project initiation, improves resource utilisation, and enhances programme flexibility.

Code Snippet 1 below provides the namespaces used throughout the following chapter, which contains simplified examples illustrating the integration of various data sources into the Semantic Common Data Environment (CDE). These namespaces enable the structured representation and linking of assets, projects, requirements, and analytical results across different disciplines, facilitating enhanced interoperability and knowledge sharing. It is important to note that these namespaces are provided solely for demonstration purposes. The examples include both standard namespaces, which provide widely accepted definitions for data representation and interoperability, and custom namespaces, which are tailored to address the specific needs of renovation and replacement projects. A detailed overview of these namespaces is provided in Table 12.

Code Snippet 1

```
<rdf:RDF
  xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
  xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
  xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
  xmlns:ifc="http://example.org/ifc#"
  xmlns:asset="http://renovationandreplacement.org/asset#"
  xmlns:prog="http://renovationandreplacement.org/programme#"
  xmlns:proj="http://renovationandreplacement.org/project#"
  xmlns:sysml="http://example.org/sysml#"
  xmlns:relatics="http://example.org/relatics#"
  xmlns:change="http://example.org/change#"
  xmlns:rro="http://example.org/renovation-replacement#"
  xmlns:tool="http://example.org/tools#"
  xmlns:skos="http://www.w3.org/2004/02/skos/core#"
  xmlns:sh="http://www.w3.org/ns/shacl#"
  xmlns:geo="http://www.w3.org/2003/01/geo/wgs84_pos#"
>
```

Table 12 - Namespaces

Namespace Type	Namespace	Description
Standard Namespaces	rdf, rdfs, xsd	Standard RDF syntax, schema definitions, and data types.
	ifc	Represents data originating from Building Information Modeling (BIM) IFC models.
	skos	Enables the use of taxonomies to enhance knowledge management and classification.
	sh	Supports SHACL constraints for data validation and consistency checks.
Custom Namespaces Created for the Example	geo	Represents geographical locations for clustering and spatial analysis.
	rro	Provides a unified ontology for renovation and replacement projects, incorporating programme (prog), project (proj), and asset (asset) data to enable comprehensive management across all levels.
	asset	Describes assets such as bridges, structural components, and control systems.
	prog	Represents programme-level data, including strategic objectives and aggregated insights.
	proj	Defines project-specific elements and their relationships within the programme.
	sysml	Captures SysML-based requirements and design relationships for system engineering.
	relatics	Manages requirement-related data from tools like Relatics.
	change	Tracks modifications, audit trails, and accountability within the system.
	tool	Describes analytical tools used for calculations.

4.1.7.1 Tools Integration

Below is a simplified example of the BIM IFC4 representation of a pivot mechanism, see Code Snippet 2. To ensure seamless integration with the Semantic Common Data Environment (CDE), the IFC data is converted into RDF, aligning with the ontology and taxonomy defined for the renovation and replacement programme. This conversion ensures a consistent understanding of concepts across tools and disciplines, reducing miscommunication and promoting interoperability. IFC entities (e.g., IFCPROJECT, IFCBUILDING) are mapped to semantic classes (e.g., prog:Programme, asset:SwingBridge), while their attributes are represented as semantic relationships, preserving domain-specific context. The representation is shown here in XML format for its readability and compatibility with widely-used tools, while alternative formats like Turtle or JSON-LD can also be employed for their compact syntax and web-focused integration capabilities.

Code Snippet 2

```
#1 = IFCPROJECT(IFC-GUID1, $, 'Swing Bridge Renovation', $, $, $, (#2), $);
#2 = IFCBUILDING(IFC-GUID2, $, 'SwingBridge (SB-001)', $, $, $, $, $);
#3 = IFCSTRUCTURALITEM(IFC-GUID3, $, 'Pivot Mechanism', $, $, $, $, $);
#4 = IFCPROPERTYSET(IFC-GUID4, 'Pivot Mechanism Properties', $,
  (IFCPROPERTYSINGLEVALUE(IFC-GUID5, 'Material Type', IFCTEXT('Steel'))));
```

In this example, the original IFC representation of a swing bridge is translated into a Linked Data format, with the entity IFCBUILDING mapped to the asset:SwingBridge class. The

rdfs:isDefinedBy property explicitly links the semantic ontology representation to its IFC counterpart. This approach allows BIM data to be enriched and contextualised within the Semantic CDE. See Code Snippet 3 for details.

Code Snippet 3

```
<rdf:RDF>

  <!-- Original IFCBUILDING Mapped to RDF -->

  <ifc:IFCBUILDING rdf:ID="IFC_SwingBridge_SB001">

    <rdfs:label>SwingBridge (SB-001)</rdfs:label>

    <ifc:hasGlobalID>asset:SwingBridge_SB001</ifc:hasGlobalID>

    <ifc:hasName>SwingBridge</ifc:hasName>

    <ifc:hasDescription>SwingBridge (SB-001)</ifc:hasDescription>

  </ifc:IFCBUILDING>

  <!-- Semantic Ontology Representation -->

  <asset:SwingBridge rdf:ID="SwingBridge_SB001">

    <rdfs:label>Swing Bridge (SB-001)</rdfs:label>

    <asset:hasComponent rdf:resource="#PivotMechanism001" />

    <rdfs:isDefinedBy rdf:resource="#IFC_SwingBridge_SB001" />

  </asset:SwingBridge>

</rdf:RDF>
```

Code Snippet 4 demonstrates how outputs from different tools are integrated into the Semantic CDE while linking critical project elements. Real-time data from the wear and tear sensor and analytical results from ANSYS, linked via the asset:calculatedBy property, are associated with the pivot mechanism. The snippet also connects the swing bridge to its parent project, "Swing Bridge Renovation," managed by a project manager whose experience is documented through proj:hasExperience. Properties of the bridge, such as material type and load capacity, are explicitly defined and linked to relevant analytical tools and requirements, creating a unified framework. This setup enables consistent connections between assets, projects, tools, and personnel, forming a cohesive structure for managing data and supporting future analysis and decision-making.

Code Snippet 4

```
<rdf:RDF>

  <!-- Programme Definition -->

  <prog:Programme rdf:ID="RenovationAndReplacementProgramme">

    <rdfs:label>Renovation and Replacement Programme</rdfs:label>
```

```

    <proj:hasProject rdf:resource="#SwingBridgeRenovation"/>
</proj:Programme>

<!-- Project Definition -->
<proj:Project rdf:ID="SwingBridgeRenovation">
    <rdfs:label>Swing Bridge Renovation</rdfs:label>
    <proj:hasAsset rdf:resource="#SwingBridge_SB001"/>
    <proj:managedBy rdf:resource="#ProjectManager001"/>
</proj:Project>

<!-- Asset Definition -->
<asset:SwingBridge rdf:ID="SwingBridge_SB001">
    <rdfs:label>Swing Bridge (SB-001)</rdfs:label>
    <asset:hasComponent rdf:resource="#PivotMechanism001"/>
</asset:SwingBridge>

<!-- Pivot Mechanism Definition -->
<asset:PivotMechanism rdf:ID="PivotMechanism001">
    <rdfs:label>Pivot Mechanism</rdfs:label>
    <asset:hasPropertySet rdf:resource="#PivotMechanismProperties"/>
    <sysml:hasRequirement rdf:resource="#WearToleranceRequirement"/>
    <relatics:hasRequirement rdf:resource="#WearToleranceSensorRequirement"/>
    <sysml:hasDiagram rdf:resource="http://example.org/sysml#PivotMechanismActivityDiagram"/>
</asset:PivotMechanism>

<!-- SysML Requirement for Wear Tolerance -->
<sysml:Requirement rdf:ID="WearToleranceRequirement">
    <rdfs:label>Wear Tolerance Requirement</rdfs:label>
    <sysml:constrains rdf:resource="#PivotMechanism001"/>
    <sysml:requiresValue>0.5</sysml:requiresValue>
</sysml:Requirement>

<!-- Relatics Requirement for Sensor Inclusion -->

```

```

<relatics:Requirement rdf:ID="WearToleranceSensorRequirement">
  <rdfs:label>Wear Tolerance Sensor Inclusion</rdfs:label>
  <relatics:definesSensor rdf:resource="#WearAndTearSensor001"/>
  <relatics:constrains rdf:resource="#PivotMechanism001"/>
</relatics:Requirement>

<!-- Sensor Definition -->
<asset:Sensor rdf:ID="WearAndTearSensor001">
  <rdfs:label>Wear and Tear Sensor</rdfs:label>
  <asset:monitors rdf:resource="#PivotMechanism001"/>
  <asset:latestValue>0.7</asset:latestValue>
</asset:Sensor>

<!-- Property Set Definition -->
<asset:PropertySet rdf:ID="PivotMechanismProperties">
  <rdfs:label>Pivot Mechanism Properties</rdfs:label>
  <asset:hasProperty rdf:resource="#Material"/>
  <asset:hasProperty rdf:resource="#LoadCapacity"/>
</asset:PropertySet>

<!-- Material Property -->
<asset:Property rdf:ID="Material">
  <rdfs:label>Material Type</rdfs:label>
  <asset:value>Steel</asset:value>
</asset:Property>

<!-- Load Capacity Property -->
<asset:Property rdf:ID="LoadCapacity">
  <rdfs:label>Load Capacity</rdfs:label>
  <asset:value>10000</asset:value>
  <asset:calculatedBy rdf:resource="#ANSYS"/>
</asset:Property>

```

```

<!-- Project Manager -->
<proj:ProjectManager rdf:ID="ProjectManager001">
  <rdfs:label>Felix de Ligt</rdfs:label>
  <proj:hasExperience>10</proj:hasExperience>
  <proj:experienceUnit>years</proj:experienceUnit>
</proj:ProjectManager>

<!-- Analytical Tool Definition -->
<tool:AnalyticalTool rdf:ID="ANSYS">
  <rdfs:label>ANSYS Simulation Software</rdfs:label>
  <tool:version>2024</tool:version>
  <tool:description>Tool used for structural and load capacity analysis.</tool:description>
</tool:AnalyticalTool>
</rdf:RDF>

```

Code Snippet 5 demonstrates the integration of a pivot mechanism, sensors, and requirements within the Semantic CDE using the Renovation and Replacement Ontology (RRO). The RRO namespace unifies programme, project, and asset-level data (simplifying the explanation of the case study examples). The pivot mechanism links to two requirements: wear tolerance and load capacity. A wear and tear sensor is connected to the pivot mechanism through `rro:requiresSensor`, with the requirement it verifies defined via `rro:verifies`. The latest sensor reading is recorded as 0.7, which is compared against the required tolerance of 0.5 for compliance. Similarly, the load capacity is verified against analytical results from ANSYS simulations. This bidirectional structure ensures traceability, allowing sensors to monitor compliance and requirements to verify sensor performance.

Code Snippet 5

```

<rdf:RDF>
  <!-- Project Definition -->
  <rro:Project rdf:ID="SwingBridgeRenovation">
    <rdfs:label>Swing Bridge Renovation</rdfs:label>
    <rro:hasAsset rdf:resource="#SwingBridge_SB001"/>
  </rro:Project>

  <!-- Asset Definition -->
  <rro:SwingBridge rdf:ID="SwingBridge_SB001">
    <rdfs:label>Swing Bridge (SB-001)</rdfs:label>

```

```

        <rro:hasComponent rdf:resource="#PivotMechanism001"/>
    </rro:SwingBridge>

    <!-- Pivot Mechanism Definition -->
    <rro:PivotMechanism rdf:ID="PivotMechanism001">
        <rdfs:label>Pivot Mechanism</rdfs:label>
        <rro:hasRequirement rdf:resource="#WearToleranceRequirement"/>
        <rro:hasRequirement rdf:resource="#LoadCapacityRequirement"/>
        <rro:requiresSensor rdf:resource="#WearAndTearSensor001"/>
    </rro:PivotMechanism>

    <!-- Sensor Definition -->
    <rro:Sensor rdf:ID="WearAndTearSensor001">
        <rdfs:label>Wear and Tear Sensor</rdfs:label>
        <rro:verifies rdf:resource="#WearToleranceRequirement"/>
        <rro:monitors rdf:resource="#PivotMechanism001"/>
        <rro:latestValue>0.7</rro:latestValue>
    </rro:Sensor>

    <!-- Requirement Definitions -->
    <rro:Requirement rdf:ID="WearToleranceRequirement">
        <rdfs:label>Wear Tolerance Requirement</rdfs:label>
        <rro:requiresValue>0.5</rro:requiresValue>
        <rro:verifies rdf:resource="#WearAndTearSensor001"/>
    </rro:Requirement>

    <rro:Requirement rdf:ID="LoadCapacityRequirement">
        <rdfs:label>Load Capacity Requirement</rdfs:label>
        <rro:requiresValue>10000</rro:requiresValue>
        <rro:verifies rdf:resource="#ANSYSLoadCapacityResult"/>
    </rro:Requirement>

    <!-- Analytical Result Definition -->

```

```

<rro:AnalyticalResult rdf:ID="ANSYSLoadCapacityResult">
  <rdfs:label>ANSYS Load Capacity Result</rdfs:label>
  <rro:calculatedBy rdf:resource="#ANSYS"/>
  <rro:resultValue>9500</rro:resultValue>
</rro:AnalyticalResult>
</rdf:RDF>

```

The integration of SPARQL queries within the Semantic CDE facilitates the automated verification of asset performance and analytical calculation results against predefined requirements. In this example, the pivot mechanism's compliance with wear tolerance and load capacity requirements is assessed. The query retrieves the latest sensor value from the wear and tear sensor, compares it to the wear tolerance requirement, and evaluates the analytical load capacity result from ANSYS simulations against the specified load capacity requirement from Relatics. Filters within the query ensure that any deviations from the requirements are flagged for corrective action, see Code Snippet 6. The results, as shown in Table 13, provide a clear overview of the compliance status of each pivot mechanism, indicating whether the wear and load capacity conditions meet the specified requirements.

Code Snippet 6

```

SELECT ?pivotMechanism ?wearToleranceRequirement ?wearSensorValue ?loadCapacityRequirement
?loadCapacityResult
WHERE {
  # Retrieve the pivot mechanism and its linked requirements
  ?pivotMechanism a rro:PivotMechanism ;
    rro:hasRequirement ?wearToleranceRequirement ;
    rro:hasRequirement ?loadCapacityRequirement ;
    rro:requiresSensor ?wearSensor .

  # Match the wear tolerance requirement
  ?wearToleranceRequirement a rro:Requirement ;
    rro:requiresValue ?requiredWearTolerance ;
    rro:verifies ?wearSensor .

  # Retrieve the latest sensor value
  ?wearSensor a rro:Sensor ;
    rro:latestValue ?wearSensorValue .

```

```

# Match the load capacity requirement
?loadCapacityRequirement a rro:Requirement ;

    rro:requiresValue ?requiredLoadCapacity ;

    rro:verifies ?loadCapacityResult .

# Retrieve the analytical result value
?loadCapacityResult a rro:AnalyticalResult ;

    rro:resultValue ?loadCapacityValue .

# Apply filters to check compliance
FILTER(xsd:decimal(?wearSensorValue) <= xsd:decimal(?requiredWearTolerance))
FILTER(xsd:decimal(?loadCapacityValue) >= xsd:decimal(?requiredLoadCapacity))
}

```

Table 13 – SPARQL Results Code Snippet 6

Pivot Mechanism	Wear Tolerance Requirement	Wear Sensor Value	Load Capacity Requirement	Load Capacity Result	Compliance
Pivot A	0.5	0.4	10000	10500	Pass
Pivot B	0.6	0.7	12000	11000	Fail
Pivot C	0.4	0.3	9000	9500	Pass

4.1.7.2 Knowledge Exchange and Collaboration

This example demonstrates how interdisciplinary collaboration and knowledge exchange are facilitated within the Semantic CDE through the integration of various data sources and SKOS-enriched taxonomies. A structural engineer updates the bridge deck's load capacity, and this information is linked to related components, such as bearings and sensors, within the CDE. Mechanical engineers can access these updates, ensuring efficient coordination between disciplines. The inclusion of audit trails provides a detailed history of changes, tracking who made modifications, what changes were made, and when they occurred. Cryptographic authentication mechanisms, such as user-specific cryptographic hashes, ensure data integrity by verifying the identity of users and providing a reliable record of changes. These hashes, coupled to individual users, enable stakeholders to track precisely who made modifications, verify the authenticity of the data, and identify the responsible person for follow-up questions regarding specific changes, fostering accountability and effective communication. Certain roles can be granted access to specific information, ensuring that relevant stakeholders can retrieve and contribute data securely. The SKOS taxonomy enhances information accessibility by providing structured metadata, such as alternative labels, notes, and historical insights. This allows engineers across different disciplines to query information efficiently, improving decision-making and ensuring that valuable lessons learned, such as previous maintenance

challenges and material recommendations, are readily available. The Semantic CDE enables continuous expansion as different disciplines contribute new data, linking additional related components, such as inspection records, operational parameters, and recommended maintenance strategies, further enriching the knowledge base. Programme-level queries supported by the Semantic CDE allow stakeholders to assess which bridges require renovation based on historical performance data and, when integrated with Digital Twins, real-time insights. These capabilities facilitate proactive maintenance planning, optimised resource allocation, and improved asset management. See Code Snippet 7 for the full implementation of the Semantic CDE model.

Code Snippet 7

```
<rdf:RDF>

  <!-- Project Definition -->

  <proj:Project rdf:ID="SwingBridgeRenovation">

    <rdfs:label>Swing Bridge Renovation</rdfs:label>

    <proj:hasAsset rdf:resource="#Deck_SB001"/>

    <proj:plannedRenovation>true</proj:plannedRenovation>

    <proj:lastUpdated>2024-01-20T14:30:00</proj:lastUpdated>

  </proj:Project>


  <!-- Bridge Deck -->

  <asset:BridgeDeck rdf:ID="Deck_SB001">

    <rdfs:label>Bridge Deck SB001</rdfs:label>

    <asset:hasProperty rdf:resource="#LoadCapacity"/>

    <asset:monitoredBy rdf:resource="#LoadSensor001"/>

    <asset:hasComponent rdf:resource="#Bearing001"/>

    <change:hasAuditTrail rdf:resource="#AuditTrail001"/>

    <change:hasAuditTrail rdf:resource="#AuditTrail002"/>

    <change:hasAuditTrail rdf:resource="#AuditTrail003"/>

    <skos:note>Ensure compatibility with existing foundation structures.</skos:note>

    <asset:hasAccessControl rdf:resource="#AccessControl_BridgeDeck"/>

  </asset:BridgeDeck>


  <!-- Access Control -->

  <asset:AccessControl rdf:ID="AccessControl_BridgeDeck">

    <rdfs:label>Bridge Deck Access Control</rdfs:label>
```

```

    <asset:allowedRole>StructuralEngineer</asset:allowedRole>

    <asset:allowedRole>MaintenanceEngineer</asset:allowedRole>

    <asset:restrictedRole>ElectricalEngineer</asset:restrictedRole>
</asset:AccessControl>

<!-- Bearing Component -->
<asset:Bearing rdf:ID="Bearing001">
    <rdfs:label>Main Bridge Bearing</rdfs:label>
    <asset:weight>250.5</asset:weight>
    <asset:weightUnit>kg</asset:weightUnit>
    <asset:dimensions>500x300x200</asset:dimensions>
    <asset:dimensionsUnit>mm</asset:dimensionsUnit>
    <asset:lastUpdated>2024-01-15T08:45:00</asset:lastUpdated>
    <skos:related rdf:resource="#Deck_SB001"/>
    <skos:note>Consider using composite material bearings to enhance durability.</skos:note>
    <skos:historyNote>Previous steel bearings required frequent maintenance due to
corrosion.</skos:historyNote>
    <change:hasAuditTrail rdf:resource="#AuditTrail003"/>
</asset:Bearing>

<!-- Lessons Learned Audit Trail -->
<change:AuditTrail rdf:ID="AuditTrail003">
    <rdfs:label>Bearing Maintenance Review</rdfs:label>
    <change:changedBy>MaintenanceEngineer</change:changedBy>
    <change:userHash>sha256:2b8a3c9e4d5f6a7b8c9e0d1f2a3b4c5d</change:userHash>
    <change:timestamp>2024-01-12T11:30:00</change:timestamp>
    <change:changeDescription>Recommended switch to composite bearings due to corrosion in
steel.</change:changeDescription>
</change:AuditTrail>

<!-- Properties -->
<asset:Property rdf:ID="LoadCapacity">
    <rdfs:label>Load Capacity</rdfs:label>
    <asset:value>10000</asset:value>

```

```

    <asset:unit>kg</asset:unit>
  </asset:Property>

  <!-- Load Sensor -->
  <asset:Sensor rdf:ID="LoadSensor001">
    <rdfs:label>Load Sensor</rdfs:label>

    <asset:latestReading>12000</asset:latestReading>

    <asset:readingTimestamp>2024-01-20T10:00:00</asset:readingTimestamp>
  </asset:Sensor>

  <!-- Audit Trails -->
  <change:AuditTrail rdf:ID="AuditTrail001">
    <rdfs:label>Load Capacity Change</rdfs:label>

    <change:changedBy>StructuralEngineer</change:changedBy>

    <change:userName>Felix de Ligt</change:userName>

    <change:userHash>sha256:e99a18c428cb38d5f260853678922e03</change:userHash>

    <change:timestamp>2024-01-19T09:15:00</change:timestamp>

    <change:changeDescription>Increased load capacity from 8000 to 10000
kg.</change:changeDescription>
  </change:AuditTrail>

  <change:AuditTrail rdf:ID="AuditTrail002">
    <rdfs:label>Bearing Weight Update</rdfs:label>

    <change:changedBy>MechanicalEngineer</change:changedBy>

    <change:userName>Felix de Ligt</change:userName>

    <change:userHash>sha256:5d41402abc4b2a76b9719d911017c592</change:userHash>

    <change:timestamp>2024-01-18T15:30:00</change:timestamp>

    <change:changeDescription>Updated bearing weight from 240 to 250.5 kg.</change:changeDescription>
  </change:AuditTrail>
</rdf:RDF>

```

This SPARQL query enables programme-level prioritisation of bridge maintenance and renovation within the Semantic CDE by evaluating key factors such as current load, defined capacity, required capacity, and bridge age. The query classifies bridges into priority levels, identifying those that exceed their defined capacity as high priority, with older bridges given

additional urgency. It helps stakeholders make data-driven decisions by integrating real-time sensor data with lifecycle information, ensuring efficient resource allocation and timely interventions. The query results are presented in Table 14, which provides a structured classification of bridges based on their risk levels, ordered by priority level to ensure that the most critical assets are addressed first. See Code Snippet 8 for implementation details.

Code Snippet 8

```
SELECT ?bridge ?currentLoad ?definedCapacity ?requiredCapacity ?age ?priorityLevel
WHERE {
    ?bridge a asset:BridgeDeck ;
        asset:monitoredBy ?sensor ;
        asset:hasProperty ?capacityProperty ;
        asset:age ?age ;
        asset:requirement ?requiredCapacity .

    ?sensor asset:latestReading ?currentLoad ;
        asset:readingTimestamp ?timestamp .

    ?capacityProperty asset:value ?definedCapacity .

    BIND(
        IF(?currentLoad > ?definedCapacity,
            IF(?age > 50, "Critical", "High"), # Immediate risk, critical if aged, else high
            IF(?requiredCapacity > ?definedCapacity,
                IF(?age > 50, "Medium", "Low"), # Future risk, medium if aged, else low
                "Normal"
            )
        )
    AS ?priorityLevel
}
ORDER BY DESC(?priorityLevel)
```

Table 14 - SPARQL Results Code Snippet 8

Bridge	Current Load	Defined Load Capacity	Required Load Capacity	Age	Priority Level
--------	--------------	-----------------------	------------------------	-----	----------------

Bridge A	12000	10000	11000	55	Critical
Bridge C	9500	9000	10000	60	Critical
Bridge B	11500	10000	10500	40	High
Bridge D	8000	9000	9500	35	Low
Bridge E	7000	7000	7500	25	Normal

The Semantic CDE facilitates programme-level planning and optimisation of control system updates by leveraging data across multiple assets. By integrating data such as failure rates, downtime history, failure reasons, and geographical location, stakeholders can prioritise maintenance clusters based on criticality and plan interventions efficiently. Queries enable decision-makers to identify assets with recurring control system failures, such as software malfunctions, and coordinate maintenance schedules based on surrounding assets to optimise resource allocation and reduce operational downtime. The structured data provided by the Semantic CDE not only enhances maintenance efficiency but also offers valuable insights for future bridge designs through SE. Historical failure trends and audit trails documenting corrective actions can inform engineers about potential design improvements. See Code Snippet 9 for the implementation of the Semantic CDE model.

Code Snippet 9

```
<rdf:RDF>

  <!-- Projects -->

  <proj:Project rdf:ID="SwingBridgeRenovation">
    <rdfs:label>Swing Bridge Renovation</rdfs:label>
    <proj:hasAsset rdf:resource="#Bridge_SB001"/>
    <proj:plannedRenovation>true</proj:plannedRenovation>
    <proj:lastUpdated>2024-01-20T14:30:00</proj:lastUpdated>
  </proj:Project>

  <proj:Project rdf:ID="DrawBridgeUpgrade">
    <rdfs:label>Draw Bridge Upgrade</rdfs:label>
    <proj:hasAsset rdf:resource="#Bridge_DB001"/>
    <proj:plannedRenovation>true</proj:plannedRenovation>
    <proj:lastUpdated>2024-01-18T09:45:00</proj:lastUpdated>
  </proj:Project>

  <!-- Bridge SB001 -->

  <asset:Bridge rdf:ID="Bridge_SB001">
    <rdfs:label>Bridge SB001</rdfs:label>
```

```

<asset:hasComponent rdf:resource="#ControlSystem001"/>

<geo:Point>
  <geo:lat>52.3676</geo:lat>
  <geo:long>4.9041</geo:long>
</geo:Point>

<asset:installationYear>1995</asset:installationYear>
</asset:Bridge>

<!-- Bridge DB001 -->
<asset:Bridge rdf:ID="Bridge_DB001">
  <rdfs:label>Bridge DB001</rdfs:label>
  <asset:hasComponent rdf:resource="#ControlSystem002"/>
  <geo:Point>
    <geo:lat>51.9225</geo:lat>
    <geo:long>4.47917</geo:long>
  </geo:Point>
  <asset:installationYear>2005</asset:installationYear>
</asset:Bridge>

<!-- Control Systems -->
<asset:ControlSystem rdf:ID="ControlSystem001">
  <rdfs:label>Control System v1.2</rdfs:label>
  <asset:version>1.2</asset:version>
  <asset:lastUpdate>2023-06-15</asset:lastUpdate>
  <asset:failureRate>3.2</asset:failureRate>
  <asset:downtimeHistory>2023-01-12, 2023-04-22, 2023-09-10</asset:downtimeHistory>
  <change:hasFailure rdf:resource="#FailureEvent001"/>
</asset:ControlSystem>

<asset:ControlSystem rdf:ID="ControlSystem002">
  <rdfs:label>Control System v1.5</rdfs:label>
  <asset:version>1.5</asset:version>
  <asset:lastUpdate>2022-11-10</asset:lastUpdate>

```

```

    <asset:failureRate>2.1</asset:failureRate>

    <asset:downtimeHistory>2022-03-10, 2022-08-15</asset:downtimeHistory>

    <change:hasFailure rdf:resource="#FailureEvent002"/>
</asset:ControlSystem>

<!-- Failure Events -->
<change:Failure rdf:ID="FailureEvent001">
    <rdfs:label>Software Malfunction</rdfs:label>
    <change:failureReason>Control software bug</change:failureReason>
    <change:failureDate>2023-09-10T11:00:00</change:failureDate>
</change:Failure>

<change:Failure rdf:ID="FailureEvent002">
    <rdfs:label>Sensor Failure</rdfs:label>
    <change:failureReason>Sensor calibration error</change:failureReason>
    <change:failureDate>2022-08-15T14:20:00</change:failureDate>
</change:Failure>
</rdf:RDF>

```

The SPARQL query in Code Snippet 10 identifies bridge clusters for control system updates by analysing failure rates, next maintenance dates, downtime history, and geographical proximity. It helps cluster and prioritise maintenance by selecting assets with outdated control system versions and high failure risks, ensuring efficient planning and resource allocation. The query result is presented in a table format, as shown in Table 15, displaying key information such as the cluster ID, individual bridges, their respective next maintenance dates, the average failure rate and downtime for each cluster, and the current control system version of each bridge. This structured output enables decision-makers to assess clusters effectively and coordinate updates based on critical factors.

Code Snippet 10

```

SELECT ?clusterID ?bridge ?nextMaintenanceDate
    (AVG(?failureRate) AS ?avgFailureRate)
    (AVG(?downtime) AS ?avgDowntime)
    ?controlVersion
WHERE {
    # Retrieve bridge and related properties
    ?bridge asset:hasControlSystem ?controlSystem ;

```

```

    asset:location ?location ;

    asset:nextMaintenanceDate ?nextMaintenanceDate ;

    asset:clusterID ?clusterID .

# Retrieve geolocation details for clustering

?location geo:lat ?latitude ;

    geo:long ?longitude .

# Retrieve control system data

?controlSystem asset:controlSystemVersion ?controlVersion ;

    asset:failureRate ?failureRate ;

    asset:downtimeHistory ?downtime .

# Example clustering filter for assets within a certain latitude/longitude range
FILTER(?latitude > 52.0 && ?latitude < 53.0 && ?longitude > 4.5 && ?longitude < 5.5)

# Find the latest control system version across all bridges
{
    SELECT (MAX(?version) AS ?latestVersion) WHERE {
        ?cs asset:controlSystemVersion ?version .
    }
}

# Filter bridges with outdated control system versions
FILTER(?controlVersion < ?latestVersion)
}

GROUP BY ?clusterID ?bridge ?nextMaintenanceDate ?controlVersion
ORDER BY ?clusterID DESC(?avgFailureRate)

```

Table 15 - SPARQL Results Code Snippet 10

Cluster ID	Bridge	Next MaintenanceDate	Avg. FailureRate	Avg. Downtime	Control Version
Cluster A	Bridge_001	01-06-2025	3.5	24	1.0
Cluster A	Bridge_002	16-07-2025	3.5	24	1.0
Cluster B	Bridge_003	20-05-2025	2.0	18	1.2

Cluster ID	Bridge	Next MaintenanceDate	Avg. FailureRate	Avg. Downtime	Control Version
Cluster_B	Bridge_004	08-10-2025	2.0	18	1.2

4.1.7.3 Impact Analysis and Traceability

The Semantic CDE enables impact analysis and traceability by capturing requirement changes and their cascading effects across interconnected components, such as the bridge deck, pivot mechanism, and motor. Each modification is recorded through immutable audit trails, secured with cryptographic hashes that link sequential changes, effectively forming a blockchain-like structure. Every audit trail has its own unique hash, which references the parent hash of the preceding change, ensuring end-to-end traceability and a chronological record of design modifications. This mechanism guarantees data integrity and accountability by tracking who made changes, what was changed, and when it occurred. The audit trails form a Digital Thread, allowing stakeholders to trace design decisions over time and understand their impact. As shown in Code Snippet 11, when a requirement change increases the bridge deck's load capacity, it triggers subsequent changes to the pivot mechanism and motor to accommodate the updated specifications. The revised component dimensions can be queried to facilitate multidisciplinary collaboration. Queries within the CDE facilitate traceability by enabling historical analysis and understanding interdependencies through the linked data structure, supporting informed decision-making and future design improvements. See Code Snippet 11 for the implementation.

Code Snippet 11

```
<rdf:RDF>

  <!-- Project Definition -->

  <asset:Project rdf:ID="SwingBridgeRenovation">

    <rdfs:label>Swing Bridge Renovation</rdfs:label>

    <asset:hasAsset rdf:resource="#Bridge_SB001"/>

    <asset:plannedRenovation>true</asset:plannedRenovation>

    <asset:lastUpdated>2024-02-01T09:00:00+01:00</asset:lastUpdated>

  </asset:Project>


  <!-- Bridge Deck Definition -->

  <asset:BridgeDeck rdf:ID="BridgeDeck_SB001">

    <rdfs:label>Bridge Deck SB001</rdfs:label>

    <asset:hasProperty rdf:resource="#LoadCapacity"/>

    <asset:hasComponent rdf:resource="#PivotMechanism001"/>

    <change:hasAuditTrail rdf:resource="#AuditTrail_RequirementChange"/>

    <change:hasAuditTrail rdf:resource="#AuditTrail_BridgeDeck"/>

  </asset:BridgeDeck>

</rdf:RDF>
```

```

</asset:BridgeDeck>

<!-- Pivot Mechanism Definition -->
<asset:PivotMechanism rdf:ID="PivotMechanism001">
  <rdfs:label>Pivot Mechanism</rdfs:label>
  <asset:hasComponent rdf:resource="#Motor001"/>
  <change:hasAuditTrail rdf:resource="#AuditTrail_PivotMechanism"/>
</asset:PivotMechanism>

<!-- Motor Definition -->
<asset:Motor rdf:ID="Motor001">
  <rdfs:label>Pivot Mechanism Motor</rdfs:label>
  <asset:hasProperty rdf:resource="#MotorDimensions"/>
  <change:hasAuditTrail rdf:resource="#AuditTrail_Motor"/>
</asset:Motor>

<!-- Property Definitions -->
<asset:Property rdf:ID="LoadCapacity">
  <rdfs:label>Load Capacity</rdfs:label>
  <asset:value>12000</asset:value>
  <asset:unit>kg</asset:unit>
</asset:Property>

<asset:Property rdf:ID="MotorDimensions">
  <rdfs:label>Motor Dimensions</rdfs:label>
  <asset:dimensions>1200x600x500</asset:dimensions>
  <asset:unit>mm</asset:unit>
</asset:Property>

<!-- Audit Trail Entries -->
<change:AuditTrail rdf:ID="AuditTrail_RequirementChange">
  <change:changedBy>ProjectManager</change:changedBy>
  <change:userHash>sha256:user123abc</change:userHash>

```

```

    <change:timestamp>2024-02-01T09:00:00+01:00</change:timestamp>
    <change:changeDescription>Updated load capacity requirement to 12000
kg.</change:changeDescription>
    <change:entryHash>sha256:a1b2c3d4e5f6g7h8</change:entryHash>
    <change:parentHash>0x00000000</change:parentHash>
</change:AuditTrail>

<change:AuditTrail rdf:ID="AuditTrail_BridgeDeck">
    <change:changedBy>StructuralEngineer</change:changedBy>
    <change:userHash>sha256:user456def</change:userHash>
    <change:timestamp>2024-02-04T11:00:00+01:00</change:timestamp>
    <change:changeDescription>Increased structural support for new load
requirement.</change:changeDescription>
    <change:entryHash>sha256:b2c3d4e5f6g7h8i9</change:entryHash>
    <change:parentHash>sha256:a1b2c3d4e5f6g7h8</change:parentHash>
</change:AuditTrail>

<change:AuditTrail rdf:ID="AuditTrail_PivotMechanism">
    <change:changedBy>MechanicalEngineer</change:changedBy>
    <change:userHash>sha256:user789ghi</change:userHash>
    <change:timestamp>2024-02-06T14:30:00+01:00</change:timestamp>
    <change:changeDescription>Upgraded pivot mechanism to support new bridge
load.</change:changeDescription>
    <change:entryHash>sha256:c3d4e5f6g7h8i9j0</change:entryHash>
    <change:parentHash>sha256:b2c3d4e5f6g7h8i9</change:parentHash>
</change:AuditTrail>

<change:AuditTrail rdf:ID="AuditTrail_Motor">
    <change:changedBy>ElectricalEngineer</change:changedBy>
    <change:userHash>sha256:user987xyz</change:userHash>
    <change:timestamp>2024-02-09T10:00:00+01:00</change:timestamp>
    <change:changeDescription>Upgraded motor size to meet new pivot mechanism
requirements.</change:changeDescription>
    <change:entryHash>sha256:d4e5f6g7h8i9j0kl</change:entryHash>

```

```

    <change:parentHash>sha256:c3d4e5f6g7h8i9j0</change:parentHash>
  </change:AuditTrail>
</rdf:RDF>

```

The SPARQL query in Code Snippet 12 tracks the impact of a requirement change by retrieving subsequent modifications to related components, such as the bridge deck, pivot mechanism, and motor. By following the parent hash values, the query ensures chronological traceability of changes, capturing details such as timestamps, responsible personnel, and descriptions of modifications. This enables stakeholders to analyse cascading effects over the asset lifecycle. The results, as shown in Table 16, provide a clear overview of the sequential changes and their impact on the system. This approach is valuable for accountability purposes and exploring historical immutable records, allowing organisations to gain insights from past changes and apply lessons learned to similar projects future projects.

Code Snippet 12

```

SELECT ?component ?changeDescription ?timestamp ?changedBy ?hash
WHERE {
  # Find initial requirement change
  ?initialChange change:affectsComponent ?component ;
    change:timestamp ?initialTimestamp ;
    change:changeDescription ?initialDescription ;
    change:hash ?initialHash .

  # Retrieve subsequent changes based on timestamps
  ?auditTrail change:affectsComponent ?component ;
    change:timestamp ?timestamp ;
    change:changeDescription ?changeDescription ;
    change:changedBy ?changedBy ;
    change:hash ?hash ;
    change:parentHash ?initialHash .

  FILTER (?timestamp > ?initialTimestamp)
}
ORDER BY ?timestamp

```

Table 16 - SPARQL Results Code Snippet 12

Component	Change Description	Timestamp	Changed By	Hash
Bridge Deck	Increased load capacity	2024-01-19T10:00:00+01:00	StructuralEngineer	sha256:abc123...

Component	Change Description	Timestamp	Changed By	Hash
Pivot Mechanism	Updated pivot size	2024-01-20T14:30:00+01:00	MechanicalEngineer	sha256:def456...
Motor	Upgraded motor specifications	2024-01-22T08:00:00+01:00	ElectricalEngineer	sha256:ghi789...

The SPARQL query in Code Snippet 13 identifies interdependencies between components by retrieving their relationships within the Semantic CDE. By querying linked data, stakeholders can explore how components such as the bridge deck, pivot mechanism, and motor are interconnected, revealing structural and mechanical dependencies. Additionally, other queries can be performed to retrieve detailed properties of each component, providing deeper insights into aspects such as (material) specifications and dimensions. This comprehensive view helps stakeholders understand interdependencies and assess how changes to one component may impact others, facilitating more effective impact analysis. Table 17 presents the SPARQL results retrieved from this query, showing the identified component relationships.

Code Snippet 13

```
SELECT ?component ?relatedComponent ?relationship
WHERE {
    ?component rdfs:label "Bridge Deck SB001" ;
    ?relationship ?relatedComponent .
}
```

Table 17 – SPARQL Results Code Snippet 13

Component	Related Component	Relationship
Bridge Deck	Pivot Mechanism	asset:hasComponent
Pivot Mechanism	Motor	asset:hasComponent

4.1.7.4 Digital Twin

The Digital Twin for a swing bridge integrates real-time sensor data, requirements, and analytical tools within the Semantic CDE, enabling automated monitoring and action across systems. This integration ensures traceability and interoperability, allowing data from various sources to inform and drive operational decisions. Real-time input from sensors, such as wear and tear and load measurements, is continuously monitored to assess the condition of the bridge and detect anomalies or patterns that may require action. Analytical and RAMS tools provide structural performance metrics, which further inform decision-making processes. Metadata, such as timestamps of sensor readings, inspection dates, and responsible stakeholders, enhances data reliability and enables comprehensive tracking of the asset's lifecycle. The combination of real-time monitoring, validated data, interoperable rules, and analytical insights creates a comprehensive Digital Twin ecosystem, supporting automated actions, such as triggering maintenance workflows or adjusting operational parameters, and

maintaining a robust audit trail of all changes and decisions. See Code Snippet 14 for the implementation of the Semantic CDE model.

Code Snippet 14

```
<rdf:RDF>

  <!-- Project Definition -->

  <rro:Project rdf:ID="SwingBridgeRenovation">

    <rdfs:label>Swing Bridge Renovation</rdfs:label>

    <rro:hasAsset rdf:resource="#SwingBridge_SB001" />

    <rro:startDate>2023-01-01</rro:startDate>

    <rro:endDate>2025-12-31</rro:endDate>

    <rro:status>In Progress</rro:status>

    <rro:projectManager rdf:resource="#ProjectManager001" />

  </rro:Project>


  <!-- Asset Definition -->

  <rro:SwingBridge rdf:ID="SwingBridge_SB001">

    <rdfs:label>Swing Bridge (SB-001)</rdfs:label>

    <rro:hasComponent rdf:resource="#PivotMechanism001" />

    <rro:location>Den Oever</rro:location>

    <rro:lastInspectionDate>2024-01-01</rro:lastInspectionDate>

    <rro:condition>Operational</rro:condition>

  </rro:SwingBridge>


  <!-- Pivot Mechanism Definition -->

  <rro:PivotMechanism rdf:ID="PivotMechanism001">

    <rdfs:label>Pivot Mechanism</rdfs:label>

    <rro:hasRequirement rdf:resource="#WearToleranceRequirement" />

    <rro:hasRequirement rdf:resource="#LoadCapacityRequirement" />

    <rro:requiresSensor rdf:resource="#WearAndTearSensor001" />

    <rro:lastMaintenance>2023-09-15</rro:lastMaintenance>

    <rro:status>Functional</rro:status>

  </rro:PivotMechanism>
```

```

<!-- Sensor Definition -->
<rro:Sensor rdf:ID="WearAndTearSensor001">
  <rdfs:label>Wear and Tear Sensor</rdfs:label>
  <rro:monitors rdf:resource="#PivotMechanism001" />
  <rro:latestValue>0.7</rro:latestValue>
  <rro:unit>mm</rro:unit>
  <rro:lastCalibrationDate>2023-12-01</rro:lastCalibrationDate>
  <rro:lastValueTimestamp>2024-03-15T14:30:00</rro:lastValueTimestamp>
</rro:Sensor>

<!-- Requirement Definitions -->
<rro:Requirement rdf:ID="WearToleranceRequirement">
  <rdfs:label>Wear Tolerance Requirement</rdfs:label>
  <rro:requiresValue>0.5</rro:requiresValue>
  <rro:verifies rdf:resource="#WearAndTearSensor001" />
  <rro:responsibleParty rdf:resource="#InspectionTeam001" />
</rro:Requirement>

<rro:Requirement rdf:ID="LoadCapacityRequirement">
  <rdfs:label>Load Capacity Requirement</rdfs:label>
  <rro:requiresValue>10000</rro:requiresValue>
  <rro:verifies rdf:resource="#ANSYSLoadCapacityResult" />
  <rro:responsibleParty rdf:resource="#StructuralEngineer001" />
</rro:Requirement>

<!-- Analytical Result Definition -->
<rro:AnalyticalResult rdf:ID="ANSYSLoadCapacityResult">
  <rdfs:label>ANSYS Load Capacity Result</rdfs:label>
  <rro:calculatedBy rdf:resource="http://example.org/tools/ANSYS" />
  <rro:resultValue>9500</rro:resultValue>
  <rro:calculationDate>2024-01-10</rro:calculationDate>
</rro:AnalyticalResult>

```

```

<!-- Personnel Definitions -->

<rro:Person rdf:ID="ProjectManager001">
  <rdfs:label>Project Manager</rdfs:label>
  <rro:contact>name@example.com</rro:contact>
</rro:Person>

<rro:Person rdf:ID="InspectionTeam001">
  <rdfs:label>Inspection Team</rdfs:label>
  <rro:contact>inspection@example.com</rro:contact>
</rro:Person>

<rro:Person rdf:ID="StructuralEngineer001">
  <rdfs:label>Structural Engineer</rdfs:label>
  <rro:contact>engineer@example.com</rro:contact>
</rro:Person>

</rdf:RDF>

```

Data validation is essential to ensure the accuracy and reliability of inputs within the Semantic CDE. SHACL (Shapes Constraint Language) is employed to enforce data quality by validating that all incoming data, including sensor readings, analytical results, and metadata, meet the expected formats and constraints. For instance, SHACL ensures that wear and tear measurements fall within a valid numeric range and are correctly linked to the corresponding pivot mechanism of the swing bridge. Additionally, the Code Snippet below validates that each timestamp associated with the sensor data conforms to a standardised format, ensuring consistency across the system. See Code Snippet 15 for further details.

Code Snippet 15

```

<rdf:RDF>

  <!-- Node Shape Definition for Sensor Data Validation -->

  <sh:NodeShape rdf:ID="WearAndTearSensorShape">
    <sh:targetClass rdf:resource="rro:Sensor"/>

    <!-- Validate Latest Value -->

    <sh:property>
      <sh:PropertyShape>
        <sh:path rdf:resource="rro:latestValue"/>
      </sh:PropertyShape>
    </sh:property>
  </sh:NodeShape>
</rdf:RDF>

```

```

    <sh:datatype rdf:resource="xsd:decimal"/>
    <sh:minInclusive rdf:datatype="xsd:decimal">0.0</sh:minInclusive>
    <sh:maxInclusive rdf:datatype="xsd:decimal">5.0</sh:maxInclusive>
    <sh:message>Value must be between 0.0 and 5.0 mm.</sh:message>
  </sh:PropertyShape>
</sh:property>

<!-- Validate Monitoring Relationship -->
<sh:property>
  <sh:PropertyShape>
    <sh:path rdf:resource="rro:monitors"/>
    <sh:class rdf:resource="rro:PivotMechanism"/>
    <sh:message>Each sensor must monitor a pivot mechanism.</sh:message>
  </sh:PropertyShape>
</sh:property>

<!-- Validate Timestamp Format in Central European Time (CET/CEST) -->
<sh:property>
  <sh:PropertyShape>
    <sh:path rdf:resource="rro:timestamp"/>
    <sh:datatype rdf:resource="xsd:dateTime"/>
    <sh:maxCount rdf:datatype="xsd:integer">1</sh:maxCount>
    <sh:pattern rdf:datatype="xsd:string">^\d{4}-\d{2}-
\d{2}T\d{2}:\d{2}:\d{2}(\+01:00|\+02:00)$</sh:pattern>
    <sh:message>Valid timestamp: YYYY-MM-DDTHH:MM:SS+01:00 (CET) or YYYY-MM-
DDTHH:MM:SS+02:00 (CEST).</sh:message>
  </sh:PropertyShape>
</sh:property>
</sh:NodeShape>
</rdf:RDF>

```

SWRL (Semantic Web Rule Language) is used in this example to automate critical decision-making processes, such as triggering maintenance when the wear tolerance threshold, measured by the wear and tear sensor, is exceeded, or initiating renovation when the applied load surpasses the defined capacity. SWRL provides a human-readable syntax, making it

accessible for domain experts and engineers to define and manage rules effectively. Additionally, these rules can be represented in XML/RDF format for improved machine readability, enabling inference engines to process and exchange rules seamlessly across different systems. Alternatively, RIF (Rule Interchange Format) can be employed to facilitate interoperability by allowing rules to be interpreted and executed by various tools and platforms, ensuring broader compatibility within the Digital Twin ecosystem. See Code Snippet 16 for the SWRL implementation of the maintenance and renovation rules.

Code Snippet 16

Rule to trigger maintenance if the wear and tear sensor exceeds the defined threshold

```
WearAndTearSensor(?wearSensor) ^  
monitors(?wearSensor, ?pivotMechanism) ^  
latestValue(?wearSensor, ?wearValue) ^  
PivotMechanism(?pivotMechanism) ^  
hasRequirement(?pivotMechanism, ?wearRequirement) ^  
requiresValue(?wearRequirement, ?wearThreshold) ^  
greaterThan(?wearValue, ?wearThreshold)  
-> triggersMaintenance(?pivotMechanism, true)
```

Rule to trigger renovation if the load capacity exceeds the defined requirement

```
LoadCapacitySensor(?loadSensor) ^  
monitors(?loadSensor, ?pivotMechanism) ^  
latestValue(?loadSensor, ?loadValue) ^  
PivotMechanism(?pivotMechanism) ^  
hasRequirement(?pivotMechanism, ?loadRequirement) ^  
requiresValue(?loadRequirement, ?loadThreshold) ^  
greaterThan(?loadValue, ?loadThreshold)  
-> triggersRenovation(?pivotMechanism, true)
```

To enable comprehensive oversight and strategic planning across multiple assets, Digital Twins are integrated at the programme level within the Semantic CDE. This integration aggregates performance data from various projects, such as swing bridges and sluice gates, into a centralised performance dashboard. The dashboard facilitates data-driven decision-making, allowing programme managers to identify trends, prioritise critical assets, and optimise resource allocation, ultimately enhancing capacity efficiency. Additionally, the structured maintenance schedule within the Semantic CDE enables more effective planning and coordination of maintenance activities across the programme, ensuring timely

interventions, reducing downtime, and improving overall asset lifecycle management. See Code Snippet 17 for implementation details.

Code Snippet 17

```
<rdf:RDF>

  <!-- Programme Definition -->

  <prog:Programme rdf:ID="RenovationAndReplacementProgramme">

    <rdfs:label>Renovation and Replacement Programme</rdfs:label>

    <prog:hasProject rdf:resource="#SwingBridgeRenovation" />

    <prog:hasProject rdf:resource="#SluiceGateRenovation" />

    <prog:analysesDataFrom rdf:resource="#PerformanceDashboard" />

  </prog:Programme>


  <!-- Swing Bridge Project Definition -->

  <proj:Project rdf:ID="SwingBridgeRenovation">

    <rdfs:label>Swing Bridge Renovation</rdfs:label>

    <proj:hasAsset rdf:resource="#SwingBridge_SB001" />

    <proj:feedsIntoDashboard rdf:resource="#PerformanceDashboard" />

    <proj:lastUpdated>2024-01-19T12:00:00</proj:lastUpdated>

    <proj:hasMaintenancePlan rdf:resource="#SwingBridgeMaintenancePlan" />

  </proj:Project>


  <!-- Sluice Gate Project Definition -->

  <proj:Project rdf:ID="SluiceGateRenovation">

    <rdfs:label>Sluice Gate Upgrade</rdfs:label>

    <proj:hasAsset rdf:resource="#SluiceGate001" />

    <proj:feedsIntoDashboard rdf:resource="#PerformanceDashboard" />

    <proj:lastUpdated>2024-01-18T10:30:00</proj:lastUpdated>

    <proj:hasMaintenancePlan rdf:resource="#SluiceGateMaintenancePlan" />

  </proj:Project>


  <!-- Swing Bridge Asset Definition -->

  <asset:SwingBridge rdf:ID="SwingBridge_SB001">

    <rdfs:label>Swing Bridge (SB-001)</rdfs:label>
```

```

    <asset:hasComponent rdf:resource="#PivotMechanism001" />
    <asset:status>Operational</asset:status>
</asset:SwingBridge>

<!-- Sluice Gate Asset Definition -->
<asset:SluiceGate rdf:ID="SluiceGate001">
    <rdfs:label>Sluice Gate (SG-001)</rdfs:label>
    <asset:hasComponent rdf:resource="#ControlSystem001" />
    <asset:status>Under Maintenance</asset:status>
</asset:SluiceGate>

<!-- Maintenance Plans -->
<asset:MaintenancePlan rdf:ID="SwingBridgeMaintenancePlan">
    <rdfs:label>Swing Bridge Maintenance Plan</rdfs:label>
    <asset:includesActivity rdf:resource="#InspectPivotMechanism" />
    <asset:includesActivity rdf:resource="#LubricateBearings" />
    <asset:nextScheduledDate>2024-06-01</asset:nextScheduledDate>
</asset:MaintenancePlan>

<asset:MaintenancePlan rdf:ID="SluiceGateMaintenancePlan">
    <rdfs:label>Sluice Gate Maintenance Plan</rdfs:label>
    <asset:includesActivity rdf:resource="#UpdateControlSystem" />
    <asset:includesActivity rdf:resource="#ReplaceSeals" />
    <asset:nextScheduledDate>2024-07-15</asset:nextScheduledDate>
</asset:MaintenancePlan>

<!-- Maintenance Activities -->
<asset:MaintenanceActivity rdf:ID="InspectPivotMechanism">
    <rdfs:label>Inspect Pivot Mechanism</rdfs:label>
    <asset:frequency>12</asset:frequency>
    <asset:responsibleParty>Inspection Team</asset:responsibleParty>
</asset:MaintenanceActivity>

```

```

<asset:MaintenanceActivity rdf:ID="LubricateBearings">
  <rdfs:label>Lubricate Bearings</rdfs:label>
  <asset:frequency>3</asset:frequency>
  <asset:responsibleParty>Maintenance Crew</asset:responsibleParty>
</asset:MaintenanceActivity>

<asset:MaintenanceActivity rdf:ID="UpdateControlSystem">
  <rdfs:label>Update Control System</rdfs:label>
  <asset:frequency>1</asset:frequency>
  <asset:responsibleParty>Technical Team</asset:responsibleParty>
</asset:MaintenanceActivity>

<asset:MaintenanceActivity rdf:ID="ReplaceSeals">
  <rdfs:label>Replace Seals</rdfs:label>
  <asset:frequency>6</asset:frequency>
  <asset:responsibleParty>Maintenance Contractor</asset:responsibleParty>
</asset:MaintenanceActivity>

<!-- Performance Dashboard Definition -->
<prog:PerformanceDashboard rdf:ID="PerformanceDashboard">
  <rdfs:label>Programme Performance Dashboard</rdfs:label>
  <prog:aggregatesDataFrom rdf:resource="#SwingBridgeRenovation" />
  <prog:aggregatesDataFrom rdf:resource="#SluiceGateRenovation" />
  <prog:providesInsights>
    Aggregated performance metrics for programme-wide insights.
  </prog:providesInsights>
</prog:PerformanceDashboard>
</rdf:RDF>

```

4.1.7.5 Participatory System

Code Snippet 18 provides a clear and simplified demonstration of a participatory system enabled by the Semantic Common Data Environment (CDE). In this example, two individual contractors each bring different specialisations and available capacity. Since neither contractor alone meets the required expertise and capacity, they self organise into a temporary joint team within the CDE to collaboratively take on the renovation of Swing Bridge SB001. The system

supports this process by making bridge requirements, contractor capabilities, and team formation both transparent and machine readable. Instead of handling each bridge through a separate tendering procedure, which often takes considerable time, the Semantic CDE allows for automated matching between project needs and suitable contractors. This matching is based on clear metrics such as capacity, expertise, and past performance, enabling faster and more objective decision making.

In addition, contractors are able to interact directly with the CDE. They can propose alternative arrangements such as forming teams, reprioritising projects, or negotiating for increased budgets where needed. This interaction enhances flexibility and creates space for strategic dialogue between contractors and the system. All assignments are logged with provenance data, ensuring that every action is traceable and verifiable.

The result is a participatory system that supports trust, empowerment, and engagement. These values form the foundation for a dynamic and decentralised programme structure. They ensure that actors can collaborate with autonomy while staying aligned with shared goals, enabling more adaptive and efficient project execution across the infrastructure renovation and replacement programme. This does not mean that control disappears, but that it operates through system rules and programming that guide collaboration and ensure efficient programme execution.

Code Snippet 18

```
<rdf:RDF>

  <!-- Individual Contractors -->

  <rro:Contractor rdf:ID="ContractorABC">

    <rdfs:label>Contractor ABC</rdfs:label>

    <rro:hasSpecialisation>Steel Bridges</rro:hasSpecialisation>

    <rro:capacityAmount>1</rro:capacityAmount>

    <rro:availabilityStatus>Available</rro:availabilityStatus>

    <rro:pastPerformanceRating>High</rro:pastPerformanceRating>

    <rro:hasExperienceYears>10</rro:hasExperienceYears>

  </rro:Contractor>

  <rro:Contractor rdf:ID="ContractorXYZ">

    <rdfs:label>Contractor XYZ</rdfs:label>

    <rro:hasSpecialisation>Mechanical Systems</rro:hasSpecialisation>

    <rro:capacityAmount>2</rro:capacityAmount>

    <rro:availabilityStatus>Available</rro:availabilityStatus>

    <rro:pastPerformanceRating>Moderate</rro:pastPerformanceRating>
```

```

    <rro:hasExperienceYears>7</rro:hasExperienceYears>
</rro:Contractor>

<!-- Self-Organised Contractor Team -->
<rro:ContractorTeam rdf:ID="Team_ABC_XYZ">
    <rdfs:label>Joint Team: ABC & XYZ</rdfs:label>
    <rro:includesContractor rdf:resource="#ContractorABC"/>
    <rro:includesContractor rdf:resource="#ContractorXYZ"/>
    <rro:combinedSpecialisations>Steel Bridges, Mechanical Systems</rro:combinedSpecialisations>
    <rro:combinedCapacity>3</rro:combinedCapacity>
    <rro:availabilityStatus>Available</rro:availabilityStatus>
    <rro:formedSpecificallyFor rdf:resource="#Bridge_SB001"/>
</rro:ContractorTeam>

<!-- Asset to be Renovated -->
<rro:Bridge rdf:ID="Bridge_SB001">
    <rdfs:label>Swing Bridge SB001</rdfs:label>
    <rro:requiresRenovation>true</rro:requiresRenovation>
    <rro:requiredExpertise>Steel Bridges, Mechanical Systems</rro:requiredExpertise>
    <rro:requiredCapacity>3</rro:requiredCapacity>
    <rro:estimatedCost>350000</rro:estimatedCost>
</rro:Bridge>

<!-- Assignment Record with Provenance -->
<rro:Assignment rdf:ID="Assignment_Team001">
    <rro:assignedTeam rdf:resource="#Team_ABC_XYZ"/>
    <rro:assignedAsset rdf:resource="#Bridge_SB001"/>
    <rro:assignmentDate>2025-03-23</rro:assignmentDate>
    <rro:initiatedBy>SemanticCDE_MatchEngine</rro:initiatedBy>
    <rro:provenanceHash>sha256:match123team456</rro:provenanceHash>
</rro:Assignment>
</rdf:RDF>

```

4.2 Assessment of MBSE against Needs and Key Quality Metrics

Technical Metrics

The MBSE framework strengthens the technical performance of infrastructure projects by improving collaboration, adaptability, error reduction, and traceability. By leveraging a Semantic Common Data Environment (CDE), disciplines can directly and transparently share data, including provenance information and change histories (who, when, what, and why). This promotes efficient communication and reduces dependence on document-based workflows. Requirement changes are automatically propagated to associated components through a shared ontology and Reference Data Library, and common sources of error such as ambiguous specifications and fragmented documentation are actively mitigated. The CDE provides a central and consistent structure that supports full lifecycle traceability of design decisions and system changes, with support for automated verification mechanisms and standardised data storage. It also enables interoperability between tools and systems by providing a unified, structured environment for data exchange. To realise usability and engagement, a user-friendly interface must be developed that aligns with the workflows of different disciplines. This technical foundation enables a more resilient and coordinated design and delivery process across disciplines and project phases.

Organisational and Sector-Wide Metrics

The successful adoption of MBSE relies not only on technological infrastructure but also on organisational readiness, leadership commitment, and sector-wide collaboration. Transitioning from traditional systems engineering to MBSE represents a cultural shift from project-based thinking to programme-oriented knowledge sharing. A change in implementation approach is necessary: experimentation must be embraced, and a willingness to collaborate with other companies is essential to scale MBSE across the sector. Leadership plays a key role in driving this transition by allocating resources, setting clear objectives, and facilitating space for incremental and iterative development. Without claiming a complete organisational solution, the framework should be seen primarily as a technical enabler that initiates broader change. In the socio-technical system, changes to the technological environment have significant implications for related processes, organisational structures, and people. This means the technical solution alone will not be sufficient. Establishing a small consortium can be the first step to raise awareness of the framework, develop it further, and ensure it gains traction through limited but representative experiments. The consortium could coordinate standardisation efforts, promote cross-organisational knowledge exchange, and maintain long-term governance over the Semantic CDE. Organisationally realising this framework is the greatest challenge. Creating sector-wide knowledge and skill related to Linked Data will require a gradual process. Without a shared vision and coordinated effort across the sector, MBSE risks remaining in a fragmented or exploratory phase without reaching its full potential.

Strategic and Long-Term Metrics

Strategically, MBSE contributes to innovation, standardisation, and long-term resilience within the Dutch Renovation and Replacement Programme. By adopting open standards and software-independent structures, vendor lock-in is avoided and interoperability across tools and organisations is supported. The Semantic CDE enables data-driven decision-making and supports the implementation of RAMS (Reliability, Availability, Maintainability, Safety) principles, as well as integration with emerging digital technologies such as AI and Digital Twins. MBSE also improves user experience and satisfaction by making consistent and structured information accessible to operators, maintenance teams, project teams, and programme managers. Financially, this results in improved resource allocation, reduced failure costs, and enhanced programme efficiency, provided that implementation is backed by structural investment and embedded within the wider programme governance.

A detailed assessment of each quality metric is provided in Appendix E.1.

4.3 Strategic SWOT Analysis

This section presents a Strategic SWOT Analysis to evaluate the internal strengths and weaknesses, alongside external opportunities and threats, associated with the adoption of the Semantic CDE in the Renovation and Replacement Programme. The analysis identifies key factors influencing successful implementation and highlights strategic approaches to increase benefits and mitigate challenges.

Section 4.3.1 presents the SWOT Matrix (see Table 18), categorising key insights into strengths, weaknesses, opportunities, and threats. Section 4.3.2 outlines the Strategic Actions (see Table 19), specifying how to leverage strengths, address weaknesses, and respond to opportunities and threats through targeted approaches. Finally, Section 4.3.3 outlines the key organisational, technical, and strategic components required for full MBSE implementation. A possible implementation roadmap is provided in Appendix B.4 as an indicative thought experiment, illustrating what such a phased approach could look like in practice.

4.3.1 SWOT Matrix

Table 18 – SWOT Matrix

Strengths	Weaknesses
Enhanced collaboration and communication: MBSE and the Semantic CDE enable seamless interdisciplinary collaboration through structured data sharing, reducing miscommunication and improving coordination across disciplines.	High initial investment and resource allocation: The adoption of MBSE and a Semantic CDE requires substantial financial commitment for development, standardisation, and implementation.
Improved flexibility and adaptability: The Linked Data model supports iterative and incremental project development, enabling efficient design changes and reducing dependency on static documentation.	Resistance to change: Many organisations in the infrastructure sector are accustomed to traditional document-based systems and may be reluctant to adopt MBSE practices.
Error reduction and accuracy: The centralised data structure ensures consistency, reduces errors in requirement interpretation, and provides structured lessons learned from past projects.	Lack of existing MBSE consortium: There is no coordinated body in the Netherlands to drive sector-wide MBSE adoption, leading to fragmented progress and company-specific solutions instead of programme-wide improvement.

Strengths	Weaknesses
Robust traceability and auditability: The Semantic CDE enables real-time tracking of design changes, providing transparency and accountability across project lifecycles.	Complex standardisation requirements: Successful implementation requires strong governance structures, shared ontologies, and alignment with existing standards such as RDLs, which may be difficult to coordinate.
Sector-wide knowledge retention: The CDE enables long-term data storage, ensuring that design decisions, maintenance history, and infrastructure insights remain accessible for future projects.	Integration challenges with existing systems: Many organisations rely on legacy software and may face difficulties in integrating MBSE approaches with their current workflows.
Scalability and future-proofing: The Semantic CDE supports long-term infrastructure planning, enabling the use of machine learning, AI, and predictive analytics to improve project outcomes over time.	Dependence on vendor alignment: While MBSE promotes open standards, interoperability challenges may arise if vendors do not align with sector-wide data exchange principles.
Opportunities	Threats
Programme-wide efficiency gains: By improving project governance, reducing rework, and enhancing decision-making, MBSE increases the programme's capacity and enables better management of renovation and replacement projects.	Short-term financial constraints: Due to strict budget controls, asset owners and infrastructure organisations may hesitate to allocate funding for MBSE implementation, delaying progress.
Standardisation and interoperability: Establishing shared ontologies and RDLs promotes standardised engineering models, enabling seamless data exchange and improving project alignment.	Lack of clear contractual requirements: Without contractual obligations for MBSE and CDE implementation in infrastructure projects, adoption may remain inconsistent across organisations.
Expansion of MBSE expertise and workforce: The transition to MBSE creates new job opportunities, such as data managers, CDE specialists, and digital engineering coordinators, fostering sector-wide innovation.	Cybersecurity and data privacy concerns: Increased digitalisation and data-sharing introduce risks related to data security, intellectual property protection, and unauthorised access.
International leadership in digital infrastructure management: The Netherlands can establish itself as a frontrunner in MBSE-based infrastructure programme governance, creating exportable models for other countries. By demonstrating how the implementation of new technologies like the Semantic CDE can catalyse sector-wide transformation in the socio-technical system.	Market-driven fragmentation: Without a sector-wide effort to establish MBSE best practices, different organisations may develop incompatible solutions, reducing the benefits of a unified approach.
Better prioritisation of infrastructure investments: With data-driven decision-making, asset owners can allocate resources efficiently, prioritising projects based on (real-time) infrastructure performance and risk assessments.	Potential software interoperability issues: If major software vendors do not support MBSE interoperability efforts, integration challenges may limit the effectiveness of the Semantic CDE.
Scaling of automation and AI-driven insights: As more structured data is collected, automation and AI applications can increasingly support risk management, optimise maintenance planning, and enhance lifecycle management of infrastructure assets.	Failure to institutionalise sector-wide collaboration: If asset owners and programme managers do not take proactive leadership in MBSE adoption, the sector may continue to struggle with fragmented development efforts.

4.3.2 Strategic Actions

Table 19 – Strategic Actions

Category	Strategy Description
SO Strategies (Leverage Strengths to Maximise Opportunities)	- Develop the Semantic CDE consortium to lead MBSE standardisation and accelerate sector-wide adoption. - Leverage programme-wide data integration to improve decision-making and create long-term efficiency gains.

Category	Strategy Description
	- Promote cross-project knowledge sharing to enhance programme-wide efficiency and learning. - Align with international MBSE developments to establish the Netherlands as a leader in infrastructure digitalisation. - Strengthen the interoperability of MBSE with emerging technologies to drive innovation and global competitiveness.
WO Strategies (Address Weaknesses to Capture Opportunities)	- Secure dedicated financial investment for MBSE development to prevent fragmented progress and ensure sustainable innovation. - Establish structured training programmes for engineers, managers, and operators to improve MBSE adoption and adaptation. - Increase organisational awareness of MBSE benefits to reduce resistance and enhance adoption rates. - Encourage asset owners to allocate resources for experimentation in MBSE applications, allowing for iterative development and improvement. - Develop clear guidelines and governance frameworks to help organisations transition from DBSE to MBSE without disruption.
ST Strategies (Use Strengths to Mitigate Threats)	- Embed MBSE adoption in procurement contracts to prevent inconsistent implementation across different projects. - Standardise MBSE practices across organisations to avoid inefficiencies caused by fragmented development. - Strengthen cybersecurity and data governance within the Semantic CDE to address risks related to data security and access control. - Ensure open and long-term access to infrastructure data by designing the Semantic CDE to prevent vendor lock-in. - Use the Semantic CDE's structured data approach to proactively identify and mitigate infrastructure risks (e.g., maintenance forecasting, failure predictions).
WT Strategies (Minimise Weaknesses to Reduce Threats)	- Ensure strong leadership commitment to drive MBSE implementation and counter resistance to change. - Develop an open standard for MBSE interoperability to prevent vendor lock-in and promote sector-wide compatibility. - Implement a phased transition strategy to allow organisations to gradually adopt MBSE without overwhelming existing workflows, while also identifying and demonstrating quick wins to build confidence and secure commitment from companies. - Encourage public-private collaboration to ensure that government financing structures allow room for MBSE advancements and innovation. - Monitor and refine MBSE applications through continuous feedback loops within projects to prevent stagnation in development.

4.3.3 Key Components for Semantic CDE Implementation

Table 20 – Key Components for Full Semantic CDE Implementation

Dimension	Key Component Required
Organisational	Leadership commitment to drive MBSE adoption and allocate necessary resources
	Cultural and behavioural change to shift from siloed, project-based to collaborative, programme-oriented thinking
	Workforce training and academic partnerships to develop sector-wide MBSE and Linked Data skills
	Establishment of a cross-sector Semantic CDE consortium for joint development and governance
	Coordination of governance, standardisation efforts, and stakeholder interaction within the consortium
	Change management strategies to enable experimentation and reduce resistance to adoption
	Shared best-practice repositories and cross-project knowledge development mechanisms

Dimension	Key Component Required
Technical	Adherence to participatory system values such as trust, empowerment, and engagement
	Gradual scaling of the Semantic CDE consortium, starting small and expanding as sufficient foundations of the changed socio-technical system are established
	Development and phased deployment of a Semantic CDE as central technical infrastructure
	Creation and maintenance of a Reference Data Library (RDL) and standardised, reusable ontology including taxonomy
	Implementation of open standards and interoperability mechanisms across MBSE methods, Building Information Modelling (BIM), and asset management environments
	Deployment of Digital Twins linked to the Semantic CDE for monitoring and predictive analytics
	Data governance via SHACL validation rules, provenance-based logging, and role-based access controls
	Cybersecurity measures including authentication, cryptographic audit trails, and data integrity protocols
Strategic	Scalable and flexible system architecture that can evolve with organisational and technical needs
	Development of intuitive, user-centred interfaces aligned with engineering workflows
	Securing of long-term financial investment from asset owners, public sector, and private stakeholders
	Alignment with infrastructure programme strategies and governance frameworks
	Integration of MBSE and CDE deliverables in procurement, tendering, and contracting processes
	Prevention of vendor lock-in through open architectures and collaboration with software providers
	Phased, incremental, and iterative implementation via pilot projects before full-scale application
	Enablement of decentralised, data-driven governance through Semantic CDE adoption
	Establishment of continuous feedback loops and evaluation mechanisms for incremental and iterative improvement
	Synergistic incremental and iterative development of socio-technical elements, including the three MBSE pillars (language, method, tool): technology, processes, organisational structures, and people

4.4 Verification and Validation

This section outlines the processes used to verify and validate the proposed MBSE and Semantic CDE framework. Verification ensures that the framework meets its intended design requirements, aligns with the research objectives, and supports the framework's intended goals. Validation assesses whether the framework is practical, relevant, and effective for real-world application.

Verification was conducted through a systematic review of the framework's components, ensuring consistency with theoretical principles, sector standards, and the intended outcomes (see Table 21). Validation involved interviews with industry professionals to gather expert feedback, assess practical feasibility, and identify areas for refinement. This combined approach ensures that the framework is both theoretically sound and practically applicable within the infrastructure sector.

4.4.1 Verification

Table 21 – Verification

Verification Criteria	Verification Approach (Case Study)	Evidence (Thesis Chapter)	Outcome
Technical, Technical Management, and Organisational Project-Enabling Processes (ISO/IEC/IEEE 15288)	The case study demonstrates the application of processes such as risk management, configuration management, decision management, and information management within the Semantic CDE and MBSE framework.	Chapter 3.5.6 (MBSE Framework in Action), 3.5.7 (Case Study Examples)	Strengthens technical, technical management, and organisational project-enabling processes, improving traceability and lifecycle data integrity.
Ontology and Reference Data Library (RDL) Alignment	The case study shows how the ontology (Taxonomy and RDL) is applied to structure programme, project, and asset data, enabling alignment with standards like ISO/IEC 30141 (IoT) and ISO/IEC 30173 (Digital Twin). SPARQL queries demonstrate how taxonomies are structured to maintain alignment with these standards.	Chapter 3.5.2 (Semantic Technology and RDL)	Alignment is possible between the semantic model, RDL, and standards through consistent data structuring and namespace definitions.
Governance and Auditability	The case study illustrates how audit trails with cryptographic hashes in the Semantic CDE enable traceability of design changes and decision-making processes, improving governance. SPARQL queries are used to verify audit trails, tracking changes and ensuring accountability. Additionally, team formation and assignment logging in the participatory system are recorded with provenance data.	Chapter 3.5.7.3 (Impact Analysis and Traceability), 3.5.7.5 (Participatory System)	Governance is improved by ensuring traceability and accountability for changes through immutable audit trails within the Semantic CDE. The participatory system example illustrates how provenance ensures the transparency and verifiability of team formation.
Interdisciplinary Collaboration and Knowledge Sharing	The case study highlights how Linked Data and the Semantic CDE support knowledge sharing across disciplines, enabling secure, real-time data access and interdisciplinary querying. Cross-project SPARQL queries retrieve lessons learned across projects to facilitate collaborative learning.	Chapter 3.5.7.2 (Knowledge Exchange and Collaboration)	Enhances collaboration by providing shared data environments and secure, structured knowledge sharing.
Agility, Adaptive Design, Impact Analysis, and Traceability	The case study demonstrates how the Semantic CDE enables impact analysis and adaptive design by linking historical design choices, requirements, and interdisciplinary decisions. Stored knowledge and SPARQL queries facilitate retrieval of past design alternatives, allowing improved decision-making for future iterations. Immutable audit trails and cryptographic hashes ensure traceability of changes, tracking decisions over time.	Chapter 3.5.7.2 (Knowledge Exchange and Collaboration), 3.5.7.3 (Impact Analysis and Traceability)	Enhances agility by providing structured insights into past decisions, enabling rapid adaptation and improved design alternatives. Ensures traceability of modifications through audit trails and cryptographic verification.

Verification Criteria	Verification Approach (Case Study)	Evidence (Thesis Chapter)	Outcome
Digital Twin Integration	Demonstrates how the Digital Twin integrates real-time sensor data for automated monitoring, validated using SHACL and reasoning with SWRL and RIF for decision-making. SPARQL queries extract real-time data from the Digital Twin for validation against system constraints.	Chapter 3.5.7.4 (Digital Twin)	Ensures automated monitoring, validation, and predictive maintenance, supporting efficient decision-making.
Information and Configuration Management	The case study shows how configuration data is managed and traced using Linked Data, ensuring consistent data updates and configuration control. SPARQL queries track configuration changes over time to maintain data integrity.	Chapter 3.5.6 (MBSE Framework in Action)	Improves configuration control and information integrity across the asset lifecycle.
Standardisation and Reusability	The case study illustrates how components are standardised within the ontology for reusability and modular integration in future projects. SPARQL queries demonstrate component standardisation by retrieving and reusing predefined model elements.	Chapter 3.5.2.1 (Taxonomy)	Facilitates standardisation and reusability by defining components and processes within the semantic framework.
Organisational Collaboration and Consortium Formation	Highlights how the Semantic CDE fosters collaboration among project stakeholders and external parties through structured data integration. The participatory system example demonstrates how contractors can self-organise into temporary teams by aligning capacity and expertise, enabling decentralised collaboration within a shared data environment.	Chapter 3.5.7.2 (Knowledge Exchange and Collaboration), 3.5.7.5 (Participatory System)	Supports effective organisational collaboration by enabling secure and structured information exchange. Demonstrates how a participatory system empowers self-organised teams and aligns them with shared programme goals.

4.4.2 Validation

To validate the proposed approach for applying Model-Based Systems Engineering (MBSE) and Linked Data principles to the infrastructure replacement and renovation programme, a series of expert interviews were conducted with representatives from engineering firms, client organisations, and sector initiatives (see Appendix E.2 for validation interview summaries). The interviews provided critical insights into the relevance, feasibility, and practical challenges associated with the framework.

Overall, all experts strongly recognised the problems identified in the problem analysis. Key challenges confirmed include incomplete documentation, interdisciplinary miscommunication, repeated mistakes, and fragmented data management. Interviewees emphasised that these issues collectively contribute to inefficiencies and capacity limitations in infrastructure programmes.

There was broad endorsement of the conceptual solution to use a semantic Common Data Environment (CDE) based on Linked Data technologies within an MBSE framework. Linked Data was recognised as a uniquely promising method to systematically address information fragmentation, improve cross-project knowledge sharing, and support long-term asset lifecycle management. The importance of building and maintaining a standardised ontology, taxonomy, and Reference Data Library (RDL) to ensure interoperability and reuse of information across projects was a recurring theme.

However, all experts underlined that the primary challenges lie not in the technical feasibility, but in the organisational transition required. Several interviews highlighted that the real barrier is the human and organisational adoption of new working methods, not the technological maturity of Linked Data or MBSE tools. The transition demands strong leadership from client organisations (particularly Rijkswaterstaat), structured collaboration between contractors and engineers, and clear governance and change management strategies. Without addressing these organisational dynamics, the long-term benefits will remain out of reach.

The need for stepwise, incremental and iterative implementation was also consistently stressed. Experts advised starting small at the project level with pilots and gradually expanding towards a programme-level semantic environment. Early wins, such as sharing risk libraries or condition monitoring data across projects, were seen as critical to building momentum and demonstrating tangible value to stakeholders.

The interviews also emphasised the growing importance of sector-wide standardisation initiatives, such as Forum Standaardisatie and DigiGo, and the need for open data standards to avoid vendor lock-in. There was broad agreement that broader sector movements towards data openness will create a favourable context for adopting semantic approaches, but that active client leadership and coordinated sector initiatives are needed to drive practical adoption.

Finally, several experts highlighted additional success factors, including the need for flexible data visualisations tailored to different user groups, investments in digital skills training, proactive stakeholder management to overcome resistance, and long-term configuration management across both physical and digital asset lifecycles.

In summary, the validation interviews confirmed the relevance of the identified problems and endorsed the proposed semantic MBSE framework as a promising direction. At the same time, they clearly indicated that technical soundness alone is not sufficient: the successful realisation of the framework requires significant attention to organisational, governance, and human factors.

Chapter 5: Conclusions

5.1 Sub Research Questions Answers

5.1.1 Research questions 1 and 2

What are the needs of infrastructure renovation and replacement projects to manage complexity, and is MBSE suitable according to theory to solve the related problems?

Infrastructure renovation and replacement projects increasingly face complexity due to fragmented communication, limited design agility, outdated documentation, and organisational inefficiencies. Literature and Systems Engineering (SE) principles indicate that Model-Based Systems Engineering (MBSE), if thoughtfully applied under appropriate conditions, provides a promising solution to these issues. Table 8 summarises the key challenges faced by the infrastructure sector, outlining the underlying needs, preconditions for implementation, and theoretical benefits MBSE offers. These challenges negatively impact individual project performance, create inefficiencies at the programme level, and restrict the programme's capacity to deliver renovation and replacement works on schedule and within budget.

Three key domains emerge from this analysis: integration, agility (and resilience), and governance.

Integration is fundamental to Systems Engineering, aiming to harmonise multidisciplinary processes and designs to achieve coordinated outcomes. In the Dutch infrastructure sector, current approaches often lack effective interdisciplinary collaboration and sufficient client interaction, leading to design inefficiencies, misunderstandings, and frequent variations. Existing software tools typically fail to support complex functional and behavioural integration across engineering disciplines or to adequately facilitate stakeholder engagement. Outdated, inconsistent documentation further complicates traceability and reuse.

MBSE addresses these integration challenges by offering a shared modelling environment with a common language to represent system elements unambiguously. It enables early-stage system simulations, aiding stakeholders in proactively identifying design conflicts. By formalising designs through structured logic and shared semantics, MBSE clarifies communication, enhances traceability, and improves interdisciplinary coordination. For successful implementation, organisations must adhere to MBSE's three foundational pillars (Language, Method, and Tool) and ensure alignment with standards like ISO 15288. Effective adoption requires adequate training, proper onboarding, and realistic planning constraints.

Agility and resilience are essential for managing complexity in infrastructure projects. A primary source of complexity is frequent changes in client requirements, often due to evolving needs or insights gained during the project lifecycle. Traditional SE methods are often inflexible in accommodating these changes, primarily due to inadequate traceability, slow impact analysis, and limited reuse of design knowledge. MBSE, by contrast, facilitates agility through structured, reusable model constructs, enabling rapid adaptation and effective

handling of changing requirements. It enhances visibility of design impacts, allowing quicker feedback loops and reducing the risk of errors arising from late-stage adjustments.

Resilience in infrastructure projects also depends significantly on the effective storage, reuse, and accessibility of knowledge. By codifying project knowledge within structured, reusable models, MBSE ensures critical insights and lessons learned are preserved and readily available for future use. This capability substantially enhances resilience and agility, empowering teams to anticipate and respond effectively to future uncertainties and variations.

Governance challenges at the programme level include capacity shortages, limited cross-organisational learning, and weak collaboration among stakeholders. These issues manifest as fragmented knowledge, mistrust, and overly project-centric approaches, hindering coordinated action and innovation. MBSE can effectively address governance issues by embedding expert knowledge into reusable, standardised models that facilitate knowledge sharing across projects and organisations. This promotes continuity, fosters collective learning, and strengthens overall governance.

To further enhance governance effectiveness, integration is required between asset-level and project-level systems and programme-level governance structures. This can be achieved through coherent data structures and standardised information management practices, enabling improved decision-making, resource allocation, and strategic alignment across infrastructure projects and programmes. Additionally, MBSE supports strategic ambitions, including Digital Twins and Digital Threads, requiring consistent, semantically structured, and traceable data across the entire asset lifecycle. Realising these ambitions necessitates that clients and asset owners foster an organisational environment conducive to knowledge sharing, experimentation, and continuous improvement without undermining healthy competition.

5.1.2 Research Question 3

What MBSE components does the infrastructural sector apply?

In the infrastructure sector, various MBSE components are applied to enhance the renovation and replacement programme, leveraging tools that cover analysis, simulation, requirements management, and data integration. Each of these categories contributes significantly to the management and development of infrastructure projects. These tools can be used separately or in combination, depending on the specific needs of the project. Selecting the right tools for the right application requires sufficient knowledge by systems engineers about both the tools and their application possibilities, ensuring the best outcomes for the project.

In the **Analysis and Simulation** category, tools for structural, mechanical, and geotechnical design enable detailed analysis of the physical aspects of bridges and other structures. These tools ensure that designs meet safety and performance standards and facilitate verification through physical models, aligning with technical requirements. The model serves as a tool to facilitate stakeholder validation, ensuring that the final design of the bridge aligns with expectations and accurately reflects real-world conditions and intended use. In conjunction, BIM tools like Autodesk Revit aid in detailed 3D visualisations, offering a more intuitive

understanding of the system's physical aspects. These 3D models simplify complex design concepts for stakeholders, facilitating clearer communication and quicker adjustments based on feedback, thereby accelerating the design process. Predictive analysis tools forecast future trends and performance, while visualisation and environmental analysis tools offer an immersive experience, helping stakeholders understand complex designs in context. RAMS analysis tools focus on long-term operational efficiency and safety, ensuring reliability, availability, maintainability, and safety throughout an asset's lifecycle. Integrating RAMS analysis throughout the entire lifecycle allows systems engineers to leverage insights from past projects, addressing potential issues related to system failures and maintenance early on. This iterative process, supplemented by further RAMS evaluations after implementation, enables continuous adjustments and improvements, ensuring that the asset adapts to evolving conditions and consistently meets functional and safety requirements.

In **Requirements and Systems Engineering**, tools such as modelling languages, requirements management platforms, and synthesis-based engineering (SBE) solutions play a critical role in managing project requirements and ensuring alignment with specifications. SysML, for example, facilitates the creation of system architecture diagrams, behaviour models, and functional representations, which provide an abstract view of the system. These models ensure traceability from the requirements phase to the final system design, allowing for automatic checking of requirements to ensure consistency throughout the project lifecycle. This helps manage the many requirements a project may have, keeping them up to date and verified across the lifecycle. SBE takes this process further by automating the design based on pre-set verification rules. Unlike traditional approaches that require manual design and checking, SBE generates designs that meet specific requirements through predefined rules, automating both the design and verification process.

Data Integration and Interoperability tools ensure that data can be shared across platforms in a structured and consistent way, supporting seamless collaboration across different phases of a project. Some of these tools support efficient data storage and retrieval, enabling all project information to remain up-to-date and aligned with system requirements, ensuring consistency and traceability throughout the lifecycle. Middleware platforms facilitate communication between tools, allowing data generated by one system to be utilised by others without the need for manual intervention. Linked Data, for instance, plays a crucial role in interconnecting data from various sources, making it machine-readable and easily accessible across systems. By leveraging a Common Data Environment (CDE), organisations can maintain a unified source of truth, where all stakeholders have access to up-to-date data and information, supporting both operations and asset management. This cohesive approach enhances decision-making, collaboration, and overall efficiency in managing complex infrastructure projects.

The **Digital Twin** category utilises platforms and IoT sensors to create real-time simulations of the physical assets, enabling continuous monitoring and data collection throughout the infrastructure's lifecycle. By integrating data from various sources, the digital twin models provide a holistic view of the system's performance, facilitating predictive maintenance and operational efficiency. This constant flow of real-time and operational data ensures that digital

twin models remain aligned with the physical state of the infrastructure, allowing for proactive adjustments based on performance data.

The **interaction and prioritisation between these categories** are key to the effectiveness of the MBSE framework. While each category contributes to the overall system, their relevance may vary depending on the specific phase or needs of a project. For instance, certain projects require a robust Common Data Environment (CDE) to ensure seamless data sharing and consistency across stakeholders, which is critical for maintaining traceability and interoperability. Others might benefit more from the addition of SysML models, which offer clear system architecture and behaviour representations via high-level diagrams, supporting requirements traceability and facilitating the visualisation of complex system interactions. This flexibility allows systems engineers to tailor the MBSE approach, focusing on the most impactful tools and methods, thus optimising resources and better aligning with project goals.

Analysis and Simulation tools generate essential data, such as structural reports and performance metrics, which are integrated into the Linked Data environment within the Data Integration and Interoperability tools. This Linked Data-based system ensures that data from various sources is stored in a consistent, machine-readable format, making it accessible across platforms. Middleware platforms support seamless communication between tools, allowing data generated by one system to be utilised by others without manual intervention. The CDE further enhances this by serving as a central repository for all project data, ensuring that information is not siloed but can be accessed and updated across the project's lifecycle.

The Digital Twin platforms collect real-time data from IoT sensors, which feed into the Linked Data-based Common Data Environment (CDE). This enables the data to be analysed and utilised by other tools, such as RAMS tools, analysis systems, and requirements management platforms. The continuous flow of operational data creates a feedback loop, where insights from real-time monitoring inform both ongoing analyses and requirements updates. This process allows infrastructure designs to be continuously refined based on evolving operational conditions, supporting proactive decision-making and enhancing overall asset performance.

5.1.3 Research Question 4

How can infrastructure organisations practically apply MBSE to improve the Renovation and Replacement Programme?

In the solution for the challenges regarding the Renovation and Replacement Programme (RRP), Semantic Technology is central. By making data machine-readable, it provides solutions for the programme's increasing complexity and capacity challenges. To effectively apply Model-Based Systems Engineering (MBSE) within infrastructure organisations, a strategic approach is needed that integrates technical tools, organisational alignment, and collaborative practices. MBSE complements traditional document-based methods by adopting a model-centric approach that enhances, rather than replaces, conventional processes. Through the use of a Semantic Common Data Environment (CDE), project teams can work within a structured life cycle model that connects design, construction, operation, and

maintenance phases. This strengthens systems engineering practices by enabling traceable model reuse, knowledge building, and adaptive management across the asset's life cycle, capabilities that traditional document-based systems engineering approaches typically lack. The integration of structured, linked information ensures more consistent, data-driven, and transparent decision-making across the full programme lifecycle.

Centralising data through integrated models eliminates the need for manual reinterpretation and enables faster processing, ensuring that critical projects are prioritised efficiently. Semantic technology improves coordination across interventions, allowing programme managers to balance priorities and align operational realities with strategic goals. Especially for assets such as moveable bridges, data-driven insights can help maintain traffic availability while addressing increasing maintenance needs. As infrastructure programmes become more complex, a model-centric, semantic approach becomes essential for managing interconnected systems effectively and proactively.

The foundation for MBSE application lies in a Fit-for-Purpose framework that integrates tools such as SysML, Building Information Modelling (BIM), Semantic Technologies, and engineering analysis tools. At the heart of this framework is the Semantic Common Data Environment (CDE), which centralises structured data storage through Linked Data. All project data and models remain interconnected, facilitating collaboration, supporting traceability, and strengthening long-term asset management. Open standards and interoperable solutions help ensure that tools can work across projects, provided they adhere to the ontologies and standards used within the Semantic CDE. This approach reduces dependency on specific vendors by ensuring that data and information remain accessible and resilient to (technological) changes, even though vendor collaboration for interoperability remains necessary.

SysML provides a structural foundation for visualising system architecture and interactions, particularly at a high level, making complex systems more accessible and easier to interpret. Its standardised diagrams allow stakeholders to quickly understand system structures, which becomes valuable as projects grow more complex. SysML can work effectively to describe high-level system components. However, when scaling up, it can lose clarity because of the excessive number of diagrams. To maximise their usefulness within MBSE, tools such as SysML should align with the ontology and data structures adopted in the Semantic CDE, ensuring integration and consistency across system representations.

BIM tools like Autodesk Revit aid in detailed 3D visualisations, ensuring that design concepts align with physical realities. The integration of these models ensures that both abstract and concrete design elements remain consistent and traceable throughout the asset's lifecycle. BIM and systems engineering complement each other by bridging the gap between functional and physical perspectives. While new versions of tools like Relatics have introduced capabilities to link requirements to BIM models, Linked Data provides a more advanced solution by enabling the creation of complex, machine-readable relationships between information objects. The Semantic CDE plays a crucial role in enabling this integration, ensuring that BIM models and other system models remain consistent and accessible across

tools and disciplines. BIM and SysML are further critical for engaging stakeholders during verification, validation, and design discussions.

The Semantic CDE plays a pivotal role in supporting governance within the MBSE framework, particularly for infrastructure renovation and replacement programmes. It integrates data storage, knowledge sharing, and lifecycle management into a single platform, balancing hierarchical central management with network-centric collaboration. By using linked data, the Semantic CDE enables a participatory system where structured models and operational data form the foundation for adaptive governance. Programme managers can mandate critical data delivery while allowing flexibility for optional exchanges, enabling centralised resource management and adaptive decision-making. The linked-data structure strengthens organisational resilience by enhancing cross-project learning and building institutional knowledge through comprehensive access to structured information. Asset owners are responsible for maintaining the Semantic CDE's models over time and ensuring their continuity across different projects, safeguarding knowledge and enabling reuse throughout the infrastructure lifecycle.

The Semantic CDE enables a participatory socio-technical collaboration environment, supported by ICT. Trust, engagement, and empowerment are critical values, requiring fair, transparent management by the governing body. Stakeholders must feel confident that their contributions are valued and that their data is handled responsibly. Transparency is enhanced by governance decisions that are based on structured, traceable information stored within the semantic framework. To further support adoption, it is important that users from different disciplines can interact with the CDE through role-specific interfaces that simplify access to relevant information without unnecessary complexity.

The linked data CDE establishes a robust foundation for lifecycle management by enabling the creation and evolution of Digital Twins. Initially, pre-Digital Twin setups can be developed by linking objects in the CDE to historical data, providing detailed system representations for analysis, such as identifying maintenance patterns. Over time, real-time sensor data can be integrated, transforming these into dynamic Digital Twins capable of real-time monitoring. By embedding such sensor information, the CDE enables programme managers to prioritise maintenance tasks, optimise resource allocation, and manage assets proactively. Furthermore, by connecting multiple Digital Twins, an interconnected network can be created to support cross-project analysis and holistic programme governance. By providing a structured, machine-readable foundation, the Semantic CDE also creates future opportunities for enhanced capabilities through Machine Learning and Artificial Intelligence applications, enabling even more advanced analysis.

One of the Semantic CDE's key strengths is its ability to establish feedback loops by integrating sensor data for continuous analysis and improvement. This data can be analysed alongside inputs from tools like Relatics, enabling comparisons between RAMS (Reliability, Availability, Maintainability, and Safety) performance data and initial design requirements. Discrepancies or areas for refinement can be identified, guiding maintenance or design adjustments. For example, in the improvement of SBE (Synthesis-Based Engineering)-

designed control modules for movable bridges, real-time operational data, historical records, and performance metrics integrated into the Semantic CDE allow iterative refinements. Furthermore, the CDE enables programme managers to synchronise software updates with maintenance schedules, reducing disruptions and ensuring consistency across the asset network.

A critical organisational pillar of the CDE's implementation is the Semantic Technology Consortium (STC). This consortium unites government bodies, asset owners, contractors, and technology developers to establish shared strategies, standards, and best practices for MBSE and semantic technology. Foundational repositories such as the Reference Data Library (RDL) and Object Type Library (OTL) ensure the consistent application of standards across tools, aligned with ontology-based (including taxonomy) approaches. The use of open standards within the Semantic CDE prevents vendor lock-in regarding data and information, ensuring flexibility and adaptability, even though tool interoperability still requires collaboration with software providers. With sufficient participation, the STC can influence vendors to adopt interoperable standards, strengthening the CDE's long-term compatibility with evolving technologies. To support adoption, the STC fosters an inclusive environment through clear guidelines, open communication (knowledge sharing), and training initiatives that enhance understanding of MBSE and semantic technologies. Public-Private Partnerships between asset owners and private sector partners can further operationalise these strategies, enabling the effective and phased implementation of the CDE and supporting continuous refinement through pilot projects.

Asset owners hold a central responsibility for ensuring the long-term utility and alignment of the CDE with infrastructure lifecycle needs. They must integrate the CDE into project workflows and share it with project teams during design, construction, and maintenance phases. This involves embedding CDE requirements into project contracts, specifying mandatory data and information to be delivered, and clarifying the responsibilities of project teams regarding the CDE. Some of this data will remain accessible only to asset owners and the governance body, while other information can be shared more broadly among programme participants. To ensure the STC's strategic vision is realised, asset owners must allocate sufficient resources for innovation and experimentation, and seek governmental support.

5.1.4 Research Questions 5 and 6

What are the strengths, weaknesses, opportunities, and threats of applying MBSE in infrastructure renovation and replacement, and under which conditions can its implementation be considered feasible and viable?

The qualitative evaluation shows that the proposed MBSE framework, based on the use of Semantic Technologies and a Common Data Environment (CDE), offers significant potential for addressing the complex challenges of infrastructure renovation and replacement programmes. The strengths, weaknesses, opportunities, and threats have been systematically analysed based on technical, organisational, and strategic perspectives.

The key strengths of the MBSE framework lie in its ability to enhance interdisciplinary collaboration, increase flexibility and adaptability during the lifecycle, reduce errors through structured data handling, and provide robust traceability across projects. Through the use of a semantic CDE, design changes and decisions can be centrally managed and transparently tracked, reducing the risk of fragmented documentation and inconsistent information management. The ability to retain sector-wide knowledge and ensure scalability towards future applications, such as machine learning and AI, further strengthens the framework's long-term value.

However, the framework also faces important weaknesses. The initial implementation requires significant investment in developing a shared CDE, standardising ontologies and data structures, and managing organisational change. Resistance to adopting new, model-based ways of working remains a critical barrier, particularly among organisations accustomed to traditional document-based systems engineering. Additionally, the current absence of a coordinated MBSE consortium in the Netherlands means that progress risks remaining fragmented across individual organisations.

From a strategic point of view, several opportunities arise. MBSE can create major programme-wide efficiency gains by improving governance, prioritisation, and knowledge reuse across renovation and replacement projects. It also aligns well with ongoing national and international movements towards digitalisation and standardisation, offering the Netherlands the chance to position itself as a leader in digital infrastructure governance. The expansion of MBSE expertise across the sector will foster innovation, new job roles, and improved infrastructure asset management.

At the same time, several threats could hinder adoption. Financial constraints, cybersecurity risks, fragmented developments by different organisations, and a lack of contractual enforcement for MBSE and CDE use could undermine broader sector-wide implementation. The failure to build strong sector collaboration or to ensure vendor interoperability would risk limiting the framework's effectiveness and long-term sustainability.

The SWOT analysis (Table 18) summarises these strategic factors across technical, organisational, and sectoral dimensions, while the corresponding strategic actions (Table 19) offer targeted measures to reinforce strengths, reduce weaknesses, and facilitate MBSE implementation under viable conditions. In addition, Table 20 outlines the key socio-technical components required for successful long-term implementation.

For MBSE implementation to be considered feasible and viable, several conditions must be met, as synthesised from the qualitative evaluation in Chapter 4:

Strong leadership: Public asset owners, particularly Rijkswaterstaat, must actively lead and demand the use of Semantic CDE approaches in procurement and project contracts.

Establishment of a sector-wide consortium: Coordinate shared ontologies, Reference Data Libraries, and implementation guidelines to avoid fragmented development.

Stepwise, incremental and iterative implementation: Start with a small, dedicated consortium and pilot projects, gradually developing the socio-technical system (technology, organisation, people, and processes) and the three MBSE pillars (language, method, and tool) in synergy through coordinated change management and learning feedback loops.

Focus on open standards, interoperability, and data governance: Ensure cross-platform compatibility and prevent vendor lock-in by enforcing open, standardised data structures. Robust data governance is essential for scalability and flexibility, including cybersecurity, provenance tracking, and role-based access control.

5.2 Main Research Question Answer

How can one use MBSE to manage increasing project complexity in renovating and replacing existing infrastructure to improve programme performance in the infrastructure sector?

The complexity of infrastructure renovation and replacement programmes stems from fragmented communication, limited adaptability, and outdated knowledge management practices. Model-Based Systems Engineering (MBSE), when enhanced with Semantic Linked Data that structures the Common Data Environment (CDE), provides a powerful means to manage the increasing complexity of infrastructure renovation and replacement.

By shifting from document-based systems engineering to a model-centric, data-driven approach, MBSE enables the structured, transparent, and traceable integration of design, requirements, operational data, and lifecycle knowledge. The Semantic CDE plays a central role in this transformation by linking structured data across disciplines and project phases, supporting interdisciplinary collaboration, knowledge reuse, and adaptive governance. A programme-wide shared ontology ensures consistent structuring, interpretation, and exchange of information across assets and projects.

Importantly, the framework operates across two levels: it supports systems engineering practices at the asset level while simultaneously enabling better programme-level governance. This dual structure improves decision-making, resource prioritisation, and cross-project learning. Moreover, compared to traditional document-based approaches, the model-centric system enables a more participatory environment, where stakeholders interact with structured information through role-specific interfaces, enhancing engagement, transparency, and trust.

The Semantic CDE can be considered a new technological foundation that requires corresponding changes in processes, organisational structures, and the roles of individuals. Its introduction must be managed as part of a broader socio-technical transition, where technical development progresses in synergy through change management, including organisational learning and cultural adaptation

Successful application depends on strong leadership from asset owners, stepwise, incremental, and iterative development through pilot projects, development of a sector-wide Semantic

Technology Consortium, investments in digital skills and change management, and a commitment to open standards and interoperability.

If these conditions are met, MBSE, supported by Semantic Technologies, offers a feasible and viable pathway to significantly improve programme performance, resilience, and long-term asset management across the Dutch infrastructure sector. This integrated vision is illustrated in Fig. 16, which presents the Semantic Linked Data Common Data Environment Framework as a foundation for connecting systems engineering, asset management, and programme-level governance

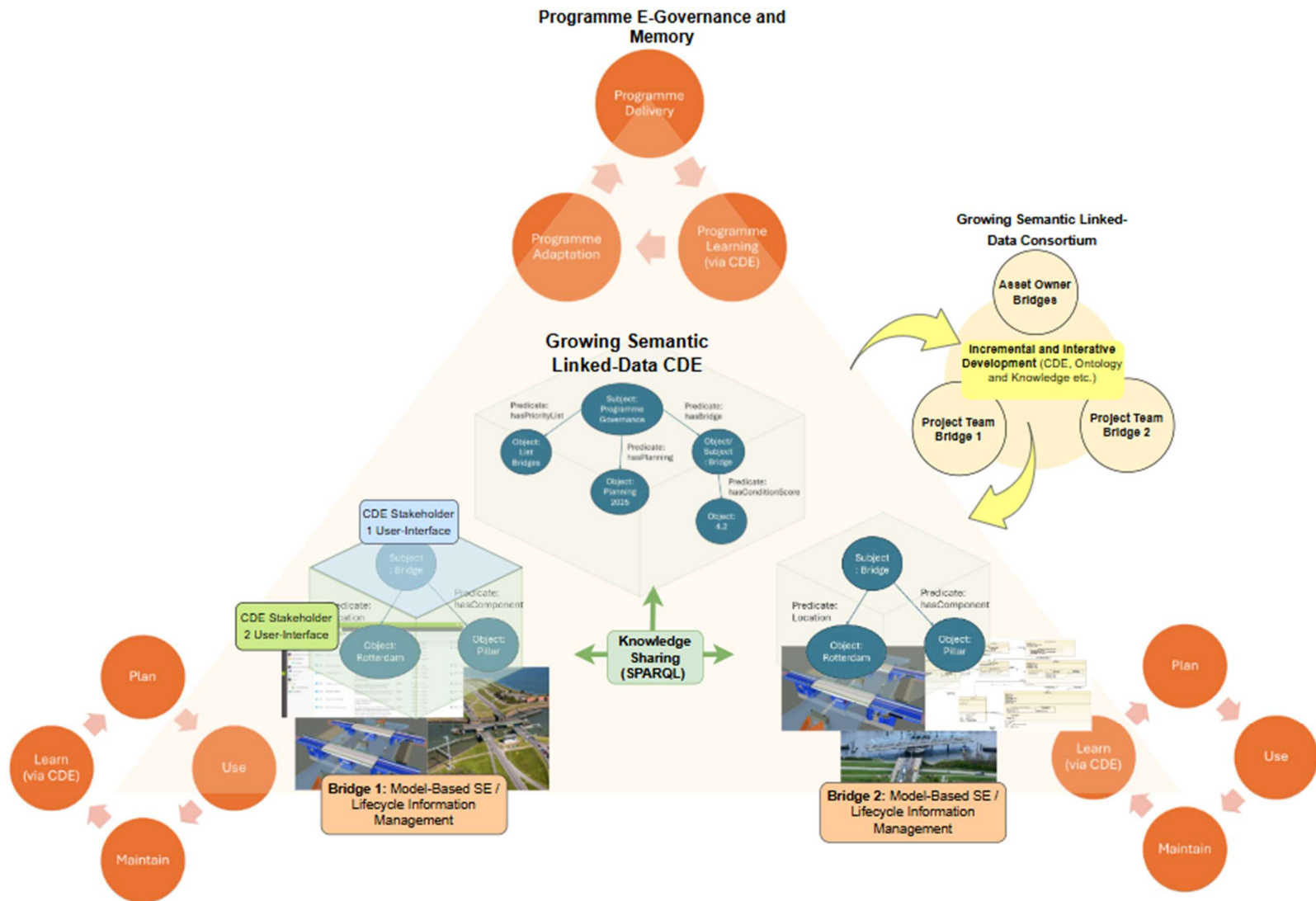


Figure 16 –Semantic Linked Data Common Data Environment Framework

5.3 Discussion

This research confirms that Model-Based Systems Engineering (MBSE), when enhanced with Semantic Technologies and implemented through a structured Common Data Environment (CDE), offers a robust strategy for addressing the growing complexity of infrastructure renovation and replacement programmes. The sub-questions and the qualitative evaluation demonstrate that MBSE strengthens interdisciplinary collaboration, improves traceability, enables better knowledge retention, and fosters more transparent and adaptive programme governance.

Moreover, it is evident that within the Dutch infrastructure sector, the concept of MBSE is still not fully understood. There is limited awareness of what model-based systems engineering truly entails beyond tool usage, and how it should be correctly applied in complex, multidisciplinary, and long-lifecycle environments such as infrastructure renovation and replacement programmes. Misconceptions risk reducing MBSE to isolated modelling activities rather than recognising it as an integrated approach combining structured system descriptions, lifecycle management, and data-driven decision-making. While isolated MBSE applications may deliver localised benefits, this study shows that to realise its full potential, MBSE must be embedded within an overarching, coherent MBSE system. Furthermore, the Semantic CDE does not merely store information but can enable a culture of continuous learning and long-term value creation by structuring data semantically and making it reusable. Such collective knowledge building is not yet structurally applied through data infrastructures in the current practice of infrastructure projects. A clearer understanding of different MBSE types' principles, benefits, and conditions is essential to ensure effective and context-specific application.

It is also essential to recognise that MBSE is not solely a matter of technology; it encompasses tools, processes, and people. This research mainly focuses on the technological foundation within the broader socio-technical system, especially the role of a Semantic CDE and the structured use of data and ontologies. The organisational, process, and human aspects of this transition require further research. The Semantic CDE can be seen as a push factor, an initiating technical intervention, which requires corresponding pull developments in the other socio-technical aspects.

This study can therefore be considered a starting point for such further exploration. It particularly addresses the language pillar of MBSE, as defined in the triad of language, method, and tool. The remaining two pillars, method and tool, require further elaboration in follow-up studies. These three MBSE pillars overlap with the socio-technical system dimensions: language and tools with technology, and method with process. Understanding these overlaps and the dependencies between them is key to realising a successful MBSE implementation.

The social and organisational dimensions remain underdeveloped. Importantly, in the infrastructure sector, the success of MBSE depends less on the technical feasibility of the approach and more on the organisational and cultural transition required within the sector. The technical foundations (such as ontology design, data structuring, and tool interoperability) are largely mature, and the technical feasibility of the proposed solution is therefore relatively straightforward to achieve. However, significant barriers remain in achieving sector-wide collaboration, overcoming resistance to change, and ensuring standardisation. While change management is briefly discussed in this report, a more comprehensive implementation plan should be developed to enable cross-organisational collaboration in a sector that remains largely competitive and fragmented. Without such a plan, the necessary alignment of interests and practices across public and private stakeholders will be difficult to realise. In this context, transitional strategies that allow integration with existing document-based practices can help organisations adopt MBSE incrementally, without disrupting ongoing operations.

In this regard, Linked Data emerges as a powerful enabler of a participatory systems approach to programme governance. It supports shared understanding, distributed knowledge development, and transparent decision-making across stakeholder boundaries. Semantic data modelling is a crucial element in making this possible, as it provides the structured, machine-readable foundation needed to interlink perspectives and enable traceable communication between actors. This aligns with the notion that governance in complex sociotechnical systems requires not only top-down control mechanisms but also participatory structures that support adaptive and inclusive coordination. Such participation is essential to navigate uncertainties, adapt to emerging conditions, and ensure sustained stakeholder engagement throughout the infrastructure lifecycle.

Therefore, follow-up research is needed to explore how the proposed semantic framework can be organisationally realised in practice. This includes understanding how to get companies, asset owners, and leaders to collaborate, and how to initiate and structure this cooperation effectively. Particular attention should be paid to developing tailored change management strategies that address the needs and concerns of different stakeholder groups. Since stakeholders operate from diverse perspectives, tailored approaches are needed to align their interests and foster collective commitment to a shared MBSE approach. To build momentum, it is important to identify and communicate quick, demonstrable gains for each stakeholder group.

5.4 Recommendations

Based on the findings of this research, several strategic, organisational, and technical recommendations are proposed to facilitate the practical implementation of Model-Based Systems Engineering (MBSE) in the context of infrastructure renovation and replacement programmes. These recommendations aim not only to bridge the gap between systems engineering practice and programme governance, but also to strengthen both domains individually. Linked Data plays a central role in connecting these perspectives by enabling more coherent integration of information and collaboration across organisational and technical boundaries.

Strengthen sector-wide understanding of MBSE as a system approach

There is a clear need to enhance the sector's understanding of MBSE beyond tool or language usage. Systems Engineers should receive targeted training on the three foundational pillars of MBSE: modelling language, method, and tool. These elements must be applied coherently across the technical and technical management processes described in ISO 15288. This will ensure MBSE is recognised and adopted as an integrated, lifecycle-oriented system approach rather than a collection of isolated modelling activities. In practice, many Systems Engineers are familiar with processes and human collaboration, but often lack a structured understanding of the range of available MBSE tools and methods, and how these can be effectively applied across different project contexts. Improving understanding of how methods, tools, and languages relate in different infrastructure scenarios will help close this gap. In addition, a deeper understanding is needed of how the three MBSE pillars relate to the broader socio-technical system aspects, namely technology, processes, people, and organisational structures, and how these interdependencies can be developed in synergy. It often makes sense to take the technological foundation as the starting point, and then adapt processes, roles, and organisational structures accordingly. This pattern of technology-driven organisational change is seen more broadly in society; for example, the introduction of computers transformed communication systems, and the adoption of BIM has reshaped collaboration in the construction sector. However, implementing a new technology such as an MBSE application may not yield its full potential if other socio-technical aspects remain misaligned. Therefore, it is essential to identify which constraints in the broader system may limit effectiveness, and determine how they can be addressed to enable successful implementation. This includes assessing whether the technological capabilities align with the intended system goals and how they can be operationalised through appropriate values, such as participatory system principles, to ensure meaningful and sustainable integration.^f

Promote differentiated and context-aware MBSE application

Different infrastructure projects and organisations operate under varying constraints and stakeholder dynamics. It is therefore recommended to support stakeholders in identifying which parts of the ISO 15288 lifecycle benefit most from MBSE in their specific context. Practical implementation guidelines and decision-support tools should be developed to help configure MBSE approaches accordingly. To ensure actual usability across roles, tool interfaces and visualisations should also be adapted to the needs and working methods of specific programme and discipline domains.

Establish a Semantic Technology and Governance Consortium

To overcome fragmentation and enable interoperability across projects and organisations, it is recommended to formalise a public-private consortium that coordinates the development and maintenance of the Semantic Common Data Environment (CDE), Reference Data Libraries (RDL), and standardised ontologies. Asset owners should take a leading role in initiating and sustaining this consortium, given their long-term responsibility for infrastructure performance and data continuity. This body should also facilitate long-term knowledge exchange, support pilot projects, and ensure that vendors align their tooling with standardised interoperability

frameworks. Such a consortium is essential not only to establish consistent technical integration, but also to create the collaborative governance mechanisms needed to support scalable, cross-organisational use of MBSE and semantic technologies.

In addition to technical harmonisation and governance coordination, the consortium should also take responsibility for building sector-wide competence in digital and semantic technologies. Training programmes should be supported or initiated for engineers, project managers, and programme participants, with a focus on semantic data modelling, lifecycle systems thinking, and collaborative model use. This shared learning infrastructure will help embed a resilient, model-centric engineering and governance culture in the Dutch infrastructure sector.

Conduct follow-up research into organisational integration and change

While the technical maturity of MBSE and semantic data integration is no longer the primary barrier, further research is needed into how MBSE can be successfully integrated into work routines and organisational processes. This includes understanding how to initiate collaboration in a competitive and fragmented sector, developing change management strategies for different stakeholder types, and identifying enabling conditions for trust and shared ownership. Follow-up research should also explore how to communicate early demonstrable benefits to build momentum. Additionally, research should examine how participatory systems thinking can be embedded in procurement, contract models, and governance structures, with Semantic Linked Data as a key enabler for transparent collaboration and information sharing.

Develop an incremental and iterative implementation approach

Organisations should avoid large-scale rollouts without incremental and iterative learning and experimentation. It is recommended to start with small-scale pilot projects to test the Semantic CDE, adapt socio-technical aspects, and demonstrate added value. These pilots should contribute to a broader implementation approach and roadmap. Implementation efforts should also consider hybrid strategies that allow for alignment with existing document-based workflows while gradually shifting towards data-centric collaboration. A hierarchical approach initiated by asset owners is essential to provide coherence and alignment, while system development must also emerge from real project work, building the data from the bottom up to inform higher-level decision-making. Too often, the focus lies on new tools while stepwise implementation and organisational change are underestimated. These aspects must be explicitly addressed to ensure sustainable adoption.

Facilitate participatory governance through data infrastructure

To enable long-term, adaptive decision-making across organisational boundaries, infrastructure programmes should invest in data infrastructures that support participatory governance. Linked Data technologies and semantic standards offer a foundation for transparent communication, traceability, and shared control over system definitions and changes. This helps to align technical collaboration with programme-level governance needs.

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Chapter 6: Appendices

Appendix A: Literature Study

The Problem Analysis provides information for Chapter 3, MBSE Application Analysis. The Problem Analysis aims to comprehensively capture information to generate needs for the proposed MBSE approach through which the researcher found the fitting solutions. The information also concerns socio-technical problems and weaknesses, threats and opportunities for the SWOT analysis conducted later in the research.

A.1 MBSE

Systems Engineering

Systems Engineering (SE) is the leading method for managing complexity. (Stevens, 1998). SE is the discipline developed to deliver successful projects in complex environments through a multi-disciplinary approach considering the whole system life cycle (Bahill & Dean, 1996), ensuring customer satisfaction (Locatelli, Mancini, & Romano, 2014). The multi-disciplinary approach and its principles enable the successful management of complex systems when organisations design individual elements in different phases of the project life cycle (Kossiakoff, 2003). The SE Integration Process aims to manage internal and external systems interfaces. It ensures that subsystems integrate into one system (Walden, 2010).

MBSE

Because existing emergent properties are hard to predict, more than traditional approaches are needed to manage current complexity and obtain successful project results. Also, the communication of the conventional DBSE approaches to produce artefacts and models is ineffective, and the documentation is not as accurate as expected. Because when making individual models or changes, it is complex to integrate them into a coherent model. Additionally, considering the modelling activities performed by SE in different project teams, it is often difficult to fully integrate with other SE process activities. Therefore, the current (hybrid) document-based approach tends to produce a chain of inconsistencies along all the artefacts owned by different teams on the project (Friedenthal, Moore, & Steiner, 2014). Due to the unique nature of the construction sector, the development and deployment of systems integration and collaboration technologies are behind other sectors (Shen, et al., 2010), and many problems in communication and cooperation between different disciplines still need to be solved (Albers & Lohmeyer, 2012).

For better project performance and to manage the increasing complexity, the construction industry could apply Advanced Systems Engineering, more specifically Model-Based Systems Engineering (MBSE), which means using models as artefacts for SE activities (Schmidt & Stark, 2020) and provides an approach for top-down consideration of systems (Whyte, 2016). The Institute of Project Management defines modelling as creating simplified representations of systems, solutions, or deliverables such as prototypes, diagrams, or storyboards. Modelling can facilitate further analysis by identifying gaps in information, areas

of miscommunication, or additional requirements (Institute Project Management, 2021). MBSE is the formalised modelling application to support systems requirements, design, analysis, verification and validation activities from the conceptual design phase to later life cycle phases. One expects the MBSE approach to become the standard SE practice and be crucial to supporting an effective collaborative development environment and facilitating SE activities (Ramos, Ferreira, & Barceló, 2011).

MBSE simulation is essential for designing multi-disciplinary, closely linked component systems to achieve optimal performance (Sinha, Liang, Paredis, & Khosla, 2001) (Locatelli, Mancini, & Romano, 2014). Analysis, experimentation, modelling, prototyping, evaluation and testing are part of MBSE and ensure that cost and timescale remain controlled (Albers & Lohmeyer, 2012). Also, MBSE could function as a collaborative tool facilitating trust and cooperation (Das & Teng, 1998). According to (Masiar, Schneider, Kürümlüoglu, & Riedel, 2020), the project team should use MBSE to enhance complexity management, which is also supported by (Locatelli, Mancini, & Romano, 2014), stating that modelling is the principal means of coping with project complexity improving project performance. However, the current MBSE state should be more transdisciplinary and integrative (Schmidt & Stark, 2020). ISO 15288:2023 provides a list of benefits of executing system life cycle processes in an MBSE environment in its appendix. Kelly X. Campo researched the benefits of MBSE from 60 academic sources and coded over 2900 claims (Campo, et al., 2022). Table A.1 provides both benefit lists.

Appendix A Table 1

ISO 15288	Kelly X. Campo
A more thorough understanding of the concept and system definition	Better communication
Better ability to perform trade-offs	Better analysis capability
More effective and efficient measurement	Improved system understanding
Better ability to perform impact analysis	Improved consistency
Help ensure consistency and completeness of requirements	Reduce time
Help ensure consistency and completeness of architecture and design	Increased efficiency
Enable reuse and adaptability.	Better manage complexity
Surrogate for verification and validation activities	Reduce cost
Reduction of risk	Reduce errors
Early detection of interface/integration issues	Increased traceability
Better understanding and management of dependencies	

Due to the interactions and relationships between system elements, traditional analysis and modelling techniques can fail to incorporate the intricate dependencies between system entities and emergent system behaviour. MBSE can help address existing practices' failures throughout the construction lifecycle (Baudains, et al., 2014). Madni and Purohit found that the expected gains of MBSE depend primarily on the system's intrinsic characteristics, such as complexity, operational environment and lifespan (Madni & Purohit, Economic Analysis of Model-Based Systems Engineering, 2019), indicating that research has to focus on these aspects. Madni and Purohit concluded that the infrastructure sector could benefit significantly from MBSE and, therefore, is an incentive to commence a more detailed study of MBSE as a

tool for complexity management for renovation and replacement projects along with the organisation of the programme.

Currently, no infrastructure organisations are applying a complete MBSE method. The sector's most used software conforming to ISO/IEC 15288 for conducting hybrid Document-Based Systems Engineering (DBSE) and MBSE is Relatics (Relatics, 2023). Relatics uses models to capture and understand complexity. However, it is impossible to use the software as entirely MBSE. This research provides in Chapter 3 a description of the existing MBSE application, describing the MBSE and DBSE elements of the current approach. Due to Relatic's lasting dominance in the infrastructure sector and the reluctant development of MBSE, organisations are now taking initiatives to innovate.

An initial model is mainly used to validate critical decisions about the system and mitigate specific technical risks early in the design process (Madni, Madni, & Lucero, Leveraging Digital Twin Technology in Model-Based Systems Engineering, 2019). Model-centric approaches are, in contrast to document-centric methods, capable of formal definition and description of systems, which are necessary for enabling the systems thinking perspective and the automatic processing of interrelationships between system elements as well as the impact assessment of changes (Kunnen, Adamenko, Pluhna, & Nagarajah, 2019). Initial modelling of the solution concept helps identify the known unknowns and clusters of known knowns distributed among individuals and across teams. Furthermore, it allows the project team to communicate knowledge more efficiently and faster (Asan, Albrecht, & Bilgen, 2014). One should consider that the effectiveness of MBSE increases by applying various activities across the life cycle. Therefore, the proposed MBSE approach should consist of several activities working correctly in synergy (Madni & Purohit, Economic Analysis of Model-Based Systems Engineering, 2019).

Research on managing complexity and collaboration through MBSE is relevant since the current studies seek to understand infrastructure as a complex system that enables production systems to allow prospective visualisation of interconnections, interactions, and interdependencies. (Whyte, 2016). This research approaches MBSE from sector-specific knowledge about complexities for successful and improved application. Additionally, MBSE research can contribute a variety of system modelling constructs that Digital Twins (DT) can exploit (Madni, Madni, & Lucero, Leveraging Digital Twin Technology in Model-Based Systems Engineering, 2019). DT is another upcoming ASE method in the infrastructure sector. There is no consensus yet among researchers and practitioners regarding how DT can support the design and construction of civil engineering constructions (Sacks, Brilakis, Pikas, Xie, & Girolomi, 2020) (Opoku, Perera, Osei-Kyei, & Rashidi, 2021). Therefore, this research could obtain additional insights regarding DT since it overlaps with MBSE.

The interoperation of a physical facility and its digital components, such as digital twins, is called Digital Thread. The aim of the Digital Thread is the creation of a digital lifecycle ecosystem that links together the data generated throughout a product's lifecycle and represents the data, processes and communication platform that supports a product and its production at any instance of time (Margaria, Pesch, & McGibney, Digital Thread in Smart

Manufacturing, 2022). Digital Thread that connects real things and their twin models, but also the communication networks, the decision algorithms, and the visualisations needed to work in design, construction, and operation within a mature Industry 4.0 environment are still not in the sphere of awareness of the responsible (Margaria & Schieweck, The Digital Thread in Industry 4.0, 2019). Having a well-established Digital Thread that holistically considers the entire construction project lifecycle and ecosystem is fundamental for the digital transformation of the industry. The data encompassed in the Digital Thread is essential for all stakeholders and supports short- and long-term decisions and could lead to better project predictability and performance, greater collaboration and transparency between stakeholders, and more standardisation of the industry (Hatoum, Nassereddine, AbdulBaky, & AbouKansour, 2023).

Delligatti classifies the three most crucial elements of MBSE as a modelling tool, method and language and names them together The Three Pillars of MBSE. As a design team member creating an integrated system model, one will use a dedicated *modelling tool* to perform a set of design tasks prescribed by a *modelling method* to add elements and relationships between elements to an integrated system model expressed in a standard *modelling language*. One has to master all three skills to gain the ROI that the MBSE approach offers.

A modelling language is a semiformal language that defines the kinds of elements one allows put into the model, the allowable relationships between them, and, in the case of a graphical modelling language, the set of notations one can use to display the elements and relationships on diagrams. MBSE practitioners commonly use the Systems Modeling Language (SysML) to construct models of a system's structure, behaviour, requirements, and constraints. Modelling languages are, for example, UML, UPDM, BPMN, MARTE, SoaML and IDEFx, and Verilog and Modelica are text modelling languages. The key is that each modelling language is a standardised medium for communication; the rules defined in a given language give the elements and relationships unambiguous meaning. A modelling language is a documented set of design tasks that ensure that everyone on the team builds the system model consistently and works toward a common endpoint.

A modelling method dictates how and when to use the language to create a model. A modelling method is a documented set of design tasks a modelling team performs to create a systems model. According to Delligatti, every MBSE project requires a plan beginning with a purpose and a scope. The scope determines the modelling method the team will follow. Examples of well-known methods spanning the SE lifecycle stages are OOSEM, SYSMOD and IBM Telelogic Harmony-SE. Modelling tools are a particular class designed and implemented to comply with the rules of one or more modelling languages, enabling one to construct well-formed models in those languages. Modelling tools are distinct from diagramming tools such as Visio, Schematic, SmartDraw, ProcessOn, and others. With a diagramming tool, one creates merely diagrams. With a modelling tool, one creates a model, a set of elements and relationships between components, and charts that serve as views of the underlying model. The underlying model automatically ensures consistency. When one modifies a part of a diagram within a modelling tool, one changes the element in the underlying model.

There are many factors to consider when one selects a tool. However, Delligatti recommends selecting an XML Metadata Summary 9 Interchange (XMI) compliant tool. XMI standard compliance enables the exchange of model data. This capability will ensure that the team avoids the vendor lock-in trap when needs change in the future. Free modelling tools are, for example, Modelio and Papyrus (Delligatti, 2013).

SysML

Different modelling languages exist to design successful models for various applications. The most used MBSE modelling language is Systems Modeling Language (SysML), developed for SE specifically to improve communication among the involved stakeholders (SysML™, 2019). However, SysML models still need to improve in representing complete system life cycle information, flexible reduction regarding present needs and interdisciplinary integration of models; continuousness and consistency still are the subject matter of research (Albers & Lohmeyer, 2012). (Geyer, 2012) Argues that only graphical languages, such as SysML, can fundamentally provide for both system analysis and system synthesis. SysML is a modelling language consisting of a toolbox offering several ways to describe a complex system. SysML is not a method, and the Object Management Group (OMG) does not propose a specific approach. INCOSE aims to develop an MBSE (SysML) approach and standard for all sectors. However, the infrastructure sector significantly differs from other sectors and demands a specific method for the projects' life cycle. Before starting modelling, the modellers must define the intended objective to ensure that the model improves communication, analysis design and risk management (Casse, 2017). Still, the use of MBSE in the SE procedure, specifically for the infrastructure sector, is unclear, resulting in lower application than in other sectors and, therefore, requires more research. It is important to note that MBSE focuses on behaviour and abstract functional structure, while a BIM model is a concrete three-dimensional (project management-related) information of the included elements. (Ammon & Paech, 2018). A significant advantage of SysML is that implementation is done at an abstract level, allowing for the involvement of stakeholders with less technical understanding. One can complement SysML validation models by employing simulation models as virtual prototypes, which can gradually expand into digital twins (Wagner, Portenlänger, & Zuccaro, 2023). Furthermore, one can apply SysML to create a digital thread, including DTs (for simulating, testing, monitoring and maintaining the system), that defines the traceability between requirements, design, analysis, and testing (Pessoa, Pires, & Wu, 2022).

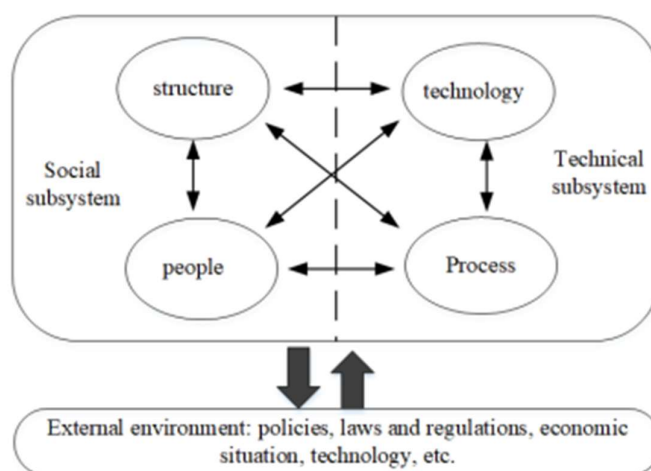
A.2 General Complexity

A.2.1 Theory

The concept of socio-technical systems entered the engineering sector, originating in post-World War 2 British coal mining studies. In contrast to previous studies that had often considered technology as an independent force, the organisational and labour studies influenced by the socio-technical approach emphasised the close interdependence of the social and technical subsystems (Bauer & Herder, 2009). Sawaragi mentions that it is necessary to focus on the socio-technical performance-shaping factors that depend on the relevant context, the dynamic aspect resulting from the interaction between the human being and the situation,

the interdependency among the influencing factors, and the overall impacts (Sawaragi, 2020). Three factors that characterise socio-technical systems are Technology, Organisations and People. One designed almost all technologies today with implicit or explicit relations between those three factors (Brandt & Černetič, 2000). Carter and Rogers found that organisational sustainability comprises three components: Environment, Society and Economics (Roger, 2008). Moreover, Espinosa defines a viable and sustainable organisation as one capable of independent existence without severance from its niche or alienating itself from the needs of future generations (Espinosa, Walker, Grover, & Vachkova, 2023). Therefore, one should consider how new technology could contribute to the RRP's objective of providing the future generations of the Netherlands with safe infrastructure through a sustainable and viable organisation.

How well one designs the social and technological systems concerning one another and concerning the demands of the external environment determines how effective the organisation will be (Dougherty, 2001). The socio-technical system's elements are interdependent and interact within the organisation. Element changes in one subsystem will lead to changes in the other subsystem. The system's performance depends on interaction and joint optimisation between social and technology subsystems under external influence (Bostrom & Heinen, 1977), see Fig. A.1.



Appendix A Figure 1 – Socio-Technical System (Bostrom & Heinen, 1977)

Sam McLeod researched feasibility studies in different sectors and aimed to find similarities between other sectors' feasibility studies and synthesise the principles. McLeod's research question relates to this research since it is a feasibility study for a novel project: "How should organisations design feasibility studies for novel, complex, or unfamiliar projects?". McLeod's feasibility principles are not a checklist but a guide to developing a project-specific framework since there is no specific way to conduct a feasibility study (McLeod, 2021). The feasibility areas (Capability, Acceptability, Long-term, Technical, Economical, Sustainability, and Time) indicate that the benefits of the novel MBSE approach outweigh the additional complexity. Furthermore, crucial is that the proposed approach contributes to a long-term solution for the maintenance, renovation, and replacement of moveable bridges, considering different organisational levels of potential MBSE application.

Complexity drivers are factors related to project size, variety, interdependence, and context (Vidal & Marle, 2008). Brazier describes complex systems as systems that display unexpected, emerging and unpredictable behaviour, and its characteristics as large scale of applications, involvement of many stakeholders, requiring cooperation and coordination, and decision-making based on uncertain, incomplete, inconsistent or ambiguous information (Brazier, Langen, Lukosch, & Vingerhoeds, 2018). Project complexity research focuses on four areas: complexity influencing factors, project complexity impact, complexity measurement methods, and project complexity management (Luo, He, Jaselskis, & Xie, 2017). There is no universal construction industry-accepted definition of project complexity (Baccarini, 1996) (Luo, He, Jaselskis, & Xie, 2017); however, in the current research, project complexity is broken down into at least technical, organisational and environmental complexity. Bosch-Rekvelde found various complexity factors, shown in Table A.2, allocated to those categories for large engineering projects (Bosch-Rekvelde, 2011).

Appendix A Table 2 – Technical, Organisational and External Complexity Factors (Bosch-Rekvelde, 2011)

Technical Complexity	Organisational Complexity	External Complexity
Number of project goals	High project schedule drive	Number of external stakeholders
Non-alignment of project goals	Lack of Resource & Skills availability	Variety of external stakeholder perspectives
Uncertainty of project goals	Lack of Experience with parties involved	Dependencies on external stakeholders
Uncertainties in scope	Lack of Health, Safety, Security, and Environment awareness	Political influence
Strict quality requirements	Interfaces between different disciplines	Lack of company internal support
Project duration	Number of financial sources	Forced cooperation with local parties
Size in Capital Expenditure	Number of contracts	Interference with existing site
Number of locations	Number of different nationalities	Weather conditions
Newness of technology	Number of different languages	Remoteness of location
Lack of experience with technology	Presence of Joint Venture partner	Lack of experience in the country
Number of tasks	Involvement of different time zones	Company internal strategic pressure
Variety of tasks	Size of project team	Instability of project environment
Dependencies between tasks	Incompatibility between different project management methods or tools	Level competition
Uncertainty in methods	Lack of trust in project team	Risks from environment
Involvement of different technical disciplines	Organisational risks	
Conflicting norms and standards	Lack of trust in contractor	
Technical risks		

Furthermore, complex systems have "many interrelated, interconnected, or interwoven elements and interfaces" (Crawley, 2007). Complexity results from interactions among numerous and varied elements that are dynamic and uncertain. (Luo, He, Jaselskis, & Xie, 2017) (Masior, Schneider, Kürümlüoglu, & Riedel, 2020). Therefore, many authors see a high degree of interconnectivity between the terms' complexity' and 'uncertainty' (Suh, 2005) (Menshenin, Moreno, Brovar, & Fortin, 2021). Ignoring the potential cause-effect relationships between the complexities and risks may cause an insufficient understanding of

project risks (Andringa, Ökmen, Leijten, & Bosch-Rekveldt, 2022). Suh defines complexity as "a measure of uncertainty in achieving the specified functional requirements" - more information needed to achieve the functional requirement increases complexity (Suh, 2005) (Menshenin, Moreno, Brovar, & Fortin, 2021).

As shown in Fig. A1 above, environmental factors play a role in the performance of the socio-technical system. In the case of this research, the main external factor to focus on is the RRP for moveable bridges in the Netherlands. Other external factors currently increasing challenges of socio-technical systems include the desired climate adaptation and circularity. Infrastructure organisations must react to and manage these issues individually and collectively to continue achieving desirable project performances. Describing the effects of complexity on the RRP and projects is essential to understand how MBSE could be valuable in approaching this assignment and expanding current knowledge about project complexity.

Design errors, lack of effective communication, and increasing project complexity are causes of variations. Designers often operate independently, making decisions without considering their impact on other disciplines in the supply chain (Love, Edwards, & Smith, 2013). When major root causes of variations are addressed early or eliminated, there will be a significant reduction in the total number of variations a construction project will record. Variation is a change in design, material, scope or method different from what one specified in the initial contract. A definition of Variation is an amendment to the basis on which a contract is agreed (Noruwa & Arewa, 2020). Hibberd stated that "there is no one definition of what is a variation" but referred to variation as any amendment to the original contract agreement, which is the most significant problem in contract management (Hibberd, 1986). JCT defined variation as "the alteration or modification of the design, quality or quantity of the works, materials or goods which are not according to the contract" (JCT (Joint Contracts Tribunal), 2016). Ibbs defined variations as "additions, deletions, or other revisions within the general scope of a contract that cause an adjustment to the contract price or time" (Ibbs, 1994). Jones has discussed the cumulative disruptive impact of variations whose impact on productivity and cost surpasses the actual cost of the changed work (Jones, 2001). Variation is a significant source of delays and disruptions (Akinsola, Potts, & Ndekugri, 1994) and significantly causes construction disputes (Perera, Ekanayake, Jayalath, & Jayathilaka, 2019). Notably, pressure on the variation limitations during projects considerably increases the chance of committing errors (Lopez & Love, Design Error Costs in Construction Projects, 2011).

The design stage of construction is the most crucial stage to focus on to minimise variations and problems on site (Arian & Low, 2005). The most frequent reasons for variation are errors in design and incompetent detailed drawings regardless of the procurement method adopted. One recorded a Significant reduction in the number of variations at project completion due to eliminating most project risks, design errors, omissions, rework and effective design coordination (Noruwa & Arewa, 2020). The causes and effects of committing errors are not unidirectional or linear but are reciprocal or looped in their relationships. Understanding how such relationships emerge is necessary for error prevention. The ideal error prevention approach is to view errors as symptoms of underlying problems so they become sources of information to understand how systems work. Literature suggests one can classify the design

error causes according to people, organisation and project. Table A.3 presents the classification of significant design error causes (Lopez, Love, Edwards, & Davis, 2010).

Appendix A Table 3 – Classification of significant design error causes (Lopez, Love, Edwards, & Davis, 2010)

Personal	Organisational	Project
Loss of biorhythm	Inadequate training/experience	Client/end-user issues
Adverse behaviour	Ineffective utilisation	Time constraints
	Competitive professional fees	Ineffective coordination
	Inadequate quality assurance	Inadequate consideration of constructability

Various studies that have examined design errors treated the terms changes, omissions, defects, quality deviations, nonconformances, and failures interchangeably. Correct definitions of those terms are crucial to avoid confusion (Lopez & Love, Design Error Costs in Construction Projects, 2011). Study findings demonstrated that one could eliminate variation if their origin and causes are determined and addressed (Awad, 2001). Clients are significant causes of variations in construction projects. Most variations in projects implementing useful technologies are due to clients' changing needs rather than incorrect designs (Mohammad, Ani, Rakmat, & Yusof, 2010).

Furthermore, current strategies for design error management neglect the role of proper information flow and communication between project players (Hattab & Hamzeh, 2015). Minimising variation is one of the prerequisites of keeping the cost within budget and completing the project on time. Strategies Chan and Yeong propose, among others, are clear and thorough project briefs, design detailing, and excellent communication and cooperation among project teams (Chan & Yeong, 1995). Providing designers with adequate time to produce documentation, implementing audits, reviews, and verification, using CAD applications, and circumventing time boxing will help contain errors but not mitigate them. Similarly, at the project level, the implementation of constructability analysis, BIM, benchmarking, quality, management, risk management, alliancing, and integrated procurement methods can also be used to contain errors, but they eliminate errors to a limited extent. Wholistically and complete application of these strategies will most effectively prevent problems due to safety, rework, claims and disputes (Lopez, Love, Edwards, & Davis, 2010). Love proposes the following strategies for error reduction during the design phase: instigating situated learning, computer technology (e.g. building information modelling), simplifying and standardising procedures, the use of integrated procurement structures, implementing systems to reduce an individual's reliance on memory and the number of project organisational interfaces, decentralised decision-making, and, increased communication within and across a project team (Love, Edwards, & Smith, 2013). Another problem is the interpretation of requirements since unambiguously writing down requirements in documentation is difficult, creating a discrepancy between specification and implementation (Hendriks, 2022).

BIM is significant in minimising undesirable variations in construction projects by increasing the coordination of designs. To effectively minimise variations in construction projects, a combination of other appropriate emerging technologies with BIM along the construction process is required. BIM allow virtual twinning of the structures and a quick decision-making

process. It enhances the effective management of changes and enables designers to run various design scenarios to meet clients' required functional and aesthetic needs. However, despite the emergence of BIM, changes in scope and errors and omissions are the main contributors to rework costs that arise (Love, Teo, & Morrison, 2017). Moayeri developed a model capable of comparing the original model of a building with a revised model by using BIM to visualise the changes and illustrate the ripple effect of the change (Moayeri, Moselhi, & Zhu, 2015). Variation always increases the capital cost of construction projects. They result in a heavy administrative load, requiring reviews, discussion, and tracking (Keane, Sertyesilisik, & Ross, 2010). Other technologies, such as collaboration platforms, mobile apps on phones or tablets, cloud computing, and Common Data Environment (CDE), led to effective and efficient communication among project teams and the sharing of project information among project teams (Noruwa & Arewa, 2020).

A.2.2 Renovation and Replacement Programme

Any infrastructure Renovation and replacement assignments bring additional complexities within project and programme organisations. Understanding the complexity helps determine the difficulty of problems and how to solve them through measurements. Infrastructure is inherently highly complex due to its social, technological and economic aspects. The performance of the integrated physical and social system, including bridges, determines the service reliability. From an economic perspective, there is an undeniable sense of urgency to place reliability high on the political agenda and demand better control through technological innovation and knowledge development (Weijnen & Bouwmans, 2006). From a programme perspective, a complexity-increasing factor is the increasing number of necessary renovation and replacement projects, due to deferred maintenance and changing requirements, and the capacity shortage to tackle it.

Furthermore, organisational inefficiencies demand better programme governance and coordination to align interests between various owners and control uncertainties. Other organisational challenges are a lack of trust and high competition within the civil engineering sector (Dorée, 2004), contradicting the need for solid collaboration regarding knowledge and innovation development (Marktvisie, 2020). There is a need for adaptable programmes to respond to contextual changes that could harm programme outcomes. Learning and adaptation throughout programmes benefit the programme approach (Van Herk, Rijke, Zevenbergen, & Ashley, 2013) (Rijke, et al., 2014). Therefore, it is valuable to investigate how technology, used at the project level, can contribute to learning for improved adaptation and change management.

One must coordinate inter-organisational and across project boundaries to make innovations successful (Rutten, Dorée, & Halman, 2019), which is complex since the Dutch civil engineering sector is a non-hierarchical, polycentric and decentral system consisting of multiple autonomous, interdependent, collaborating and competing actors. Menard defines three broad categories of organisational structures that govern the interactions among actors dependent on the degree of autonomy the actors wish to retain: market, hybrid and hierarchical structures. Polycentric programmes naturally lean towards a hybrid organisational

structure – given that the actors wish to retain their autonomy yet engage in some form of cooperation (Ménard, 2011).

Innovation is essential when current approaches are not sufficient anymore to achieve the desired results. However, if one does not appropriately facilitate innovations, it constrains innovation within the superstructure of the civil engineering sector (Dubois & Gadde, 2002). The clients within the superstructure represent the demand side of innovation and can stimulate innovation through procurement (Edler & Georghiou, 2007).

Rijkswaterstaat, a significant client in Dutch infrastructure, created Roadmap Bridges, which describes the innovation development necessary to realise the goals before 2030 (Rijkswaterstaat, 2023). From 2030, Rijkswaterstaat wants to conduct more renovation and replacement projects for bridges. These will be future-oriented and more cost and capacity-effective, achieved through collaboration with the market, aiming for innovation on standardisation, merging, digitalisation and sustainability. Table A.4 shows the strategies and corresponding steps from 2023 to 2030 to achieve Rijkswaterstaat's objectives. As one can see, Rijkswaterstaat is aiming for more standardisation, which could offer repeated design economies through rationalisation and greater use of preassembled manufactured components. However, investigation shows that it is complex and that factors could limit the benefits of standardisation (Robinson & Gibb, 2012). TNO states that, currently, most projects are customised and not standardised, which provides flexibility but also is inefficient, costing time and money because one has to re-design and re-construct every object (Hendriks, 2022). In the Industrial Automation (IA) context, RWS developed building blocks to prevent inefficiencies (re-design and quality and integration problems) and design errors due to insufficient knowledge about IA components. RWS expects that the blocks will contribute to accelerating the renovation and replacement assignment. RWS experiments with the 3BB blocks for bridge operation, control and monitoring. However, Adviescollege ICT-toetsing (BIT) found shortcomings in the IA-Sourcing programme (IAS), such as insufficient insight into integrating other technical systems and the impossibility of re-useability verification due to not considering different bridge configurations and detailed bridge design differences. Also, IAS expects one to update the blocks once a year. However, one can not adapt some objects' maintenance planning to the updates, making the update infeasible, resulting in different block versions and increasing complexity (Adviescollege ICT-Toetsing, 2021). MBSE could provide a test environment and verification and validation possibilities.

Appendix A Table 4 - the strategies and corresponding steps from 2023 to 2030 Rijkswaterstaat

Strategies	Steps from 2023		Till 2030
<i>Standardisation Bridges</i>	New bridge parts will be standardised and demountable	RWS will add the standardisation of parts as a learning task to the project scope	One will test parts during realisation, and if successful, standardised
<i>Standardisation Services</i>	Application of Synthesis Based Engineering Model (SBEM) for bridges to validate control requirements		Knowing how to safely, intelligent and future-proof design bridge control and security through collaboratively

<i>Strategies</i>	<i>Steps from 2023</i>	<i>Till 2030</i>	
			testing innovations with the market
<i>Standardisation Methods</i>	Rijkswaterstaat has investigated which portfolio of bridges to tender	There is a continual tender influx of bridge portfolio	Rijkswaterstaat works with new flexible contract forms
<i>Sustainability</i>	As much as possible, reuse and recycling of existing bridges	Development and application of life-extending innovations and sustainable materials	Working circular and climate-neutral
<i>Digitalisation</i>	Investigating digitalisation, automatisisation, and robotisation for bridges	Developing systems and processes to secure standardisation in contracts	Asset Management analysis automatisisation
<i>Collaboration</i>	Assessing innovation proposals for further development	Innovation demand is apparent and tendered to the market to develop	

The construction industry has a strong project focus. Civil engineering projects have a unique character, use novel processes, and are transient (Turner & Müller, 2003), but they also have similarities that one has to exploit to improve project results. The projects share few connections with others, complicating cross-project coordination and inter-firm collaboration, which hinders long-term productivity, innovation, and learning (Dubois & Gadde, 2002).

Bletsis researched improvement to governance and found in the literature various requirements for the RRP governance design derived from obstructions and needs, see Table A.5 (Bletsis A. J., 2020). The MBSE approach must contribute to fulfilling those requirements to prove its viability since one should see concluding a single project as a contribution to the entire RRP. Correct governance could enhance performance across multiple project-based organisational layers (Garland, 2009).

Appendix A Table 5 – Renovation and Replacement Programme Governance Requirements (Bletsis A. J., 2020)

Functional requirements
The system must address the challenges of the renovation and replacement assignment.
The system must stimulate the collective action of public and private actors.
The system must engage the civil engineering sector in participative processes.
The system must maintain the autonomy of actors within the polycentric civil engineering.
The system must facilitate cross-project coordination and inter-organisational collaboration.
The system must establish higher-order strategic objectives.
The system must adapt according to contextual changes.
Behavioural requirements
The system must facilitate more diffusion and adoption of knowledge, innovation and standards than current practice.
The system must realise a reduction in cost overruns and time delays of projects compared to the current practice.
The system must realise higher-order strategic objectives and realise synergies across projects.
The system must facilitate the shift towards sector-wide and long-term thinking (instead of inter-organisational and short-term)
The system must facilitate communication, self-organisation and deliberation among public and private actors.
The system must implement changes and learn from its processes over time.
The system must facilitate the making of joint corrective actions across public and private actors.

Structural requirements

The approach's adaptation mechanism must be interoperable with governance, coordination and processes.

Align the designed approach with existing initiatives.

The approach's lifecycle should consist of multiple stages.

The organisational structure must be compatible with the project-based polycentric sector.

Enable approach by Information & Communications Technologies.

The approach must contain institutions to structure (social) behaviour.

Experiential requirements

The designed approach should realise a sense of trust, empowerment and cohesion.

Interaction should be reciprocal and fair.

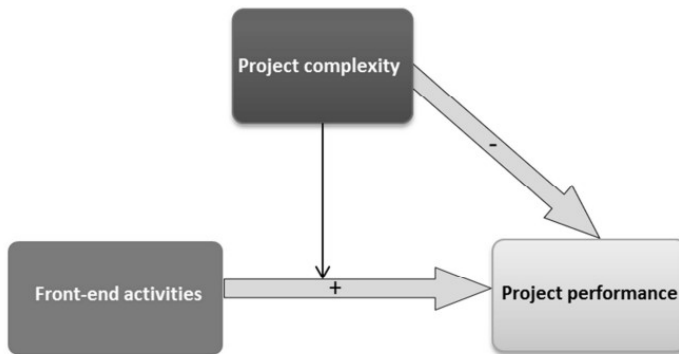
Perceive transitions and processes as reinvigorating for the sector.

Sense of autonomy

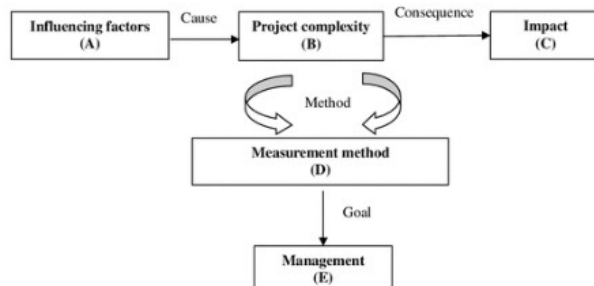
Actors should willingly participate.

A.3 Governance and Management Complexity

Fig. A.2 shows the research model of (Bosch-Rekvelde, 2011) wherein front-end activities are the independent variables, the project complexity is the moderator, and the project performance is the dependent variable. Through Value Improving Practices, one could treat aspects of those complexities in the front-end development phase. In this research, MBSE is a front-end activity, which decreases the adverse effects of complexity on project performance. Fig. A.3 shows the complexity management model of (Luo, He, Jaselskis, & Xie, 2017). The project team could decrease the negative impact of the project complexity through a MBSE method.



Appendix A Figure 2 - Model project complexity/project performance (Bosch-Rekvelde, 2011)



Appendix A Figure 3 - Model complexity management (Luo, He, Jaselskis, & Xie, 2017)

To understand and model complex systems generally, one decomposes the system into known subsystems and the relationship, and one considers the integration of the subsystems that emerge to system behaviour and the effect of external inputs and outputs on the system (Akundi, Tseng, Almeraz, Lopez-Terrazas, & Luan, 2021). To manage complexity, researchers focused their efforts on risk management, management style, and adaptive capacity (Luo, He, Jaselskis, & Xie, 2017). Still, they paid little attention to MBSE as a tool for complexity management in the civil engineering sector. (Luo, He, Jaselskis, & Xie, 2017) Recommend that future studies adopt a more robust approach to measuring project complexity, considering a project's structural, dynamic, and interactive elements. Future research could examine the following areas: influencing factors of project complexity from the perspective of different stakeholders and different phases of a project's lifecycle; the relationship between project complexity and project success; project complexity measurement that takes into account structural, dynamic, and interactive elements; and management of project complexity for different project types and increased project complexity during a project's lifecycle. This research uses complexity research as a starting point to assess whether MBSE is feasible and viable for the civil engineering sector and considers MBSE as a complexity management tool to improve project success.

Increasing project complexity demands construction companies' organisational, technical and social improvements for early-stage risk (complexity) reduction since the later one finds a defect, the more expensive it is to correct (Institute Project Management, 2021) and better performance. Researchers have agreed that complexity negatively affects project performance (Luo, He, Jaselskis, & Xie, 2017).

Underperforming projects are often delivered in an increasingly interoperable and interdependent systems environment (Jaafari, 2003) with a high number of system parts and organisations involved (Calvano & John, 2004) (Locatelli & Mancini, 2010). The integrated design process is essential for project performance, and integrating the complex context is crucial to improve results (Keusters, Bakker, & Houwing, 2022). Systems integration is the process of making a system coherent by managing interactions across system elements (Whyte, 2016), summarised as "creating a whole from parts" (Langford, 2012). Also, project teams can decrease epistemic uncertainty by better defining the entities and their relationships within each subsystem and between the various subsystems, leading us to better explain the interfaces between them (Menshenin, Moreno, Brovar, & Fortin, 2021). However, Mutual adoption of context is often hard to achieve. In particular, poor interaction between design and construction disciplines causes problems (Keusters, Bakker, & Houwing, 2022). Other suggested approaches to improve integration are early involvement, teamwork, learning and knowledge integration and collaborative working to improve the project performance (Suprpto, 2016). Front-end activities are crucial to enable efficient information exchange since underestimation or poor recognition of the complexity in an earlier project phase causes complexity to increase in later project phases (Bosch-Rekveltdt, 2011). For example, the Institute of Project Management (IPM) provides two complexity models to understand complexity better and determine how to make decisions in a complex environment. The

Cynefine Framework is a conceptual framework used to diagnose cause-and-effect relationships as a decision-making aid (Institute Project Management, 2021).

Managing complexity and delivering an integrated design involving interdisciplinary collaboration is a primary factor for successful projects to ensure an integrated design and identify lifecycle complexities. All significant construction projects require intense collaboration among multi-disciplinary teams (Sacks, Eastman, Lee, & Techolz, 2018). The integration challenges of civil engineering objects in their increasingly complex context and the integration of a growing number of disciplines dominate today (Keusters, Bakker, & Houwing, 2022). Systems integration is essential for efficient and effective collaboration (Shen, et al., 2010). Senescu (Senescu, 2013) found that communication problems in the construction industry increase when complexity increases. Aligned objectives, mutual trust, open communication, knowledge sharing, joint problem-solving, and collaborative risk management are necessary for collaboration (Suprpto, 2016). An integrated approach emphasises addressing project lifecycle issues at early design stages and allowing information to flow efficiently between different project disciplines (Halfawy & Froese, 2007). There is a need to synthesise knowledge across diverse expertise, roles and responsibilities to integrate interdisciplinary elements (Whyte, 2016) (Rangel, Guimaraes, Sa, & Alvast, 2016) (Rangel, Guimaraes, Sa, & Alvast, 2016).

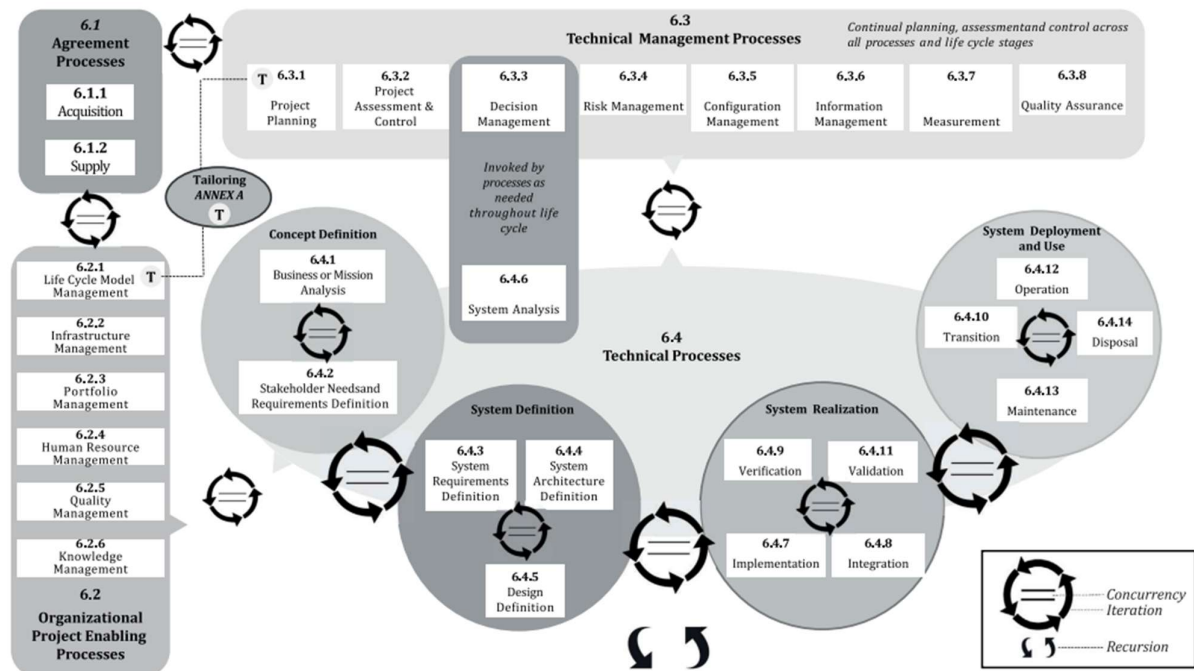
As mentioned above, SE enables complexity management, and ISO/IEC/IEEE 15288:2023 provides one of the most fundamental SE international standards to do that (Dori, 2023). According to ISO/IEC/IEEE 24748 and ISO/IEC/IEEE 15288, the life cycle stages include the concept, development, production, utilisation, support and retirement, and describes that development and support are recurring at every phase. Brazier describes the life cycle of a project through the concept, development, production, utilisation and support, and retirement stage. In those subsequent phases, one revises the designs, including the requirements, due to the changing environment, the concept, preliminary, detailed, implementation, monitoring and retirement design (Brazier, Langen, Lukosch, & Vingerhoeds, 2018). More specifically, one could describe the life cycle of the construction industry through the design, manufacture, construction, maintenance and use, disposal, and recycling phases (Kubler, Buda, Robert, Främling, & Traon, 2017). Since most bridges have an extended life span, one could visualise the life cycle as circular and use the project model as a central point (Underwood, Goulding, Kurugolu, & Açıkalın, 2009).

Table A.6 shows all the lifecycle processes, allocated to four categories, of ISO/IEC/IEEE 15288, and Fig A.4 offers the interrelationships between those processes. As one can see, the authors visualise a V-model shape, similar to Schindel's combination of the ISO and V-model (Schindel & Dove, 2016). However, also other models are possible. One developed the ISO/IEC/IEEE 15288 for various sectors and application possibilities to ensure SE compliance, providing a general framework; therefore, correct tailoring and adaptation to the organisation, methodology, and tools are crucial. Elm and Goldenson chose work products from eleven CMMI process groups (Requirements Development and Management, Project Planning, Product Architecture, Trade Studies, Product Integration, Verification, Validation, Project Monitoring and Control, Risk Management, Configuration Management, Integrated

Product Team Based Capability) to evaluate an organisation's SE capability (Elm & Goldenson, 2012). However, ISO 15288 has additional processes (Monzon & Lennon, 2012), which one must consider regarding SE capabilities since it could be decisive for the project outcome. Notably, ISO 15288 states that the scope of the document is not to provide a comprehensive set of project management processes. The main difference between project management and SE is that Systems Engineering focuses essentially on the SoS, life cycle, and technical aspects (Giorgio Locatelli, 2014), while project management focuses on the project, including tools and methods (Xue, Baron, Esteban, Zheng, & Jakjoud, 2015) (Xue, Improving Cooperation between Systems Engineers and Project Managers in Engineering Projects, 2017).

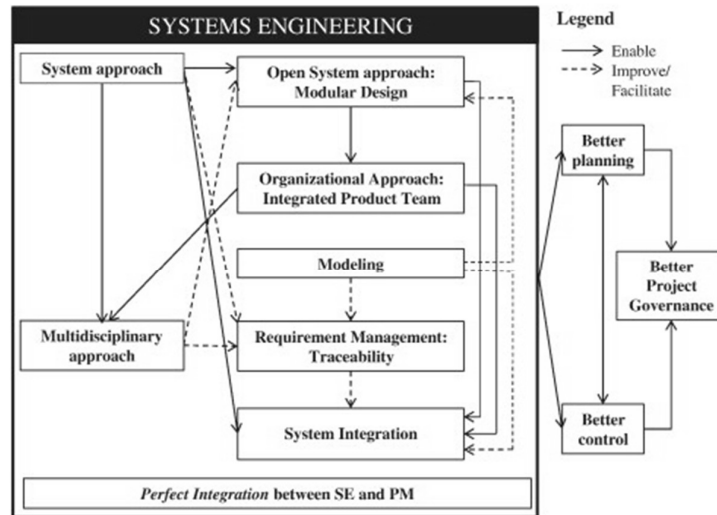
Appendix A Table 6 – ISO 15288 Lifecycle Processes

Agreement Process	Organizational Project-Enabling Process	Technical Management Process	Technical Process
Acquisition	Life Cycle Model Management	Project Planning	Business or Mission Analysis
Supply	Infrastructure Management	Project Assessment and Control	Stakeholder Needs and Requirements Definition Process
	Portfolio Management	Decision Management	System Requirements Definition
	Human Resource Management	Risk Management	System Architecture Definition
	Quality Management	Configuration Management	Design Definition
	Knowledge Management	Information Management	System Analysis
		Measurement	Implementation
			Integration
			Verification
			Transition
			Validation
			Operation
			Maintenance
			Disposal



Appendix A Figure 4 – ISO 15288 Interrelationships

As mentioned above, SE enables complexity management, especially at the early project stages, and ISO 15288 covers all essential processes of the project organisation. Also, ISO 15288 describes that one can conduct its processes often through MBSE, and the appendix provides information regarding MBSE implementation, practices, benefits and helpful model types. Furthermore, ISO/IEC/IEEE 24641:2023 specifies a reference framework for systems and software engineering with a model-based approach. In this approach, the system engineering activities rely on evolving models that serve as the primary source of knowledge about the SoI (System of Interest) and its life cycle processes. SE (MBSE) can improve the project organisation's design and life cycle processes and governance. For example, Fig. A.5 shows how modelling facilitates SE and contributes to better project governance (Locatelli, Mancini, & Romano, 2014).



Appendix A Figure 5 – MBSE and Governance governance (Locatelli, Mancini, & Romano, 2014).

Also, Brazier designed an integrated approach to the life cycle management of complex socio-technical systems, including Governance and Design Process Coordination (DPC). The DPC coordinates and manages the design process concerning the allocation of resources, given process objectives and progress booked. The DPC uses interaction with stakeholders on process requirements and with the Requirements and Artefact Design on the implications of process requirements for the coordination strategy. DPC provides Requirements and Artefact Design with information on the chosen or adapted design strategy and stakeholders with details of design progress.

Systems Design and Engineering, on the one hand, and Governance, on the other, are critical to the success of projects, as they have complementary views of the same technical developments. The governance body establishes policies and continuous monitoring, and its primary duty is to enhance the organisation's viability. Therefore, it is crucial to understand how MBSE could contribute to governance. Governance relies on information about the internal and external context and the progress of the system's life cycle stages. Furthermore, it provides system information to external stakeholders and objectives for each life cycle stage. Governance is more comprehensive in scope than project management – it encompasses the complete set of policies and monitoring that define an organisation. Project management is mainly concerned with operational control and execution at the project level (Turner J. , 2009), whereas project governance represents a higher-level structure, defining processes and structures to govern multiple projects and manage strategic objectives (Nielsen, 2010). Programme governance refers to aligning internal programme stakeholders and anticipating external stakeholders to execute the programme strategy efficiently and enhance individual projects and programmes (Beringer, Jonas, & Kock, 2013) (Too & Weaver, 2014).

Simulation/Experimentation/Implementation (Modelling) is central in Brazier's design model, connecting the life cycle stages with DPC and Governance. Modelling assesses the feasibility of a set of requirements and design in practice, in interaction with the Requirements Design, Artefact Design, and DPC. Moreover, Modelling provides a Requirements and Artefact

Design assessment and DPC assessment of the progress (Brazier, Langen, Lukosch, & Vingerhoeds, 2018). Thus, modelling could potentially enhance both the system design and governance.

Sometimes, one must adapt the programme to address or anticipate contextual changes (Ritson, Johansen, & Osborne, 2012). Whether one conducts the changes depends on the fit between programme and organisational strategies, programme structure flexibility and the adaptability of a programme to its context (Shao, Muller, & Turner, 2012) (Rijke, et al., 2014). Good proposes a holistic approach to managing large projects. Hierarchical management is necessary to exercise the execution of the master plan with rigorous control mechanisms in place to facilitate the harmony, uniformity and consistency of projects (Shehu & Akintoye, 2009), while the network-centric approach is more appropriate under complex conditions during which the project pivots in response to emerging challenges or changes in the political and economic environment. The Holonic approach combines hierarchical and network-centric approaches interchangeably, thus ensuring flexibility and control (Gorod, Hallo, Statsenko, Nguyen, & Chileshe, 2012).

Programmes have central control of projects and have the characteristic of sharing resources from one project to another within a programme since programmes tend to share common resources. There is an indication in the literature that centralising adequate resource management is one of the driving forces of effective programme management. Planning projects with standard tools and techniques is essential for effective programme management. Thus, resources, infrastructure and equipment should be provided to be efficient. Sharing is needed to maintain quality, ensure a steady workforce supply, and make knowledge management more effective, helping save money and time. It works out cheaper and more efficiently if the project reuses elements around the programme instead of procuring new ones (Shehu & Akintoye, 2009). However, it is crucial to inform designers about the limitations of the re-usability of a design. Designers may distribute their errors and omit to involve others in design decisions, inform others of their assumptions, elicit others' needs and schedules, and understand the history of another's problem-solving in a replicated design (Love, Edwards, & Smith, 2013). Therefore, MBSE will be more effective when it is possible to correctly and thoughtfully reuse models throughout the programme, which depends on project similarities and variations, allowing learning and development.

Bletsis believes combining the RRP with participatory systems will improve the programme's results (Bletsis A. J., 2020). Participation is an essential enabler of collective actions through self-organisation. Participatory stems are distributed socio-technical systems enabled by ICT wherein the goal is to accomplish some collective mission based on the design values of trust (transparency, security, privacy, identifiability, traceability, accessibility, proportionality, reliability, robustness), engagement (interaction, presence, enactment, communication, awareness, co-creation) and empowerment (autonomy, self-regulation for human actors and automated systems, emergence). The attributes of participatory systems include autonomy engagement, merging realities, emergence, self-organisation, trust, empowerment, ability to act, and ability to take responsibility (Brazier & Nevejan, Vision for Participatory Systems Design, 2014). The civil engineering sector is a polycentric system, subjected to polycentric

governance, where actors are autonomous systems with their own social, communications and technical systems. Additional complexities of networked systems are subsystems with different norms and values, rules of engagement and agreement, communication architectures and requirements for trust and continuous change (Brazier, Langen, Lukosch, & Vingerhoeds, 2018). However, participatory systems demand a certain degree of similarity between the actors' systems such that they are interoperable (Kurapati, et al., 2012). All aspects mentioned above have substantial implications for technology design, such as MBSE.

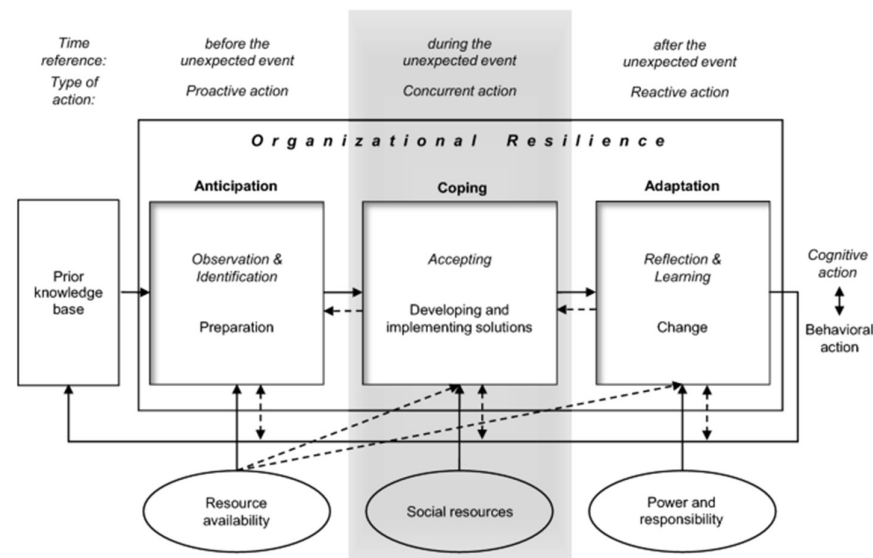
Given the scale of the renovation and replacement assignment, the programme requires an approach that can evolve and adapt to changing contexts. The perspective of development, diffusion and adaptation of innovation and knowledge through leveraging advancements in ICT is assumed to be the most appropriate resolution to benefit across-project coordination and multi-actor collaboration in project-based systems (Bletsis A. J., 2020). There is an increasing demand for collaboration, knowledge development and sharing, innovation and cross-project and sector-wide thinking such that productivity and control within the sector can be improved. One considers adaptability and the ability to generate learning effects across projects and organisations essential to a programme approach (Rijke, et al., 2014). Both adaptability and learning manifest in the implementation and execution of programme stages while maintaining feedback loops within the programme's organisation (Van Herk, Rijke, Zevenbergen, & Ashley, 2013). The Saudi Ministry of Interior has adopted a new Standard Design Model (SDM) approach to develop its construction programme to manage its complex project portfolio and improve project performance effectively. A review of existing literature indicates that despite the adoption of SDM repetitive projects, which enable learning from past mistakes and improve the performance of future projects, one realised that there is a lack of learning instruments to capture, store and disseminate Lessons Learn (Shabbab Al-Otaibi, 2013). Because projects are temporary endeavours, much of the knowledge is lost once one completes the project. Being attentive to knowledge transfer serves the organisation by not only the project delivering value but also allowing the organisation to gain knowledge from the experience of running projects (Institute Project Management, 2021).

Love and Lopez found that design errors are a symptom of dysfunctional organisational and managerial practices in the construction industry. One could have prevented many failures if one conducted design checks and reviews. They propose a systemic learning framework to reduce errors and failures. The design causal variables, divided into people, organisation and project categories, include experience and poor use of technology, governance, project scope and design integration (Lopez & Love, Design Error Costs in Construction Projects, 2011). Viewing error prevention as a continuous process rather than a product of certain activities or behaviours involves exploring people, organisations, and project management systems to map dependencies and interfaces that influence the error prevention process (Lopez, Love, Edwards, & Davis, 2010). Design professionals are repeatedly making the same types of design errors. Determining the most effective error-minimising strategies to implement remains a challenge. Future research will emphasise implementing a combination of people, organisational and project-related strategies to prevent errors. One suggests that people,

through learning, significantly influence the propensity for design error education (Love, Edwards, & Smith, 2013).

Beer invented and developed the Viable System Model, which provides criteria for designing organisations capable of managing the complexity of their interactions with uncertain and changeable environments. In his view, a heterarchical organisation is more likely to remain viable long-term, especially if the environment is uncertain and changeable (Beer, 1994). Espinosa developed a V&S approach based on Beer's Viable System Model principles for managing organisational complexity and states that the more transient the environment, the more the organisation needs to develop capabilities for learning to co-evolve with and adapt to its niche. Organisational learning is the basis for adaptation and developing collective intelligence, and adaptation is the basis for viability and sustainability (Espinosa A. , 2022).

In every field, literature commonly represents resilience as "an ability to adapt to a changing environment and to survive flexibly despite facing difficulties, and to recover from a destabilising perturbation in the work as it attempts to reach its primary goals." Furthermore, resilience has received increased attention as an ability for risk-aversion and crisis control at every level of society, from individuals to entities such as businesses and governmental organisations (Sawaragi, 2020). Duchek suggests three successive resilience stages: anticipation, coping and adaptation. The primary sources of resilience are resource availability, social resources, power, and responsibility (Duchek, 2019). Since resilience is a significant demand for the infrastructure sector, it is essential to research how MBSE could improve Duchek's conceptual framework, see Fig A.6.

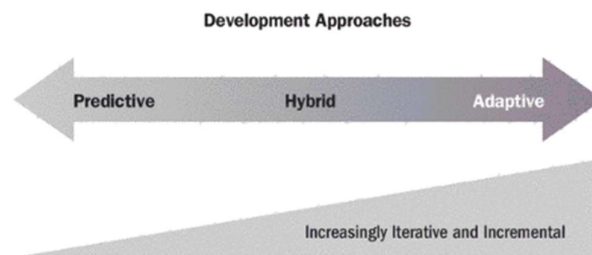


Appendix A Figure 6 – Organisational Resilience (Duchek, 2019)

Institute Project Management describes the three commonly used development approaches at the project level: predictive, hybrid and adaptive. As Fig. A.7 shows, one views these approaches often as a spectrum. A predictive approach is practical when the project and product requirements can be defined, collected, and analysed at the start of the project. One refers to this as a waterfall approach. The scope, schedule, cost, resource needs, and risks can

be well defined in the early phases of the project life cycle, and they are relatively stable. A hybrid development approach is a combination of a predictive and adaptive approach. This development approach is practical when there is uncertainty or risk around requirements. Hybrid approaches often use an iterative or incremental development approach. An iterative approach helps clarify requirements and investigate various options. An iterative approach may produce a deliverable throughout a series of iterations. Each iteration adds functionality within a predetermined time frame. An iterative approach tries different ideas to clarify scope, approach and requirements, and an incremental approach progressively develops features and functions. Adaptive approaches are helpful when requirements are subject to high uncertainty and volatility and are likely to change throughout the project. One establishes a clear vision at the start of the project and then refines, details and changes or replaces initial known requirements by user feedback, the environment, or unexpected events.

The iterations tend to get shorter on the far side of the adaptive methods, and the product is more likely to evolve based on stakeholder feedback. Agile approaches can be considered adaptive. Institute Project Management divides the factors that influence the selection of development approach into product, service, or result; the project; and organisation (Institute Project Management, 2021). One considers the civil engineering sector's commonly used V-model predictive since it assumes that the requirements are well-defined upfront and the development process proceeds in a planned and sequential manner. Since an MBSE model represents reality, it could allow a more adaptive design approach, resulting in improved suitability to the sector and project results. A more agile approach, through MBSE, could contribute to a better ability to balance and manage to change project constraints, such as delivery dates, regulatory codes, budget, scope, and quality. Furthermore, it improves stakeholder engagement and communication throughout the project, enhancing satisfaction and results. Key benefits of agile methods to systems engineering are improved quality of engineering data, improved engineering efficiency, satisfied stakeholders, increased project control, responsiveness to change and earlier and more significant reduction in project risk (Douglass, 2016).



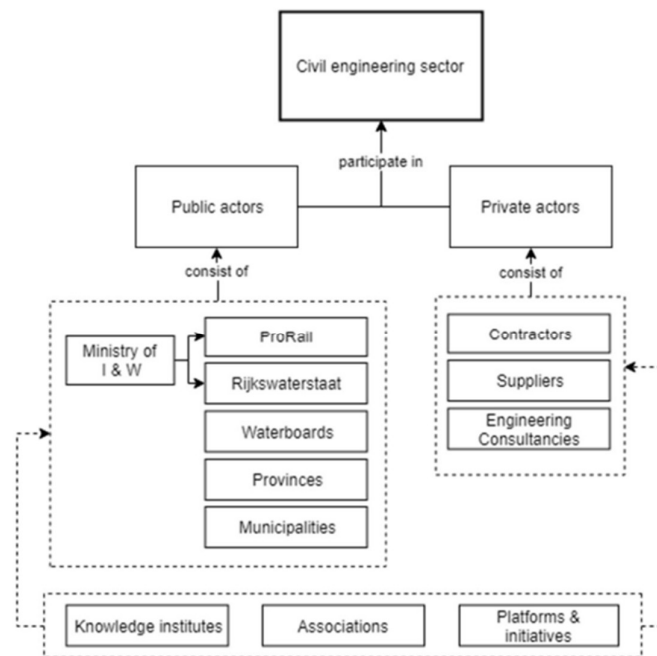
Appendix A Figure 7 – Predictive and Adaptive Approaches Spectrum (Institute Project Management, 2021)

A.4 Stakeholder Analysis

This paragraph analyses infrastructure organisations, the overarching RRP organisation, and stakeholders regarding moveable bridge projects. As explained above, the entire organisation consists of autonomous interdependent companies and governmental organisations responsible for the governance of the entire replacement and renovation operation. This

research considers MBSE within infrastructure organisations and how it contributes to better performance of the companies and RRP. A stakeholder analysis is crucial to consider all stakeholders' perspectives accordingly.

The civil engineering sector is a poly-centric organisation consisting of public and private actors, as Fig. A.8 below shows (Bletsis A. J., 2020). The public actors are collaboratively governing the polycentric RRP. The moveable bridge in Den Oever, which this investigation uses as a case study, is one of the 167 moveable bridges Rijkswaterstaat owns. The provinces also own bridges and viaducts (TNO, 2021) and ProRail 68 moveable bridges. Therefore, it is relevant to investigate how MBSE could improve the collaboration between different owners, making the RRP more efficient. Private actors are the companies selected by the Dutch government to execute specific renovation and replacement projects. As mentioned above, a complex dynamic exists between private actors since collaboration is crucial, yet there is competition among them. One deems competition necessary for innovation and development in the long term. However, collaboration should not suffer as a consequence of this harming the goals of the national total renovation and replacement operation.



Appendix A Figure 8 – Civil Engineering Sector Organisational Chart (Bletsis A. J., 2020)

Companies have an internal organisation to govern their organisation and achieve their goals. During projects, different private actor departments collaborate to achieve the desired results and have to collaborate with external organisations.

One has to break down the moveable bridge to understand and consider what aspects are essential to conducting the renovation and replacement assignment. A moving bridge is a machine, so dynamic effects should be considered. Numerous authors divide the moveable bridge into civil, mechanical and electrical designs, which are interdependent (Langley, 2022). Specifically, there is a crucial interdependency between the superstructure, mechanical and hydraulic machinery and the electrical controls. Table A.7 provides examples of the

relationship between different disciplines' designs. Important design considerations for moveable bridges are machinery accessibility, single-mode failure analysis, failure mode and effects analysis (FMEA), life-cycle cost analysis, design quality assurance and designs of the machinery regarding robustness, redundancy and failure (safe life, fail-safe or damage-tolerant design) (Parke & Hewson, 2022). Parke and Hewson call moveable bridge machines, and therefore, to understand the complexities and potential solutions, the comparison is possible with mechatronics, having similar disciplines' designs (mechanical, electronic, software) and multi-disciplinary interactions (Cabrera, et al., 2010) (Faria & Barbalho, Mechatronics: A Study on Its Scientific Constitution and Association with Innovative Products, 2023) (Faria & Barbalho, Mechatronics: A Study on Its Scientific Constitution and Association with Innovative Products, 2023). The disciplines involved in moveable bridge projects, and partly reflecting mechatronics disciplines, at Iv-Infra are the specialists in Asset Management, RAMS, Concrete Construction, Machine Safety, Industrial Automatizations, Moveable Bridges, Costs and SE, and Project Management, Contract Management and Stakeholder Management, which are an integration of the moveable technical and SE management functions (Eisner, 2008), which also must fulfil Gräßler's MBSE role model (Gräßler, Wiechel, & Pottebaum, 2021). Moreover, RWS states to develop and integrate more intelligent systems within moveable bridge systems, such as sensors and smart cameras, to support control (Rijkswaterstaat, Ministerie van Infrastructuur en Waterstaat, 2023). Therefore, the mechatronics industry, which emerged around 1970, could provide lessons and improvements for moveable bridges in the infrastructure industry.

Appendix A Table 7 – Design Relationships

Design Relationship	Example
Mechanical - Structural	The structural action is different in the closed and open positions. Consider mechanical interaction, especially concerning displacements and distortions.
	Swing bridge machinery failure due to having excessive braking torque capacity. Prevent overpowering or -braking.
Mechanical - Electrical	Provide acceleration and deceleration of the span consistent with the mechanical machinery design (speed control of span drive motors).
Electrical - Software	Auxiliary devices require power and control, such as span locks, traffic warning and resistance gates, traffic signals, rail locks and catenary lifts.

Different factors influence those interdependent designs, such as main dimensions, loading conditions, foundations, operation time, risk assessment, mechanical- and electrical systems and maintenance costs (Thomsen & Petersen, 2019). The authors also mention the importance of considering operation and maintenance aspects in the engineering and design phases. Decisions early in a project significantly impact performance and Life Cycle Costs (LCC). Methods to reduce LCC in the early design phase may include Building Information Modelling, Risk and RAMS Analyses and Asset Management (Jensen, 2018). During a project, the project team has to integrate all the disciplines mentioned above to deliver a successful product. Disciplines which have to ensure collaboration and integration are Systems Engineering (Shenhar, 1994) and Project Management (Morris, 2013). A fully integrated multi-disciplinary team of civil, mechanical and electrical engineers is required to design a moveable bridge. Also, the programme should allow sufficient time for thorough consideration by all disciplines to ensure an optimum solution. One should intensively involve moveable bridge stakeholders with different priorities – that is, vehicular traffic

highway and shipping port authority – during design and engineering. Furthermore, set the design parameters at practical and obtainable levels (Langley, 2022).

Yenal Akgün describes mechatronics as the intersection of architecture, structural engineering and mechanism (including automated systems and electronics) design (Akgün, 2021).

Biswanath Samanta defines mechatronics as a synergistic interdisciplinary integration of multiple engineering fields – mechanical, electrical and electronics, computer, control systems, and information technology – to design, develop, and test intelligent systems with embedded learning capabilities. Furthermore, he states that mechatronics is an ideal field to incorporate systems thinking and data-information-knowledge-wisdom hierarchy through an integrated approach covering hardware and software (Samanta, 2023). Both academic and industrial sources have reported on challenges related to the design and development of mechatronic systems, such as the exchange of design models and data, cooperative work and communication among the design engineers, multi-disciplinary modelling, simultaneous consideration of design from different disciplines, early testing and verification, persistence of sequential design process, lack of tools and methods supporting multi-disciplinary design and support of design of control software. Cabrera states that model and data sharing is a vital issue to progress towards an overall solution and proposes a high-level function models as a base to a framework to support communication through tool and model integration (Cabrera, et al., 2010).

Authors developed different methodologies for multidisciplinary mechatronics design. For example, Zheng proposes a macro and micro-level process realised by a hierarchical design model and using a 3DEXPERIENCE platform. The macro level process describes the generic procedure, while the micro level process supports every specific design phase where designers can structure design sub-tasks. The authors developed an interface model to ensure consistency between macro and micro design processes (Zheng, Hehenberger, Duigou, Bricogne, & Eynard, 2017). Mhenni proposes a SysML-based iterative methodology consisting of black-and-white-box analysis (Mhenni, Choley, Penas, Plateaux, & Hammadi, 2014).

The owner tendered an Engineering and Construct (E&C) contract to renovate the moveable bridge of Den Oever. Another organisation was responsible for the moveable bridge design, construction and maintenance from 1973, which provided the documentation necessary for maintenance and renovation. Therefore, the documentation of those organisations provides the information which transfers from one party to another during the bridge's life cycle. The owner manages the information storage and distribution to all stakeholders, tenders contracts, and collaboratively manages projects' overarching programmes with other owners. Another integrated discipline is Contract Management, which creates the contracts tendered to the market through multi-disciplinary knowledge, ensuring that one includes all essential requirements. Projects often have integrated contracts that incentivise the construction organisation's involvement at an early project phase (Lenferink, Tillema, & Arts, 2013). All the disciplines mentioned above, among others, form a focal point during a project to deliver a comprehensive life cycle considered design. Commonly, the public and private sector

organisations mirror their disciplines to enhance the exchange of information and effectively monitor and control projects on distance.

The owners (RWS, ProRail, provinces, municipalities, etcetera) are essential stakeholders because they must manage the constructions for over 100 years and are fully document-oriented. Documentation quality is of significant concern to contractors and subcontractors who rely on information provided to them. One has identified erroneous design documentation as a significant contributor to rework during the design process (Lopez, Love, Edwards, & Davis, 2010). A significant problem is old, incomplete documentation caused by people not documenting changes in the execution relevant to the design and changes due to maintenance (Hendriks, 2022). DT with models as central points instead of documents is a promising technology to prevent this. The owners will only transition to an MBSE method if they experience significant benefits outweighing its implementation costs. Essential is that the necessary information stays accessible to all the stakeholders during the life cycle and up to date, even when software providers do not exist anymore. The owners tender the project, doing the procurement and programme management to deliver the desired services to the users. The questions to the owners have to be especially regarding accessibility, safety, privacy and maintainability of information over the entire life cycle. A significant task of the owners is to govern the RRP.

Asset Managers have to monitor, collect data and maintain constructions. Therefore, the proposed MBSE approach should be beneficial in storing the data in a model and using it to predict its maintenance. Although the scope of this research does not include asset management as a significant topic, it is crucial to consider how improved asset management could contribute to better engineering or design through SE. Therefore, questions to other disciplines should include how asset management data storage contributes to better life cycle engineering and design. Also, as mentioned above, MBSE provides modelling constructs that DT can exploit, and asset management experiences significant benefits from DT (Macchi, Roda, Negri, & Fumagalli, 2018).

The design of a safety-critical system, such as a movable bridge, requires an adequate prediction of its reliability, availability, maintainability, and safety (RAMS). Often, one performs the RAMS analyses once one has defined the product in terms of architecture, components, and materials. The safety assessment, requiring an evaluation, is practical, but it fully integrates safety analysis after completing the trade-off, which is too late, according to several authors. The resulting design synthesis could be ineffective and inefficient because of a lack of information about the system failures (Brusa, 2021). Considering operation and maintenance (O&M) issues early in the planning and design phase is critical since decisions made early in a project significantly impact performance and Life Cycle Costs (LCC). Monitoring bridges' exposure conditions and performance could make better assumptions during the plan and design phase. Systematic identification of Life Cycle Costs facilitates a holistic approach to cost-optimal design (Jensen, 2018). Frangopol and Soliman provide an integrated platform for civil and structural systems, combining different life cycle framework modules to establish optimum life cycle decisions (Frangopol & Soliman, 2015). Studies

demonstrate that structural health monitoring systems are crucial for improving our understanding of LCC and the reliability of mechanical components (Catbas, et al., 2012).

A.5 Performance and Success

Traditionally, project management has focused on providing outputs based on (the Iron Triangle) schedule, budget and quality, in which one defines quality as consistent conformance to stakeholder expectations (Basu, 2014). Terry Williams found that merely applying the 'Iron Triangle' is insufficient and depends on other factors. Literature also defines success as satisfying the stakeholder's needs. Also, it is crucial to establish the longer-term values the solution has to contribute (Williams & Samset, 2010). It is crucial to investigate the causes of the most significant variation in the 'Iron Triangle' to determine the improvement of the MBSE approach. Table A.8 shows Westerveld's proposed clustered project success criteria (Westerveld, 2013). Most tools focus primarily on the front end of the system life cycle (Madni & Purohit, Economic Analysis of Model-Based Systems Engineering, 2019). Therefore, one can expect higher costs in the design, conceptual and preliminary stages. Considering all project success criteria, the benefits of the MBSE approach must outweigh the cost to develop and realise the novel MBSE approach.

Project managers usually focus on delivering projects on time, within budget and satisfying stakeholders' needs. However, project funders demand a return on investment to realise its strategic benefits. Therefore, one could measure project success from different perspectives, including project efficiency, team and customer influence, business success or preparing for the future. One could divide project success into project management success and investment success. One operationalises project investment success in terms of return on investments and the successful realisation of the desired benefits (Key Performance Indicators). A benefit is an advantage for a particular stakeholder or stakeholder group. One can not easily consider non-financial benefits in a project's investment success without articulating, quantifying and measuring how they can affect the financial benefits. Also, quantifying the benefits is necessary for managing, monitoring and controlling their realisation. Project success as management and investment success classification has to reflect project efficiency, organisational benefits, impact, stakeholder satisfaction and future potential. One could also classify project success under process, product and organisational success (Badewi, 2016).

Appendix A Table 8 – Project Success Criteria (Westerveld, 2013)

Result Area	Explanation
Project results: Budget, Schedule, Quality.	Almost all projects will have specific scheduling, budget and quality constraints (the original iron triangle of project goals).
Appreciation by the client	The client initiates the project to fulfil a specific need (the aspects and factors the client values in judging the project's success).
Appreciation by project personnel	The project workers will be concerned with reaching their personal goals and an excellent working atmosphere.
Appreciation by users	Users are concerned with their overall influence on the project and the end product's functionality.
Appreciation by contracting partners	Contracting partners try to make a profit on the project. They are also concerned with getting new orders and learning possibilities.
Appreciation by stakeholders	Those parties that are not directly involved in the project but have a considerable influence. For example, environmental groups,

Result Area	Explanation
	citizens and government agencies. These parties manage their specific interest.

A.6 Problem Analysis Summarising Notes

Problem	Solution Approach	Condition	MBSE benefit	Note
The project team ineffectively coordinates integration. There is insufficient interaction between disciplines, and disciplines incorrectly interpret requirements and information.	Enhance integration through early involvement, trust, open communication, knowledge sharing, and collaboration.	Create trust within and between organisations.	MBSE is a collaborative tool that facilitates trust and cooperation, provides a more thorough understanding of the concept and system definition, allows abstract language and gives elements an unambiguous meaning. MBSE enables automated formalised verification and validation through simulation and creates simplified representations of systems, solutions, or deliverables. Through which MBSE detects (integration) issues early.	Project teams ineffectively and inefficiently integrate designs due to insufficient information flow and communication. DBSE has decentralised and excessive textual documents, inadequately supporting the interdisciplinary design.
The project team Inadequately considers the inter-disciplinary life cycle (constructability) design due to time constraints.	Create a holistic and cohesive MBSE approach, complying with ISO 15288 (and 24748), considering the Three Pillars.	Realistic (budget and time) constraints	MBSE significantly facilitates the execution of ISO 15288 life cycle processes and reduces (development) risk, and MBSE helps identify known unknowns and known knowns distributed across disciplines.	Project teams do not consider life cycle design correctly due to the complexity of coherent and complete ISO 15288 application. For instance, no alignment exists between (IA) block updates and maintenance planning.
Insufficient design information distribution to stakeholders and disciplines.			MBSE enhances communication (efficiency) and knowledge transfer through a single source of truth.	BIM misses interdisciplinary information and the ability to capture design decisions.
BIM misses a multidisciplinary design integration process and systems function design.	Consider the multidisciplinary integrated functional (mechatronic) design.		MBSE enables multidisciplinary functional and behavioural design integration.	BIM without proper integration coordination causes an isolated work mentality.
Document status does not sufficiently reflect the design quality, and project teams do insufficient design checks and reviews (inadequate quality assurance)			MBSE enhances progress assessment and quality management	DBSE has inadequate completeness and consistency and decentralised (textual) information storage.
Ineffective software utilisation	Combine and complement MBSE with existing software, such as BIM, SBE and Relatics.	Adequate training and experience.		
There is often old, inconsistent and incomplete documentation, and project teams have difficulty maintaining decentralised information.	One should be able to store design and maintenance data, making it accessible, updateable and transferable.		MBSE provides a single source of truth and a data repository, leveraging models during downstream lifecycle phases. Furthermore, MBSE ensures consistency and completeness of architecture and design.	One does not correctly document changes during the life cycle.
The clients are a significant cause of variations due to misconception, miscommunication, poor interaction, unreasonable expectations, and design changes. Moreover, pressure on variations increases the chance of committing errors.	Conduct early validation through simulation and provide more design agility (adaptive designing), enhancing stakeholder satisfaction and		MBSE enables agile designing and enhances the ability to perform trade-offs.	Variations (design, scope and method changes) cause delays, disputes and cost increases. Organisations design through a predictive and difficult-to-adapt V-model approach.

Problem	Solution Approach	Condition	MBSE benefit	Note
	responsiveness to change and increasing project control.			
DBSE has poor traceability and impact analysis.	Enhance complexity management and design understanding through decomposed system element interrelationship modelling.		MBSE enables better relationship description between system elements and impact analysis and increases traceability	DBSE has a poor description of relationships between elements and coherence.
Difficulty with reusing requirements and design information	Enhance standardisation and reusability (considering standardisation limitations)		MBSE enables reuse and adaptability.	DBSE has inadequate completeness and consistency and decentralised (textual) information storage.
Designers repeatedly make the same design errors.	Ensure error prevention through (inter-organisational) tool-supported learning.	Realise a experimenteal and learning organisation.	MBSE enables reuse, and the models contain codified knowledge.	There is a lack of (inter-organisational) learning instruments to capture knowledge and lessons learned.
Renovation and replacement capacity shortage	Comply with the desired Iron Triangle and needs (considering different perspectives and stakeholders) and provide future-oriented (circularity, Digital Twin and Thread) solutions.		MBSE increases efficiency and productivity and can contribute a variety of modelling constructs that Digital Twin and Thread can exploit.	
Insufficient programme (inter-organisational) collaboration and knowledge development	Resilience (adaptable) organisation through inter-organisational information sharing, learning and knowledge development	Create trust and healthy competition, enhancing innovation without harming collaboration. Facilitate innovation, collaboration and inter-organisational knowledge sharing and development. Combine a hierarchy for sharing resources and a network-centric approach for participation, complying with participatory system values.		The sector has high competition and lacks trust, and organisations want autonomy. Furthermore, the sector has an excessive project focus.
Programme actors have private social, communication and technical systems.	The programme actors' (participatory) systems demand a certain degree of similarity.	Prevent adverse behaviour.		

A.7 Infrastructure Sector’s MBSE Challenges, Solution Approaches, and Benefits

Category	Problem Statement	Solution Approach	Conditions for Solution	MBSE Benefits	Notes
Team Collaboration	Project teams face challenges in effective coordination, leading to misinterpretations of requirements and insufficient interdisciplinary interaction.	Implement MBSE to foster a culture of improved collaboration and open communication across disciplines, ensuring mutual understanding and trust from project inception.	Essential trust-building within and across organisations, supported by regular and structured communication facilitated by MBSE.	Promotes a collaborative project environment where team members across disciplines work cohesively, supported by shared understandings of project goals and technical requirements.	Traditional methods often fail to support the necessary interdisciplinary design integration.
Lifecycle Design	Time constraints limit interdisciplinary lifecycle design consideration.	Implement a holistic MBSE approach, aligning with ISO 15288 and focusing on its Three Pillars.	Realistic budget and time considerations.	Streamlines lifecycle processes, reduces risks, and enhances discipline coordination, following ISO 15288.	Without MBSE, the complexity of ISO 15288 may hinder effective lifecycle design consideration.
Information Distribution	Stakeholders and disciplines face insufficient information flow.	MBSE facilitates enhanced communication and knowledge transfer, serving as a single source of truth.	A unified information source is crucial.	Improves communication efficiency and knowledge transfer, ensuring all stakeholders have consistent, accurate information.	BIM struggles with interdisciplinary information integration and decision capture.
Design Quality	Design checks and reviews are insufficient, leading to inadequate quality assurance.	Use MBSE for improved progress assessment and quality management.		Centralises and enhances design quality management, ensuring consistency and completeness across projects.	Decentralised traditional methods lead to inconsistencies and quality issues.
Software Utilisation	Underutilisation of existing software alongside MBSE.	Integrate MBSE with existing tools like BIM, ensuring team training and experience.	Comprehensive training in MBSE and tool integration.	Leverages MBSE's strengths to enhance existing software capabilities, offering a cohesive toolset.	
Agility	Variations from client-side increase error chances due to poor communication.	Adopt MBSE for early validation, simulation, and adaptive design, enhancing project agility and control.		Reduces the likelihood of errors through agile designing, trade-off analysis, and enhanced project control, even with frequent variations.	Traditional design approaches lack the flexibility to adapt to changes, increasing risk.
Governance	Repeated design errors from a lack of learning tools across organisations.	Leverage MBSE for error prevention and to support inter-organisational learning.	Culture of learning and experimentation is key.	Encodes knowledge within models for reuse, promoting a learning organisation culture and error prevention.	The absence of learning mechanisms hinders cross-organisational knowledge sharing and improvement.
Collaboration	Insufficient inter-organisational collaboration and diverse private systems among actors.	Foster resilience through MBSE-driven inter-organisational sharing and collaborative learning.	Trust, healthy competition, and participatory systems alignment (Bletsis A. J., 2020).	Streamlines collaboration, boosts efficiency, and encourages innovation through effective modeling and knowledge sharing.	High competition and autonomy desires challenge collaboration, underlining the need for systems alignment.
Standardisation and Resuability	Challenges in reusing requirements and design information due to lack of standardisation.	Enhance standardisation and reusability with MBSE, addressing limitations through structured component frameworks.	Essential framework for component reusability.	Facilitates creation of modular, interoperable design elements, enabling efficient reuse and adaptability.	Traditional methods struggle with consistency, completeness, and centralized information management.
Technical Systems Integration	Integrating multidisciplinary design processes and system functionalities presents a challenge, with BIM sometimes leading to gaps in capturing complex system interactions.	Utilise MBSE alongside BIM to ensure comprehensive integration of technical systems and design elements, emphasising early integration to identify and resolve potential conflicts.	Effective integration of MBSE with BIM is crucial, prioritising the alignment of technical disciplines and functionalities from the early design phases.	Facilitates the technical integration process, enhancing the coherence and performance of the final system design. Prevents the emergence of a siloed work culture by ensuring that technical contributions are harmonized.	Targets the technical and methodological aspects of bringing together diverse system designs and functionalities into a unified model, addressing BIM's limitations with MBSE's structured approach to system complexity.
Traceability and Impact Analysis	DBSE's limitations in traceability, impact analysis, and coherent element relationships.	Enhance system understanding with MBSE through detailed modeling of element interrelationships.		Improves traceability and impact analysis, offering clear descriptions of system element relationships.	Addresses the coherence and relationship description gaps found in traditional DBSE approaches.

Appendix B: Development, Illustration and Evaluation of the MBSE Framework

B.1 MBSE Framework Needs

Need Category	Description
Collaboration and Integration	Facilitate seamless collaboration across various disciplines and ensure continuous integration of information through software interoperability. Develop systems for shared, tool-supported information exchange and knowledge development among organisations.
Design and Life Cycle Management	Incorporate comprehensive design life cycle considerations to ensure an all-encompassing MBSE approach that addresses all stages of infrastructure development. Ensure the MBSE model supports the entire project lifecycle with effective data and information storage capabilities.
Risk Management and Quality Assurance	Improve risk management by efficiently integrating functional and behavioral designs, allowing for proactive identification and mitigation of risks. Enhance the ability to conduct thorough quality checks throughout the project life cycle.
Standardisation and Reusability	Promote the standardisation of processes and models to facilitate reusability across different projects and sectors within the infrastructure domain.
Verification, Validation, and Requiriements Managment	Enable automated verification processes to ensure that requirements are unambiguous and accurately reflected in the project execution. Enhance the agility of the V&V process to quickly adapt to changes and new information.
Future-Orientation and Capacity Enhancement	Boost the capacity for renovation and replacement projects, ensuring that infrastructure development is future-oriented (DT and prevent vendor lock-in) and sustainable.
Knowledge Development	Ensure detailed modeling of element interrelationships and traceability throughout the project to enhance understanding and coordination. Foster knowledge development and sharing across organizations, enhancing collective expertise in MBSE applications in infrastructure.

B.2 Key Qualitative Metrics (KQM) for Feasibility and Viability Evaluation Table

Key Quality Metric (KQM) Category	KQM	Qualitative Assessment Method	Theoretical Application and Case Study Analysis	Need Description	MBSE success conditions
Technical	Collaboration and Communication	Assess how MBSE improves interdisciplinary collaboration and communication clarity by analysing team interactions.	Theoretically analyse the expected improvements in communication and collaboration between civil and mechanical engineering disciplines using the MBSE framework, compared to isolated communication channels in DBSE.	Facilitate seamless collaboration across various disciplines and ensure continuous integration of information through software interoperability.	Establishment of an integrated and (open source) communication platform that supports (real-time) data exchange and collaboration tools, supporting SE and governance processes.
	Flexibility and Adaptability	Examine MBSE's adaptability by reviewing how it handles design changes or evolving requirements, comparing this flexibility to traditional methods.	Discuss a hypothetical scenario where the load capacity requirements of the bridge increase. Outline the theoretical steps and system model adjustments in MBSE, highlighting its presumed efficiency over DBSE's document revisions.	Ensure a comprehensive design lifecycle approach that not only addresses all stages of infrastructure development but also enables flexible adaptation to changing requirements and corresponding design adjustments.	Implementing a dynamic system architecture that can easily adapt to changes in requirements or design with minimal disruption and guarantee life cycle utilisation of the model.
	Error Reduction and Accuracy	Evaluate the potential of MBSE to reduce design and documentation errors and contradictions by analysing typical project scenarios.	Use a case study to theoretically explore common errors in bridge design projects (e.g., miscommunication of requirements or design decisions) and how MBSE's integrated model approach could prevent such discrepancies.	Improve risk management by efficiently integrating statical, functional and behavioral lifecycle models, allowing for proactive identification and mitigation of risks.	Adoption of a Common Data Environment (CDE) and Reference Data Library (RDL) that ensures accuracy and consistency across models.
	Traceability	Investigate the effectiveness of traceability within MBSE by following the management of requirements and changes, contrasting this with document-based methods.	Illustrate theoretically how MBSE enhances traceability by following a specific requirement (e.g., load requirements or safety standards) through all stages of project development, compared to the tracking challenges in DBSE.	Ensure the MBSE model supports the entire project lifecycle with effective data and information storage capabilities.	Utilisation of tools that support end-to-end traceability through inter-tool data exchange possibilities (requirements, changes, and project status updates).
Organisational and Sector-Wide	Organisational Readiness and Culture	Assess the organisation's readiness for MBSE, focusing on cultural and structural adaptability, and the perceived challenges and benefits of the transition.	Theoretically evaluate the organisational shifts needed to adopt MBSE, including cultural changes and structural adjustments.	Foster knowledge development and sharing across organisations (Participatory Systems), enhancing collective expertise in MBSE applications in infrastructure.	Foster a culture of learning, innovation and openness to change and experiment through an agile, incremental and iterative approach, supported by training programs.
	Management and Leadership Support	Analyse the influence of management's commitment to MBSE on its successful adoption, using insights from organisational leaders and project teams.	Discuss theoretically the role of management in driving MBSE adoption, focusing on strategic resource allocation and leadership.	Ensure management and leadership support through sufficient (budget) resource allocation, underpinning the strategic development of MBSE.	Strong support from the management, including the provision of necessary resources for MBSE implementation.
	Sector-Wide Collaboration and Model Sharing	Evaluate the potential for enhanced collaboration and model sharing under MBSE by gathering insights from various stakeholders in the sector.	Analyse theoretically the potential for MBSE to facilitate sector-wide collaboration and model sharing, based on the interoperability features of MBSE tools.	Develop systems for shared, tool-supported information exchange and knowledge development among organisations.	Establishing industry standards for collaboration, model and data sharing to facilitate interoperability across projects and stakeholders. And, Ensure data security and intellectual property protection to address concerns about sharing sensitive information.
Stragic and Long-term	Strategic Alignment and Standardisation	Discuss how MBSE aligns with strategic organisational goals (innovation, risk reduction, vendor lock-in prevention and sustainability) and sector standards, including its role in promoting standardised design in systems engineering.	Theoretically assess how MBSE aligns with strategic goals like innovation and sustainability and promotes engineering standardisation across projects.	Increase the capacity for renovation and replacement projects, ensuring that infrastructure development is future-oriented (and sustainable). Promote the standardisation of design and models to facilitate reusability across different projects.	Alignment of MBSE practices with long-term strategic goals.
	User Satisfaction and Experience	Collect qualitative feedback on expected user satisfaction, focusing on the impact of MBSE on the experiences of end-users, operators, and maintenance teams.	Hypothetically evaluate the impact of MBSE on end-user satisfaction by comparing the operational and maintenance scenarios of bridges designed with MBSE versus traditional methods.	Enhance the user experience and satisfaction levels of those directly interacting with the bridge, such as operators, maintenance teams, and end-users, ultimately leading to increased trust and satisfaction in the infrastructure's reliability and usability.	Continuous engagement with end-users and stakeholders to gather feedback and incorporate it into the MBSE development process.
	Financial Implications and ROI	Estimate the qualitative ROI by evaluating improvements in project performance, outcomes, error reduction, efficiency in collaboration and communication, and the overall impact of strategic alignment and standardisation as facilitated by MBSE on the cost and time savings and quality of infrastructure projects.	Discuss theoretically the potential cost savings, efficiency gains, and return on investment afforded by MBSE in comparison to DBSE, focusing on long-term maintenance and project lifecycle costs.	Optimise the financial investment in infrastructure projects by improving the efficiency and effectiveness of the design, construction, and maintenance phases (lifecycle design and management).	Alignment of (financial) investments and the development strategy with the organisation's budget and anticipating the hype curve.

B.3 Explorative Software MBSE Component Table

The table has been constructed by the author based on a qualitative and exploratory analysis of software commonly used in the context of Model-Based Systems Engineering (MBSE) for infrastructure projects. The categorisation of tools, their contributions to MBSE, and the identified outputs, information, and data types are based on the author’s interpretation of publicly available documentation, domain knowledge, and typical MBSE practices in infrastructure contexts. The table is intended as an illustrative overview of components within an MBSE environment, rather than a comprehensive or definitive classification.

Categories	Sub-Categories	Software Tools	MBSE Contribution	Outputs, Information and Data
Analysis and Simulation	Structural, Mechanical, and Geotechnical Design	Scia Engineer, Ansys, SAP2000, STAAD (Bentley), Robot Structural Analysis (Autodesk), Diana FEA, D-Foundations, Mathcad Prime	Enables detailed analysis of structural integrity, mechanical functionality, and geotechnical stability. This is critical for ensuring that the bridge design meets all safety and performance standards across disciplines.	Information: Structural analysis reports, mechanical system designs, geotechnical assessment reports. Data: Load and stress measurement data, soil stability metrics, geometric dimensions of design components.
	Predictive Modelling	IBM Watson, Google AI Platform, Microsoft Azure AI	Facilitates predictive modelling, data organisation, and advanced analytics to support forecasting and decision-making. Enhances the ability to anticipate future trends, degradation patterns, and performance of bridge components based on historical and real-time data.	Information: Predictive modelling outcomes, performance trend analyses, scenario-based forecasts. Data: Historical performance data, sensor-derived inputs, environmental impact projections, calculated predictive indicators.
	Design Visualisation and Environmental Analysis	Autodesk AutoCAD, Inventor, Revit, BIM 360, Autodesk Construction Cloud (ACC), Bentley Systems, ESRI ArcGIS, QGIS, Bentley Map, Unreal Engine	Supports detailed design visualisation, immersive 3D modelling, and environmental impact assessments. Facilitates the conceptualisation of complex infrastructure designs and enables spatial analysis of environmental and geographic context. Enhances stakeholder engagement through virtual simulations and visual clarity.	Information: 3D models, environmental analysis reports, VR-based visualisations Data: Geometric measurements, spatial and geographic coordinates, material and spatial specifications
	RAMS Analysis	ReliaSoft, Isograph Reliability Workbench, FaultTree+	Supports the quantitative and qualitative assessment of reliability, availability, maintainability, and safety (RAMS) aspects of infrastructure systems. Essential for ensuring long-term operational efficiency, compliance with safety standards, and proactive risk management.	Information: RAMS assessment reports, fault tree diagrams, safety and risk analysis documentation Data: Failure rates, maintenance records, mean time between failures (MTBF), safety incident records
Requirements and Systems Engineering	Requirements Management	IBM DOORS, Jama Connect, Siemens Polarion, Relatics	Supports the structured capture, management, and tracking of system and project requirements throughout the lifecycle. Facilitates consistency, change control, and traceability to ensure that the design remains aligned with specified requirements.	Information: Requirements documentation, traceability matrices, compliance reports, change logs Data: Requirement identifiers, version numbers, change timestamps, approval status codes, traceability links, structured stakeholder roles
	Modeling and System Architecture	No Magic MagicDraw, Sparx Systems Enterprise Architect, IBM Rhapsody, Modelio	Supports the development of system architecture and behavioural models using SysML. Enables visualisation and structural analysis of functional and physical system interactions, as well as traceability across requirements, components, and verification elements.	Information: SysML architecture diagrams, behaviour models, requirements traceability matrices, model-based specifications, integrated system design views Data: Model element identifiers, block property values, interface definitions, dependency links, parameterised values for simulation and analysis
	Synthesis-Based Engineering (SBE)	MATLAB/Simulink, LabVIEW (graphical programming language), Domain-specific modeling tools, Python (programming language)	Supports the synthesis and simulation of control logic and embedded systems based on formalised requirements. Enables automated generation and verification and validation of software components to ensure functional correctness, responsiveness, and compliance with safety constraints.	Information: Supervisory control models, executable control logic, simulation outputs, validation and verification reports Data: Control algorithm parameters, configuration sets for software integration
Data Integration and Interoperability	Linked Data and Semantic Technologies	Apache Jena, Stardog, Ontotext GraphDB, OSLC	Enables semantic integration, interoperability, and federated querying across systems and data sources. Supports machine-readable meaning	Information: Integrated knowledge graphs, ontology-driven data models, interoperability specifications, mapping and alignment documents

			through ontologies, enabling consistent interpretation, reasoning, and traceability of engineering data across lifecycle stages and disciplines.	Data: RDF triples, semantic relationship definitions, ontology classes and properties, SPARQL query patterns, model-specific instance data
	Middleware and Integration Platforms	MuleSoft, Dell Boomi	Facilitates integration and data exchange between MBSE tools and enterprise systems. Supports the orchestration of services, APIs, and data flows, enabling consistent communication across platforms and across lifecycle stages.	Information: System integration configurations, API management settings, integration flow diagrams Data: API request/response formats, data mapping definitions, structured interface definitions
	Collaborative Product Life Cycle Management (PLM) Platform	IBM Engineering Lifecycle Management (ELM), Siemens Teamcenter, Autodesk Fusion Lifecycle	Supports end-to-end systems engineering by integrating product data, design revisions, requirements, and workflows across disciplines and lifecycle stages. Enables collaboration, change control, and traceability within and across engineering teams.	Information: Project documentation, system design models, version-controlled change logs, collaboration records, workflows Data: Design parameters, component metadata, configuration identifiers, Bill of Materials structures
Digital Twin	Digital Twin Platform	Bentley Systems' iTwin	Enables the creation, synchronisation, and visualisation of digital twins, combining engineering data, real-time sensor inputs, and simulation outputs. Supports performance monitoring, design validation, and lifecycle management of infrastructure assets.	Information: Digital twin visualisations, simulation reports, system performance dashboards, change tracking logs Data: Sensor data, simulation parameters, geometric and spatial data, time-series telemetry
	IoT Sensors	Microsoft Azure IoT, AWS IoT	Enables real-time monitoring of bridge conditions by collecting and transmitting sensor data. When integrated with digital twins or analytics platforms, this supports structural health monitoring, predictive maintenance, and operational status assessment.	Information (via integration): Sensor dashboards, health monitoring reports, anomaly detection alerts, trend visualisations Data: Temperature readings, pressure levels, displacement measurements, vibration amplitudes, time-stamped telemetry data
	Asset Management Software	IBM Maximo, SAP EAM, Infor EAM	Supports lifecycle management of infrastructure assets by tracking their condition, usage, and maintenance history. Facilitates performance monitoring, risk mitigation, and data-driven decision-making throughout the operational phase of the system lifecycle.	Information: Asset condition reports, maintenance history documentation, lifecycle status dashboards, asset health indicators Data: Maintenance activity logs, performance metrics, failure records, inspection timestamps, operational statistics

B.4 Possible Roadmap for Implementing the Semantic CDE

Strategy	Key Actions	Responsible Stakeholders	Initiation Timeframe	Expected Outcomes
Develop a Semantic CDE Consortium	Establish a multi-stakeholder body to coordinate MBSE standardisation and adoption. Secure initial funding from asset owners, industry partners, and investors. Ensure MBSE aligns with programme-wide governance. Facilitate co-creation and engagement by involving stakeholders in shaping ontologies and project workflows. Use the consortium as a space for shared learning and interaction.	Asset owners, programme managers, government agencies, industry organisations	Short-term	A structured entity responsible for leading MBSE adoption, ensuring consistency, and long-term implementation. Builds stakeholder engagement through shared responsibility, co-design, and interaction within the Semantic CDE framework.
Develop Standards for MBSE Interoperability (Ontologies & RDL)	Define a Reference Data Library (RDL) and standardised ontologies for MBSE. Align these standards with existing infrastructure classifications.	Consortium, software providers, industry organisations	Short-term	Creates a consistent foundation and standardisation for data management, making MBSE models reusable and interoperable across projects.
Initiate MBSE & Semantic CDE Development through Pilot Projects	Select initial infrastructure projects where MBSE and Semantic CDE methods can be tested. Develop a simplified, initial version of the Semantic CDE to capture key project data. Define deliverables that contribute to RDL and ontology development. Set up practical search and input functionality to ensure effective data retrieval and usability. Validate feasibility, document lessons learned, and refine approaches based on real-world implementation. Pilot projects should aim to demonstrate quick gains to build early confidence and support among stakeholders. The user interface should be developed in close engagement with end users to ensure alignment with practical workflows.	Programme managers, consortium, project teams	Short-term	Establishes a foundational Semantic CDE structure, refines MBSE methods, and ensures early feedback informs further development and strengthens stakeholder support.
Enhance Training and	Initiate structured training programmes for users and	Consortium, universities,	Short-term	Increases MBSE expertise, ensures a

Strategy	Key Actions	Responsible Stakeholders	Initiation Timeframe	Expected Outcomes
Workforce Adaptation	developers of the Semantic CDE. Establish partnerships with universities and industry for MBSE knowledge development. Introduce change management strategies to address cultural resistance and ensure a smooth transition. Provide specific training for the Semantic CDE application, ensuring users can effectively implement, query, and manage data within the system.	professional training organisations		skilled workforce, and mitigates organisational resistance to change. Ensures effective adoption and usage of the Semantic CDE.
Strengthen Data Governance and Security	Define security protocols, access control mechanisms, and compliance frameworks. Integrate cryptographic security, including audit trails and authentication, to ensure data integrity and protection. Implement long-term data storage policies to ensure asset data sustainability. Ensure traceability, transparency, and accountability through provenance-based logging, SHACL-based validation, and role-based access to data. These measures lay the foundation for trust.	Consortium, cybersecurity teams, IT specialists, regulatory bodies	Short-to-Medium term	Ensures that the Semantic CDE is secure, trusted, and meets regulatory requirements for sensitive infrastructure data. Builds the trust layer necessary for enabling participatory interaction between actors in a transparent, verifiable, and reliable environment.
Ensure Financial Commitment for MBSE Development	Secure (long-term) investment for Semantic CDE development. Allocate dedicated funds for experimentation within pilot projects. Ensure alignment with government funding strategies and private investment opportunities.	Asset owners, programme managers, government agencies, private investors	Short-to-Medium term	Guarantees financial stability for MBSE implementation and ensures continuous improvement.
Improve Cross-Project Knowledge Sharing	Implement guidelines and define contractual requirements for data and model sharing to ensure accessibility. Develop a best-practices repository for project teams, capturing lessons learned, standardised methodologies, and validated approaches from previous projects. Ensure consistent data structuring	Consortium, project teams, programme managers	Medium term	Enhances knowledge storage, reduces redundant work, and improves design efficiency across the programme.

Strategy	Key Actions	Responsible Stakeholders	Initiation Timeframe	Expected Outcomes
	and reusability by integrating the RDL and standardised ontologies. Facilitate structured knowledge exchange between ongoing and completed projects.			
Integrate MBSE & Semantic CDE in Procurement & Contracting	Develop procurement selection criteria for MBSE and Semantic CDE deliverables. Define contractual requirements for data and model sharing, including which project information must be contributed to the Semantic CDE. Apply MBSE implementation in small-scale projects first, then gradually scale up. Establish contracts that ensure long-term Semantic CDE sustainability.	Programme managers, procurement teams	Medium-term	Encourages structured MBSE adoption, ensures consistent data contributions to the Semantic CDE, and standardises information-sharing practices across projects.
Ensure MBSE & Semantic CDE Interoperability Across Tools & Platforms	Develop interoperability frameworks for the Semantic CDE, ensuring compatibility with different (MBSE and BIM) tools, asset management systems, and engineering software. Standardise ontologies, data exchange formats, and RDLs to facilitate seamless data integration. Establish collaboration with software providers to develop open data-sharing mechanisms and prevent vendor lock-in.	Consortium, software providers, programme managers	Medium-to-Long-term	Enables cross-platform MBSE implementation, ensures long-term data accessibility, prevents reliance on proprietary software solutions, and provides structured guidelines for sector-wide interoperability.
Integrate Digital Twins for Monitoring & (Predictive) Analytics	Connect Digital Twins with the Semantic CDE for real-time data analysis. Implement predictive and advanced analytics (AI/ML) for RAMS, including problem detection, maintenance optimisation, and performance improvement.	Asset owners and managers, IT specialists, software providers, programme managers	Long-term	Enhances asset performance tracking, reduces unexpected failures, and supports data-driven asset management.
Leverage Data-Driven Decision Making for Infrastructure Programme Governance	Utilise the Semantic CDE to optimise maintenance planning, prioritise renovations, and support programme analysis. Leverage AI/ML to enhance programme analysis, governance, and	Programme managers, asset owners, consortium, contractors, IT specialists	Long-term	Improves infrastructure lifecycle management, supports fully data-driven and decentralised governance, and realises the empowerment phase of the participatory system. Programme

Strategy	Key Actions	Responsible Stakeholders	Initiation Timeframe	Expected Outcomes
	decision-making. Enable self-organisation and autonomy by allowing contractors, suppliers, and designers to act within semantically governed boundaries. Implement smart contracts and SHACL-based self-regulation to distribute decision-making across the programme ecosystem.			actors take responsibility, self-organise dynamically, and collaborate efficiently through a trusted, transparent, and rule-based Semantic CDE.

Appendix C: Explorative Interviews

C.1 Interview List

Interviewee	Organisation	Topic
Interviewee A	Public Agency A	Synthesis-Based Engineering
Interviewee B	Public Agency A	MBSE and Standardisation
Interviewee C	Engineering Consultancy A	MBSE
Interviewee D	Technology Provider A	MBSE and Linked Data
Interviewee E	Engineering Firm A	Modelling and Engineering
Interviewee F	Engineering Firm A	Modelling and Engineering
Interviewee G	Engineering Firm A	MBSE
Interviewee H	Contractor A	Ontology, Linked Data and Common Data Environment
Interviewee I	Consultancy A	Organisational aspects of MBSE
Interviewee J	Consultancy A	Organisational aspects of MBSE
Interviewee K	Engineering Firm B	MBSE
Interviewee L	Engineering Firm B	MBSE
Interviewee M	Design Consultancy A	MBSE
Interviewee N	Contractor B	Maintenance and Construction Contractor aspects of MBSE
Interviewee O	Engineering Firm C	MBSE
Interviewee P	Engineering Firm C	MBSE
Interviewee Q	Research Institute A	Linked Data

C.2 Key Findings of Explorative Interviews

C.2.1 Interviewee A (Public Agency A)

Complexity Compared to New Construction

R&R projects are inherently more complex than new construction due to the age and condition of existing infrastructure. Often, documentation is incomplete or incorrect, complicating the process of integrating new systems with old ones. Additionally, the need to preserve parts of the existing infrastructure while updating others adds another layer of complexity.

Increased Risk of Failure Costs

The risk of failure is higher in R&R projects compared to new builds. This is largely due to the unknowns associated with older infrastructure and the challenges of ensuring that all parts of the system work together as intended. Unforeseen issues can lead to significant increases in project costs.

Time Pressure in R&R Projects

Minimising Downtime: There is a critical need to minimise the time that infrastructure is out of service during R&R projects. Closures and delays have a direct impact on the availability of infrastructure for end-users, making time management a crucial aspect of these projects.

Impact on Feasibility: The sheer volume of R&R projects anticipated, combined with constraints such as limited financial resources, workforce shortages, and limited execution capacity, poses a significant challenge to the feasibility of these projects. Managing these pressures while maintaining project quality is a key concern.

System Optimisation vs. Resilience

Optimisation Leading to Reduced Resilience: Many systems within infrastructure have been optimised for efficiency, which, while beneficial in some ways, has led to a reduction in resilience. This lack of resilience means that small errors or unforeseen events can have disproportionately large impacts on the system. The trade-off between system optimisation and resilience is a crucial factor to consider in managing infrastructure projects, particularly in the context of renovation and replacement.

Critical Consequences of Reduced Resilience: The reduced resilience in both the infrastructure systems and the organisational systems managing them can lead to significant issues when small problems arise. These issues are often amplified due to the highly optimised, but less flexible, nature of the systems in place.

Adoption of Synthesis-Based Engineering

SBE in Control System Design: The use of Synthesis-Based Engineering (SBE) has been implemented for designing and verifying control systems in movable bridges. This approach allows for the verification and validation of the system before actual implementation, reducing the likelihood of errors and ensuring the system functions as expected once deployed.

Sector-Wide Implications

Shift Toward R&R Projects: Both Public Agency A and the Ministry of Infrastructure and Water Management (IenW) have made a significant shift from focusing on new construction to prioritising R&R projects. This trend is expected to continue and could become a permanent focus, given the ageing infrastructure across the country.

Importance of SE Process Implementation: While there are shortcomings in current Systems Engineering (SE) processes, Interviewee A suggests that these issues are more about the implementation and adherence to SE protocols rather than the processes themselves. Improving how these processes are followed could enhance the outcomes of infrastructure projects.

Long-Term Information Management: Managing infrastructure data over the long term is critical. Asset managers need to ensure that information remains accessible and usable throughout the lifecycle of the infrastructure, which can span over 100 years. This requires robust systems that can preserve data integrity even as software and technologies evolve.

Additional Considerations

Project Size and Complexity: Not all large projects are complex, and vice versa. The complexity of a project often lies in factors like phasing, environmental conditions, and

system resilience, rather than just size. Exploring the relationship between project size, complexity, and the applicability of MBSE could provide valuable insights.

Document-Based SE vs. MBSE: The transition from Document-Based Systems Engineering (DBSE) to MBSE is particularly significant for asset managers who must maintain infrastructure for its entire lifecycle. MBSE offers potential benefits in terms of managing data and system models over long periods, but its success depends on ensuring that the information remains accessible and usable over decades, even as technologies change.

C.2.2 Interviewee B (Public Agency A)

Transition to Synthesis-Based Engineering (SBE)

Interviewee B discussed the evolution from traditional Systems Engineering (SE) to Synthesis-Based Engineering (SBE) in the context of infrastructure projects. He explained how SBE goes beyond standard SE by using algorithms to generate deeper levels of design, particularly for control and operation systems. This approach automates much of the design process, improving consistency and reducing the potential for errors that can arise from manual design work.

Use of Relatics for Requirements Management

Interviewee B described how Relatics is currently used to manage and validate requirements within projects. While Relatics is often referred to as a Model-Based Systems Engineering (MBSE) tool, he clarified that it functions more as a requirements management system. This tool is essential for tracing requirements from top-level needs down to specific project components, ensuring that all criteria are met throughout the project's lifecycle.

Introduction of Enterprise Architect Software

Interviewee B introduced the use of Enterprise Architect software within Public Agency A for modelling various project aspects. This software supports the design process by allowing engineers to map out system states, stakeholder requirements, and other critical factors in a structured manner. The model grows and evolves as the project progresses, which helps maintain alignment between initial designs and final outcomes.

Interviewee B mentioned the use of Unified Modeling Language (UML) within Enterprise Architect as part of the formal methods applied in the design process. While UML helps in creating structured models of systems, he pointed out that not all aspects of UML are formal methods, which means that some elements still require manual interpretation. This contrasts with the more rigorous, algorithm-driven approach of SBE, which reduces the potential for misinterpretation by automating much of the design logic.

Focus on Standardisation in Civil Infrastructure

He highlighted the push towards standardisation within civil infrastructure, specifically through a product platform approach for designing bridges, sluices, and tunnels. By standardising certain components across multiple projects, Public Agency A aims to streamline both the design and construction processes. This standardisation not only reduces costs but also simplifies maintenance, as standardised parts and systems can be more easily managed and replaced.

Clustering of Sluices for Efficient Design

In line with the standardisation efforts, Interviewee B described how sluices are being grouped into clusters based on their design characteristics. By identifying commonalities across different sluices, Public Agency A can apply standard solutions more broadly, improving efficiency in both design and maintenance. This clustering approach is part of a broader strategy to develop a product platform that supports the design of various infrastructure types.

Development of a Configurator for Project Specifications

A key innovation discussed by Interviewee B is the development of a configurator tool that helps specify project details and links these to standard requirements and construction specifications via Relatics. This tool allows for more efficient project planning by automating the selection of relevant standards and modules based on specific project criteria, thereby reducing the time and effort required to prepare project specifications.

Integration of Control and Mechanical Systems

Interviewee B highlighted a significant challenge in the current infrastructure projects: the integration of control systems with mechanical systems. He noted that these systems are often developed independently, which can lead to inefficiencies and potential issues during the operational phase. Different design choices, such as using hydraulic versus electro-mechanical drives, have significant implications for the control systems. He stressed the importance of integrating these design processes to ensure that control systems are appropriately tailored to the mechanical systems they will govern, thereby enhancing overall system reliability and safety.

Challenges in Design Verification and Validation

He discussed the timing and execution of verification and validation processes within projects, noting that these are often left until the later stages of the project. This can lead to challenges, particularly when issues arise that require significant rework. Interviewee B emphasised the importance of performing these checks at various stages throughout the design process to identify and address issues early, thereby reducing the risk of costly delays and modifications later on.

Two-Phase Contract Approach

To address some of the challenges in project delivery, Interviewee B described the two-phase contract approach being used in some projects. This approach marks a shift from the previous model where contractors had significant freedom to design based on broad functional requirements set by the client. In the past, Public Agency A would provide high-level functional requirements, and contractors were responsible for the detailed design, often leading to solutions that did not fully meet the client's needs. This hands-off approach sometimes resulted in late-stage design changes, disputes, and increased costs.

In the new two-phase contract approach, the first phase focuses on developing a plan and preliminary design with close collaboration between the client and the contractor. The contractor is selected based on their proposed approach, competencies, and how well they

align with the client's vision. This phase allows Public Agency A to have greater influence over the design process from the outset, ensuring that the project stays aligned with their requirements. Only after the preliminary design is agreed upon does the project move into the second phase, where detailed design and pricing are finalised. This method helps to better align expectations between the contractor and client, reducing the risk of disputes, rework, and cost overruns later in the project. By pulling back some of the design responsibilities, Public Agency A aims to have more control and ensure that the final project outcome meets their standards and requirements.

Standardisation of Sluices Through Product Platforms

Interviewee B provided an example of how product platforms are being applied to sluices, where standard modules are being developed for common components. This approach not only streamlines the design process but also supports more efficient maintenance by allowing for the reuse of standardised parts across different projects.

Communication Challenges in Project Design

Interviewee B highlighted communication issues between designers and clients, which often lead to misunderstandings about project requirements during the design phase. To address these challenges, he emphasised the importance of early alignment through Specification Requirements Analysis (SRA). This process involves the contractor thoroughly reviewing and interpreting project requirements before detailed design begins, ensuring both parties have a shared understanding. The SRA helps prevent costly changes and disputes later in the project by clarifying any ambiguities upfront, making it a crucial step in complex infrastructure projects.

C.2.3 Interviewee D (Technology Provider A)

Provision of MBSE Support to Companies

Interviewee D explained how Technology Provider A supports companies in setting up their information management and IT systems, ensuring that data can be easily shared between different applications and parties. This support is particularly focused on standardising Systems Engineering (SE) practices across various projects. Technology Provider A has developed a standard data model/metamodel for MBSE, which was introduced 14 years ago and is now registered for broader use. This model provides the foundation for companies to develop their own software solutions or configure no-code applications like Relatics, Outsystems, and Mendix.

MBSE Data Model and Its Role in MBSE

The standardised MBSE data model is based on UML-like modelling but is specifically designed for Linked Data instead of traditional SQL/XML databases. This design focuses on how software should create data and derive logic, emphasising the importance of interoperability and adherence to ISO standards for Product Lifecycle Management and W3C

standards for data exchange. The data derived from this model is SysML-like in its representation of the system, ensuring that it aligns with global standards.

Role of Relatics in Requirements Management

Relatics, often used in infrastructure projects, is primarily a tool for data storage and requirements management rather than for deep integration within systems. It is used to document project requirements and verify them, but this verification typically occurs later in the project lifecycle, which can lead to inefficiencies.

Use of SysML and the Importance of Tool Integration

Interviewee D discussed the significance of storing SysML models as graphs to facilitate reusability and communication between different software tools. For this to be effective, agreements with companies providing these tools are necessary to ensure that different systems can work together seamlessly.

MBSE Models and Parametric Design

Regarding the structure of MBSE models, Interviewee D noted that while the metamodel is UML-based, project-level models are constructed using SysML. The communication between various software tools is crucial, yet there is still a tendency for isolated working methods due to parties wanting to delineate their responsibilities. This often hampers the early validation of designs and the adoption of agile design methodologies.

Shared Responsibilities in Project Execution

Interviewee D highlighted the need for shared responsibilities in infrastructure projects, as traditional approaches often lead to isolated working practices. They suggested that clients, such as Public Agency A, should be more involved from the early stages of the project, sharing responsibility in the decision-making and validation processes. This involvement can lead to more effective collaboration, better risk management, and smoother project execution.

Tool and Methodology Preferences

Technology Provider A employs UML for metamodeling and SysML for detailed project-level modeling. The level of abstraction and detail is determined by the specific requirements of each project.

Reusability of MBSE Models

Interviewee D touched upon the potential for reusing MBSE models across similar projects, although this practice is still in its early stages within the infrastructure sector. While parametric design and digital twins are not yet widely implemented, MBSE provides a strong foundation for future advancements in these areas.

Future Development of MBSE

Looking forward, Interviewee D sees MBSE evolving towards greater integration with digital twins, though they acknowledge that this is still a distant goal. The immediate focus remains

on refining MBSE practices to ensure they provide tangible benefits throughout the entire lifecycle of infrastructure projects.

Consultancy and Technical Services

Technology Provider A also offers consultancy and technical services, helping companies to implement the standardised MBSE data model. They have also developed a platform designed to facilitate data sharing, offer a suite of applications, and serve as a data marketplace, with a focus on aligning with global IT standards like the Resource Description Framework (RDF) for broad applicability.

C.2.4 Interviewee E (Engineering Firm A)

Challenges with Verification and Requirements in Late Stages

Interviewee E discussed common issues that arise when requirements are identified late in a project's lifecycle. They noted that introducing new requirements towards the end of a project can significantly impact the design, particularly when these requirements have not been anticipated earlier. This problem is exacerbated in projects where verification is often done at the end, leading to costly rework.

Model-Based Systems Engineering (MBSE) and Verification

While MBSE aims to integrate requirements verification into the design process more effectively, Interviewee E highlighted the challenges of ensuring that all requirements are verified early enough. Despite the benefits of MBSE, verification often occurs in bulk at the end of the process, rather than incrementally, which can result in late identification of issues and necessitate redesigns.

Challenges with Documentation and Replacement Projects

Interviewee E elaborated on specific challenges associated with renovation and replacement projects. Documentation of existing infrastructure is often incomplete or inaccurate, which requires additional inspections and sometimes necessitates assumptions in design calculations. These challenges complicate the design process and demand careful management to ensure the safety and functionality of the final design. To address these issues, Interviewee E stressed the importance of standardisation. They explained that standardisation could help mitigate the risks associated with incomplete documentation by providing a consistent framework for design and verification processes. Additionally, using standardised parameters and methods can facilitate the integration of new designs with existing structures, even when documentation is lacking.

Issues in Public Infrastructure Projects

A significant challenge in public infrastructure projects, according to Interviewee E, is the introduction of additional requirements late in the project, often from stakeholders who were

not involved earlier. This complicates the integration of these late-stage changes into the existing design, making it difficult to maintain project timelines and budgets.

Use of BIM and Limitations in Current Practice

Interviewee E explained that while Building Information Modelling (BIM) is employed for exchanging design data, its effectiveness is limited when dealing with dynamic project aspects, such as phased work or moving parts like bridges. Although tools like Inventor allow for some simulation, their ability to model complex interactions and behaviours is limited.

Reuse of Models and Parameters

Discussing the reuse of models, Interviewee E noted that while components can often be reused, entire models are typically rebuilt for each project due to unique specifications. Engineering Firm A is working on standardising certain parameters to streamline the design process, but variability in projects still requires a significant amount of custom work. Standardisation is essential here as it can reduce the amount of custom work needed, allowing for more efficient design processes and easier reuse of models across similar projects.

Model Validation and Client Interaction

For model validation, Interviewee E stated that clients typically require extensive documentation to prove that the design meets all specified requirements. This validation process is time-consuming, often involving detailed spreadsheets to track compliance with each requirement. Despite the use of 3D models, final validation remains largely based on 2D drawings and reports, which can be inefficient.

Interdisciplinary Collaboration Challenges

Interviewee E highlighted the difficulties in collaborating across disciplines, particularly when teams work with varying levels of detail and different tools. For example, inconsistencies can arise when the steel and mechanical design teams are more advanced in their detailing compared to the civil engineering team, leading to rework when integrating designs.

Software Tools Used

Interviewee E mentioned various tools used for modelling and calculations, including Inventor for 3D modelling and SCIA for structural calculations. While it is possible to integrate these tools, the process is not always seamless, and manual adjustments are often necessary to ensure consistency between the design and calculation models.

C.2.5 Interviewee O and P (Engineering Firm C)

Current State of MBSE at Engineering Firm C

Engineering Firm C is recognised for its advanced approach to digitalisation in infrastructure projects, with Model-Based Systems Engineering (MBSE) playing a crucial role in this strategy. The interviewees highlighted that Engineering Firm C has been developing and refining its MBSE processes for several years. A major focus has been on creating a standardised Relatics template, which serves as a foundational tool for implementing MBSE

across various projects. This template is designed to ensure consistency and efficiency, though it has its limitations, particularly in handling complex logic and data exchange.

Challenges in Discipline Integration

A recurring theme in the interview was the challenge of integrating different disciplines within a project under the MBSE framework. Despite efforts to standardise processes, there is still a lack of cohesion among teams. This challenge is partly due to the diverse nature of projects and the varying degrees of familiarity with MBSE practices across different disciplines. The interviewees emphasised that achieving better integration is essential for the success of MBSE, as the current siloed approach can lead to inefficiencies and miscommunication.

Industry-Wide Adoption and Standardisation

One of the significant barriers to the full implementation of MBSE identified by the interviewees is the slow adoption of these practices across the infrastructure sector. While Engineering Firm C is advancing MBSE, the broader industry, including clients and other stakeholders, often lags in adopting these methods. This disconnect makes it challenging to establish a standardised approach that can be consistently applied across projects. The interviewees stressed the importance of industry-wide standardisation and collaboration to overcome this barrier.

Furthermore, the reuse of engineering models and information across different projects is hampered by the varying levels of client engagement and the inconsistent application of standard processes. This challenge is compounded by the need to adapt tools and processes to different project contexts, which can vary significantly based on client requirements. A notable example is Engineering Firm C's work on a tunnel standard for a public infrastructure client in Flanders, which aimed to standardise and reuse best practices in tunnel design and renovation. However, the effort was only partially successful due to limited resources, highlighting the challenges in achieving comprehensive standardisation across the sector.

Software Limitations and Tool Dependence

The interviewees discussed the limitations of current software tools in supporting MBSE for complex infrastructure projects. They pointed out that while tools like Relatics are useful, they fall short in areas such as handling complex data relationships and logic. Specifically, SysML is employed for creating visual representations, such as block diagrams and functional flow diagrams, which help structure and visualise system architectures. However, SysML has its limitations, particularly in capturing the deep semantic meaning required for advanced engineering work.

Moreover, the interviewees highlighted a strong dependence between the tools used and the processes they support. This dependence means that the effectiveness of MBSE is heavily influenced by the capabilities and limitations of the tools employed. To address these challenges, Engineering Firm C is exploring the integration of SysML with Linked Data and RDF (Resource Description Framework). Linked Data is seen as a potential solution for better

data interoperability and exchange across different tools and platforms. RDF, in particular, offers a way to directly exchange data and relationships in a more flexible manner, which could significantly enhance the application of MBSE in complex projects.

The need for more adaptable and robust tools that can better support these processes was emphasised as a critical area for improvement. Additionally, the interviewees noted the importance of developing a comprehensive library for reuse. This library would store best practices, templates, and models from previous projects, enabling future projects to leverage existing knowledge and reduce redundancy. However, the challenge lies in the broader sector's lack of standardisation and insufficient knowledge of MBSE practices, which hinders the straightforward application of reusable components.

Cultural and Organisational Challenges

The interviewees also touched on the cultural and organisational challenges within Engineering Firm C itself. As MBSE practices become more advanced, there is a growing gap between the leading-edge practices being developed and the broader organisational adoption of these practices. This internal challenge is compounded by the need to bring the entire sector along on this journey, which requires significant cultural and organisational shifts both within Engineering Firm C and across the industry.

C.2.6 Interviewee F (Engineering Firm A)

Current State of MBSE in Renovation Projects

Interviewee F, who works on bridge renovation projects at Engineering A, shared detailed insights into the application of Model-Based Systems Engineering (MBSE) within these contexts. While MBSE offers substantial value, especially in visualising and coordinating complex engineering tasks, its application in renovation projects presents unique challenges. Unlike new projects where standardised models can be more readily reused, renovation work often involves existing infrastructure with specific constraints. These constraints complicate the reuse of models and standardised components, making each project highly individualised. The particular conditions of each project, such as the existing bascule bridge foundations, require tailored approaches that limit the straightforward reuse of previously developed models.

Challenges in Physical and Process Integration

A significant challenge in renovation projects is the necessity to retain and integrate with existing physical structures. For instance, in projects involving bascule bridges, the foundation and other key structural elements must be preserved, necessitating highly accurate 3D modelling. Interviewee F explained that precise physical documentation is crucial, often requiring advanced techniques like laser scanning and point cloud generation. These methods help ensure that new components are accurately designed to fit with existing structures, avoiding costly and time-consuming errors. However, the integration of new and old components remains a complex process, often requiring meticulous planning and execution.

Issues in Cross-Disciplinary Collaboration

Interviewee F also highlighted the difficulties in coordinating between various disciplines involved in these projects, such as mechanical, structural, and electrical engineering. These components often progress at different paces, leading to inefficiencies and the need for rework. He noted that MBSE practices are not uniformly applied across all disciplines, which further complicates the integration of various aspects of the project. For example, early completion and ordering of certain mechanical components, like the Panama wheel, can lead to conflicts when integrating with elements designed later, such as cable routing. This misalignment can cause delays and necessitate adjustments, highlighting the need for better synchronisation across disciplines.

Software and Tool Limitations

The limitations of current software tools were another major point of discussion. Interviewee F mentioned that while tools like Inventor are effective for 3D modelling, linking these models with calculation tools remains challenging. The varying timelines of design phases exacerbate this issue, as early detailed designs of mechanical components must later be reconciled with other systems that are developed afterwards. This lack of uniform application of MBSE practices across all phases of the project leads to integration challenges, which can significantly impact the efficiency and effectiveness of the renovation process.

Importance of Accurate Documentation and Future Use

Interviewee F emphasised the critical importance of accurate documentation throughout a project's life cycle, particularly during renovations and maintenance. However, he also noted that documentation practices have been historically inconsistent, especially with older infrastructure. This inconsistency poses significant challenges when trying to understand previous design decisions and integrate them into current renovation efforts. Accurate documentation is essential for future use, enabling engineers to make informed decisions during renovations and reducing the time and effort required to assess existing conditions.

Reuse of Models and Components

While the reuse of models and standardised components is a goal within MBSE, Interviewee F pointed out the practical difficulties in achieving this in renovation projects. Each project often has unique requirements driven by the specific conditions of the existing infrastructure, which heavily influences the design process. This individuality limits the potential for reusing models or components, meaning much of the design work needs to be tailored to the specific context of each project. Consequently, while the processes and methodologies might be standardised, the actual application often requires significant customisation.

Cultural and Organisational Challenges

Finally, the interview touched on the cultural and organisational challenges within engineering teams and the broader industry. Interviewee F observed that while there is a push towards more advanced digital methods like Building Information Modelling (BIM) and MBSE, the adoption of these practices is uneven. A more formal and systematic approach to integrating these models across disciplines could improve project outcomes, but this requires a significant

shift in both organisational culture and industry practices. The conservative nature of the civil engineering sector, particularly in comparison to the building construction sector, often hinders rapid adoption of new methodologies.

C.2.7 Interviewee G (Engineering Firm A)

C.2.8 Interviewee H (Contractor A)

A principal systems engineer from Contractor A provides profound insights into the complexities of managing large projects through advanced information management, systems engineering, and digital transformation techniques. Their expertise primarily focuses on the challenges and innovations in Model-Based Systems Engineering (MBSE), data integration, and the adoption of international standards to enhance project outcomes, particularly in high-profile projects like a reactor replacement project.

Challenges in Data and Configuration Management

The interviewee underscores the critical challenges in maintaining alignment between the "as-required," "as-designed," and "as-is" configurations across the project lifecycle. Ensuring this alignment is essential to avoid inefficiencies and operational risks, especially in complex and safety-critical projects. They highlight the fragmented nature of information within different engineering disciplines, where each operates within its own silo, utilising distinct tools and processes. This siloed approach complicates data integration and harmonisation, prompting the need for a standardised approach to enhance interoperability and accessibility across all phases of a project.

Adoption of International Standards

To address these challenges, the interviewee supports the adoption of international standards such as ISO 15926-11 for industrial data integration and ISO/IEC 81346 for project breakdown structuring. These standards, along with ISO 19650—focused on the organisation and digitisation of information about buildings and civil engineering works using BIM—are seen as vital for establishing a Common Data Environment (CDE). The CDE integrates various breakdown structures (geographical, functional, system, and product) into a unified framework. This integrated approach improves data management and communication among stakeholders, reducing errors and ensuring consistency across all project stages.

In the reactor project, these standards were essential for developing a unified data environment that aligned various project components and ensured consistent data management throughout the lifecycle.

Ontology and Data Integration

A cornerstone of the interviewee's approach is the development of a project ontology that supports MBSE, digital twins, and asset lifecycle management. This ontology, aligned with ISO 15926-11, organises and manages the extensive data generated throughout a project's lifecycle. Technologies like RDF and SPARQL are used to manage relationships between data elements, ensuring a coherent and integrated environment.

In the reactor project, limiting the data management approach to using only RDFS combined with SPARQL proved instrumental in managing the complexity of interconnected systems, enabling accurate and consistent representation of project aspects.

Limitations of the System Modelling Language (SysML)

The interviewee critiques SysML for lacking a Reference Data Library (RDL) and for its limited support in tracking changes over time when multiple users are involved. These limitations hinder effective management and documentation of evolving system designs, which are critical in complex projects that demand precise version control and traceability.

Practical Implementation and Challenges

Despite the promise of advanced data management practices, the interviewee acknowledges several implementation challenges. Variations in data quality and modelling skills among project partners can complicate the adoption of a uniform approach. They stress the need for senior management support and the development of new competencies in data management and ontology engineering.

In the reactor project, a rigorous “Car Wash for Data” process was used to clean and validate data before integration into the CDE. Based on ISO 8000, this process ensures that only accurate and reliable data is used, establishing a single source of truth that stakeholders can trust.

Digital Twin and Lifecycle Management

The interviewee advocates for the use of digital twins in infrastructure project lifecycle management. A digital twin provides a real-time, digital replica of a physical asset to monitor and manage its performance. In the reactor project, the digital twin played a crucial role in lifecycle support, offering a detailed and current view of system components.

Maintaining data integrity is crucial to ensure the digital twin accurately mirrors the physical asset. This requires robust data management tools and a strong organisational commitment to ongoing data quality and transparency.

Organisational and Cultural Challenges

The adoption of MBSE and digital twins also faces organisational and cultural barriers. Despite their benefits, these technologies are inconsistently adopted across organisations and disciplines. The conservative nature of the engineering sector contributes to this resistance.

To address these issues, the interviewee emphasises the need for strong leadership, a clear integration vision, and cross-disciplinary collaboration to ensure commitment from all stakeholders.

Harmonising Data Standards Across Systems

The interviewee highlights the importance of harmonising data standards across systems by integrating CB-NL with broader frameworks like NEN 2660. Aligning object type libraries and data delivery standards would allow CB-NL to act as a central bridge for consistent

information exchange. Standardised terminology and definitions are critical for streamlining procurement and design processes.

Achieving a Single Source of Truth (SSOT)

The concept of a Single Source of Truth (SSOT) is central to the interviewee's work. While ideal, implementing it in complex projects is difficult due to the diversity of data sources and the need for synchronisation. The interviewee proposes using linked-data ontologies to maintain consistency across databases and systems, ensuring stakeholders access accurate and up-to-date information.

C.2.9 Interviewee I (Consultancy A)

Interviewee I, a principal consultant at Consultancy A, focuses on enhancing product development processes across various sectors, including infrastructure, IT landscapes, and complex machinery. Their mission is to streamline development by improving collaboration, making information more accessible, and fostering a workflow that encourages pride in work while delivering higher quality products more quickly and cost-effectively.

Approach and Methodology

Consultancy A employs a range of best practices tailored to each sector's specific needs. In infrastructure projects, which are typically organised around structured stages and often follow a waterfall model, the organisation helps integrate diverse engineering disciplines from concept design through realisation and into maintenance. Emphasis is placed on considering the entire asset lifecycle, including use and eventual decommissioning or recycling.

Adoption of Model-Based Systems Engineering (MBSE)

Interviewee I highlights the gradual adoption of Model-Based Systems Engineering (MBSE) across different industries. While some organisations have developed basic information models, more advanced applications of MBSE, such as using models for simulation, behavioural prediction, and automated alternatives, are still emerging. In the infrastructure sector, progress is being driven by the need for better validation and simulation early in design phases.

Digital Twins and Virtual Models

A significant evolution in MBSE practices is the adoption of digital twins—virtual representations of physical systems capable of interacting with real-time data. Interviewee I gives examples from the automotive sector, where digital twins are used to optimise performance and support predictive maintenance. As organisations mature in their systems engineering practices, they begin to integrate these virtual models more deeply into operations and asset management.

Challenges in MBSE Implementation

Not all organisations have reached the same level of MBSE maturity. Many are still trying to integrate systems engineering into multiple projects, rather than applying it in isolated, one-

off efforts. A core challenge is moving beyond single-project implementations to develop scalable, reusable methods and models that can be applied consistently across different contexts.

Standardisation and Information Exchange

Interviewee I stresses the importance of standardising formats and methods for information exchange. While there is some progress in sectors such as construction through the use of BIM standards, significant gaps remain. Harmonising these standards is essential for enabling true interoperability and long-term collaboration across organisational boundaries.

Organisational Change and Learning

Implementing MBSE requires deep organisational change. Interviewee I advocates for an incremental, experimental approach that allows teams to learn by doing. This mitigates risks, supports gradual skill development, and prepares organisations for broader implementation.

Strategic Experimentation

Consultancy A promotes a strategy of small-scale, targeted experiments as a pathway to MBSE adoption. These experiments serve to validate methods and clarify where MBSE delivers the most value. Once successful, these initiatives can be scaled up and embedded into broader workflows and processes.

Long-Term Vision and Strategy

Interviewee I advises that MBSE should be approached with a long-term vision. Even though short-term returns may be limited, consistent investment in learning, tooling, and experimentation prepares organisations for a more efficient and integrated future.

Collaboration Across the Sector

Finally, the interviewee stresses the importance of cross-sector collaboration in accelerating MBSE maturity. Individual organisations can achieve much independently, but industry-wide progress depends on collective efforts to align standards, share insights, and build a common understanding of goals and methods.

C.2.10 Interviewee J (Consultancy A)

The interview with Interviewee J from Consultancy A explored various aspects of Model-Based Systems Engineering (MBSE), particularly focusing on its implementation within organisations that are new to this approach. The discussion centred around the MBSE framework and the practical challenges companies face when adopting MBSE.

Introduction to MBSE and the MBSE Framework

Interviewee J began by explaining that MBSE is not just a methodology but a transformative approach that changes how organisations design, develop, and manage complex systems. The MBSE framework developed by Consultancy A is a key tool used to guide organisations

through the adoption of MBSE. This framework provides a structured approach to ensure that all critical aspects of MBSE are addressed during its implementation.

The MBSE framework consists of several foundational elements:

Leadership: Establishing clear leadership is crucial for successful MBSE adoption. Leadership involves defining a clear vision, understanding the strategic importance of MBSE, and ensuring that all stakeholders are aligned with the organisation's MBSE goals. According to Interviewee J, top management commitment is essential, and they must be actively involved in tracking MBSE-related trends and continuously improving the state of MBSE practices within the organisation.

Foundation: Building a solid foundation is critical for MBSE. This includes cultivating the right organisational culture, setting up principles, policies, and standards, and ensuring that the terminology used across the organisation is consistent with MBSE practices. Interviewee J emphasised that having clear roles and responsibilities supported by the organisational structure is vital for effective MBSE implementation.

Execution and Support: Interviewee J highlighted that MBSE is a continuous journey, not a one-time project. Execution and support involve the practical aspects of developing, managing, and using models within the organisation. This requires mature processes, methods, and tools that support collaborative and incremental work. Additionally, organisations need to ensure that they have sufficient and competent staffing with the necessary MBSE knowledge, skills, and mindset.

Journey: The journey of MBSE implementation is iterative, requiring continuous improvement and adaptation. Interviewee J explained that organisations should focus on a result-driven approach with clear objectives, allocate qualified resources, and measure the impact of their MBSE capabilities continuously. This journey involves learning and adapting as the organisation gains more experience with MBSE.

Challenges in MBSE Implementation

Interviewee J discussed several challenges that organisations face when implementing MBSE. One significant challenge is the transition from document-based processes to a model-centric approach. This transition requires a fundamental shift in how organisations think and operate. In traditional companies, especially those with project-based cultures, there is often resistance to this change. Interviewee J noted that this resistance can be mitigated by starting small, such as piloting MBSE in a specific project, and gradually expanding its use as the organisation becomes more comfortable with the approach.

The Importance of Agile and Iterative Approaches

Interviewee J stressed the importance of adopting an agile and iterative approach to MBSE implementation. They mentioned that MBSE is not a linear process but requires continuous learning and adaptation. Organisations should avoid treating MBSE as a one-time project but rather as an ongoing transformation process. By iteratively refining their MBSE practices,

organisations can ensure that they remain aligned with evolving business needs and technological advancements.

MBSE Self-Assessment Framework

Consultancy A uses a self-assessment framework to help organisations evaluate their maturity in MBSE practices. This framework includes several categories, each with specific reference statements that organisations can use to assess their current state and identify areas for improvement. The categories in the assessment framework include:

Leadership: Assessing the organisation's understanding of MBSE's contribution to process and product improvement, top management's commitment, and the tracking of MBSE-related trends.

Foundation: Evaluating the organisation's culture, principles, policies, and standards related to MBSE, as well as the clarity of roles and responsibilities.

Journey: Assessing the organisation's continuous improvement approach, resource allocation for MBSE, and the measurement of MBSE's impact.

Model Management: Evaluating the maturity of processes, methods, tools, and the ability to manage models securely across the lifecycle.

Data Management: Assessing the tools and methods used for managing data, ensuring that data is reliable and easy to use in models, and managing data interfaces between tools.

Model Usage: Evaluating how well MBSE processes, methods, and tools are integrated with overall product-level processes and how effectively modelling is used for decision-making.

Model Development: Assessing the processes, tools, methods, and libraries for developing high-quality models, the alignment of models with stakeholder needs, and the use of metrics to measure model development and effectiveness.

Collaboration and Knowledge Sharing

Interviewee J highlighted the importance of collaboration and knowledge sharing in MBSE implementation. They noted that organisations should actively engage with other companies and industry groups to share experiences, best practices, and lessons learned. By doing so, organisations can accelerate their MBSE adoption and overcome common challenges more effectively.

C.2.11 Interviewee K and L (Engineering Firm B)

C.2.11 Interviewee K and Interviewee L (Engineering Firm B)

The interview with Interviewee K and Interviewee L from Engineering Firm B delved into the company's application and challenges of Model-Based Systems Engineering (MBSE). The conversation focused on the practical implementation of MBSE, the tools used, the integration

of different engineering disciplines, and the hurdles faced in promoting this methodology within complex projects.

Background and Introduction to MBSE at Engineering Firm B

Interviewee K and Interviewee L began by discussing their respective backgrounds and the evolution of MBSE within Engineering Firm B. They highlighted that much of their work is for major infrastructure clients like Public Agency A, especially in the areas of tunnels, bridges, and other complex infrastructural projects. Historically, these projects have been dominated by traditional engineering disciplines like civil and structural engineering, where tools like Relatics have been widely used for systems engineering. However, the dynamic nature of mechanical and electrical systems has driven the need for more advanced methodologies, such as MBSE.

The use of MBSE began to gain traction at the company towards the late 2000s, initially influenced by the need for better control over complex systems, particularly those involving dynamic behaviour, which traditional tools like Relatics could not adequately handle.

Challenges in MBSE Adoption and Integration

One of the central challenges discussed was the disparity between the traditional disciplines (civil and structural engineering) and the more dynamic disciplines (mechanical and electrical engineering). While Relatics is well-suited for static systems, it falls short for dynamic systems that require complex behavioural modelling. This has led to a divide where MBSE is more heavily adopted within the mechanical and electrical engineering teams, while the civil and structural teams remain reliant on more traditional tools.

This disparity creates a significant challenge when trying to integrate these disciplines into a cohesive MBSE framework. The ultimate goal is to achieve a "single source of truth" where all information, regardless of discipline, is synchronised and accessible. However, achieving this goal is complicated by the different tools and methodologies used by each discipline.

Tools and Methodologies

Interviewee K and Interviewee L explained that they use SysML as the primary modelling language within their MBSE efforts, implemented through tools like Enterprise Architect. SysML is used because of its ability to capture a wide range of system behaviours and relationships, which are crucial for managing the complexity of dynamic systems. The language's versatility allows it to be applied across different aspects of system design, from object trees to behavioural models.

They emphasised the importance of distinguishing between the language (SysML) and the tools used to implement it. For example, while SysML provides the modelling framework, tools like Enterprise Architect allow for the actual creation and manipulation of models.

The interview also touched on the importance of using the right tool for the right job. While SysML and Enterprise Architect are powerful, they are not necessarily the best tools for every

aspect of a project. For instance, some teams may still prefer Relatics for certain types of data management, and this needs to be integrated effectively with the MBSE tools.

Practical Applications and Project Experiences

The discussion highlighted specific projects where MBSE has been applied, including projects for Municipality A and the Blankenburg Connection. In these projects, the use of MBSE allowed the team to manage the complexity of the systems more effectively, particularly in terms of integrating software and hardware components. They described how MBSE helped streamline the design process by allowing for better coordination between different engineering disciplines and by providing a clear framework for managing system behaviours.

However, they also acknowledged that the successful application of MBSE is highly dependent on the project context and the client's understanding and acceptance of the methodology. For example, in some projects, the client may lack the in-house expertise to manage or maintain the models after the project is completed, which can limit the long-term value of the MBSE work done during the project.

Implementation Challenges and Organisational Commitment

A recurring theme in the interview was the importance of organisational commitment to MBSE. Interviewee K and Interviewee L stressed that MBSE cannot be effectively implemented by a small, isolated team; it requires buy-in at all levels of the organisation. This includes not only the engineers who use the tools daily but also management, who must understand and support the strategic value of MBSE.

Without this broad commitment, MBSE efforts can struggle to gain traction, leading to situations where the methodology is underutilised or even abandoned. They noted that this is particularly challenging in environments where traditional engineering practices are deeply entrenched, and there may be resistance to adopting new ways of working.

Future Developments and the Role of Standards

The interview concluded with a discussion on the future of MBSE at Engineering Firm B and in the broader industry. Interviewee K and Interviewee L recognised the need for continued development of standards and best practices to guide MBSE implementation. They acknowledged that while there are some existing standards, such as those from Public Agency A, there is still a need for more comprehensive frameworks that can be applied across different types of projects and disciplines.

They also discussed the potential for integrating MBSE with other emerging technologies, such as Digital Twins, which could further enhance the ability to manage and simulate complex systems. However, they also cautioned that these developments would require significant investment in terms of both time and resources, and that the industry as a whole needs to be prepared to make these investments if MBSE is to reach its full potential.

C.2.12 Interviewee M (Design Consultancy A)

The interview with Interviewee M from Design Consultancy A provided an in-depth exploration of the company's application of Model-Based Systems Engineering (MBSE) within large infrastructure projects, including a major sluice project. The discussion covered a range of topics, from the integration of engineering disciplines to the use of advanced software tools and the complexities of managing projects under Design, Build, Finance, and Maintain (DBFM) contracts. Interviewee M emphasised how MBSE facilitates more efficient processes, enhances verification and validation, and ultimately leads to more reliable and maintainable infrastructure. The conversation also touched upon the challenges inherent in aligning the various stakeholders involved in such large-scale projects, particularly under the constraints of DBFM contracts.

Integration of Disciplines

Interviewee M detailed how MBSE enables the seamless integration of various engineering disciplines, which is crucial for the success of complex infrastructure projects like the sluice project. By creating a unified model, MBSE allows different teams – such as civil, mechanical, and electrical engineers – to work collaboratively within a single framework. This approach ensures that all aspects of the project are aligned, reducing the risk of errors and improving overall efficiency. The integration of disciplines was particularly evident in the way Design Consultancy A handled the project's design, construction, and maintenance phases, ensuring that the infrastructure met both technical specifications and long-term operational goals.

Use of Software Tools

A significant portion of the interview focused on the advanced software tools employed to support MBSE in these projects. Interviewee M highlighted the use of BIM (Building Information Modelling) and digital twins as central components of their strategy. These tools allowed the team to create detailed simulations, which were used not only during the design and construction phases but also for ongoing maintenance and operational purposes. In the sluice project, the digital twin was used to conduct 3D simulations of various operational scenarios, ensuring that systems such as sluice gates would perform as expected in practice.

Throughout the project, various software tools were utilised to support the MBSE approach. Tools like Bentley's suite were highlighted for their ability to create detailed 3D models used for both design and verification purposes. Interviewee M mentioned the importance of using these tools to simulate operational scenarios, which helped identify potential issues early in the design process. For example, the 3D models were used for verifying camera placements and vision in tunnels, ensuring proper coverage and functionality.

Design Consultancy A also utilised software like Unity and other simulation tools to visualise complex systems, such as the movement and operation of sluice gates. The models created were not just static representations but were actively used to generate specific views that improved the design during the construction phase. This practical application of the model facilitated better communication among team members, allowing them to optimise the design,

conduct virtual tests, and refine construction processes. Additionally, the use of 3D models proved instrumental in incentivising discussions, as they made the designs easier to understand for both internal team members and external stakeholders. This enhanced understanding fostered more productive discussions and ensured that all parties had a clear and consistent view of the project's objectives and designs. Moreover, these models were used for training operators, demonstrating different scenarios through 3D simulations to prepare them for real-world operations.

However, Interviewee M expressed some scepticism about the linked data approach, noting that the project team often struggled to fully understand the intricacies of the linked data model, which could hinder effective implementation.

Challenges and Future Potential of MBSE

While MBSE offers numerous advantages, Interviewee M also discussed the challenges of implementing this approach in large infrastructure projects. One of the main challenges is ensuring that all stakeholders, including contractors, designers, and maintenance teams, are aligned with the project's goals and standards. This alignment is crucial for the long-term success of the project but can be difficult to achieve, especially when different teams have different priorities.

For example, the design team might focus on meeting immediate technical requirements, while the maintenance team is more concerned with the long-term operability and ease of maintenance. This misalignment can lead to increased costs, delays, and inefficiencies. Interviewee M suggested that more integrated and continuous communication throughout the project lifecycle could help mitigate these issues. Furthermore, he emphasised the potential of MBSE to evolve into more generative approaches in the future, where predefined models and configurations can be reused across different projects, thereby streamlining the design and construction processes.

Interviewee M also noted a key challenge in implementing MBSE: the resistance from asset owners who prefer traditional document-based approaches over the more dynamic and integrated model-based methods. In one instance, even after a comprehensive model and simulation were set up for maintenance, the owners opted to rely on traditional documents. This highlights the need for a paradigm shift among all stakeholders, including asset owners, for MBSE to reach its full potential.

DBFM Contracts and Their Impact

The conversation revealed that DBFM contracts, while offering significant benefits like incentivising long-term infrastructure functionality, also present unique challenges. One of the key issues highlighted by Interviewee M is the difficulty in ensuring that all parties involved in a DBFM project – such as designers, contractors, and maintenance teams – are aligned with the overall project goals and standards. This misalignment can manifest in several ways, such as when design and construction teams prioritise immediate technical specifications, potentially overlooking long-term maintenance needs.

The complexity of DBFM contracts often requires a high level of coordination and communication between all stakeholders. However, when different tools, methodologies, or data standards are used by different teams, it can lead to significant challenges in transferring and utilising data across the project lifecycle. This can result in higher costs, increased downtime, and reduced efficiency once the infrastructure is operational. Interviewee M stressed the importance of early and consistent alignment of all stakeholders to ensure that the project's long-term goals, such as durability and ease of maintenance, are met.

Redundancy in Design

Interviewee M also touched on the importance of incorporating redundancy into the design of critical infrastructure systems. Using the example of the sluice project, he explained how the design included multiple fail-safes, such as redundant sluice gate systems and hydraulic mechanisms, to ensure that the infrastructure would continue to function even if one component failed. This approach is essential for maintaining the reliability and safety of large infrastructure projects, particularly those with long operational lifespans. The use of MBSE in these projects allows for the simulation and testing of these redundant systems, ensuring that they will perform as expected under various conditions.

Practical Implementation of MBSE

Finally, the interview provided several examples of how MBSE is practically implemented in infrastructure projects. Interviewee M described how Design Consultancy A uses a combination of models and simulations to verify and validate designs before construction begins. This process includes the use of digital twins to model the real-world behaviour of infrastructure components, allowing for adjustments and optimisations to be made in the design phase. Additionally, these models are used during the construction and maintenance phases to ensure that the infrastructure is built and maintained according to the specified requirements.

In one project with Contractor B, Design Consultancy A demonstrated how the team could create their own views within the models. By leveraging the 3D models, Contractor B was able to identify and implement design improvements specifically for the construction phase, showcasing the practical benefits of using MBSE to refine and optimise designs in real-time.

The interview also highlighted the importance of using these models for training operators, demonstrating different scenarios through 3D simulations to prepare them for actual operations. Additionally, the use of 3D models proved to incentivise discussions, as they made the designs easier to understand for both internal team members and external stakeholders, facilitating more effective communication and collaboration.

However, Interviewee M pointed out that the success of these advanced methodologies depends not only on the technology but also on the willingness of all stakeholders to embrace and properly understand these new approaches. For example, despite setting up a comprehensive model and simulation for maintenance, the asset owners were reluctant to use the model for maintenance purposes and instead preferred traditional documents. This

highlights that for progress and improvement, asset owners must also undergo a paradigm shift, adopting new methods and tools to ensure the success of MBSE.

C.2.13 Interviewee N (Contractor B)

The interview with Interviewee N, a senior consultant in Systems Engineering at Contractor B and a member of INCOSE, provided valuable insights into the application and challenges of Model-Based Systems Engineering (MBSE) in the infrastructure and construction sectors. Interviewee N discussed the evolving role of MBSE in managing the growing complexity of projects, the importance of standardisation, and the need for a cultural shift in how stakeholders approach project management and collaboration. He also highlighted the potential and limitations of current tools and methodologies in achieving successful MBSE implementation, and outlined the tangible benefits of MBSE when successfully applied, illustrating how it can streamline processes, improve communication, and reduce project risks.

The Role of MBSE in Managing Complexity

Interviewee N emphasised that MBSE is increasingly seen as essential for managing the complexity of modern infrastructure projects. Traditional methods, such as document-based approaches like Relatics, are becoming inadequate for handling the intricate dependencies and interactions between systems in large-scale projects like tunnels and bridges. He cited the example of a large tunnel project, where the complexity of software and system interactions had grown to a point where they were no longer manageable without a structured MBSE approach.

He argued that MBSE, when properly implemented, provides a framework that allows engineers to manage and understand these complexities more effectively. However, this requires a significant shift in project management practice, moving towards a more integrated and transparent approach where all stakeholders have a clear understanding of the systems involved.

Benefits of MBSE

When MBSE is effectively applied, Interviewee N identified several key benefits. MBSE facilitates improved communication and collaboration between different disciplines by providing a common framework and language. This is crucial in large projects where multiple teams need to work together seamlessly. It helps align understanding between stakeholders, ensuring that what is captured in the model is clear and unambiguous, thus reducing the risk of costly errors or misinterpretations later in the project lifecycle.

Additionally, MBSE supports risk reduction by using models to simulate and verify designs before construction begins, allowing potential issues to be identified and addressed early in the process. This proactive approach minimises the risk of costly mistakes during construction and operation.

Interviewee N also discussed the efficiency of lifecycle management through MBSE, which enables the creation of comprehensive digital models that serve as a single source of truth. For

example, at a major airport project, a BIM model was used to manage 200,000 assets under a performance-based contract, ensuring that performance criteria were met and penalties avoided. This underscores how MBSE can support effective asset management across the lifecycle of complex infrastructure.

Importance of Standardisation and Collaboration

A key theme was the need for standardisation across the industry. Interviewee N discussed the challenges caused by the absence of a universal Object Type Library (OTL) or common language, which hinders the integration of different systems and tools. He referenced the failure of a national standardisation initiative (CB-NL), which collapsed due to a lack of cooperation among stakeholders.

Despite these setbacks, Interviewee N mentioned that practical workarounds, such as the use of existing classification systems (e.g. NL-SfB), are being adopted in the absence of better alternatives. He stressed that for MBSE to succeed, clients, consultants, and contractors must align around common standards and methodologies.

Use of Software Tools

Interviewee N highlighted the role of advanced software tools in supporting MBSE. He mentioned that Contractor B utilised a BIM model at a large airport project to manage the performance of assets under a performance-based contract. This model enabled monitoring and control of thousands of components, ensuring compliance with strict performance criteria. This illustrates how MBSE tools can support not only design and construction, but also long-term operation and maintenance.

Challenges of Implementing MBSE

Despite the potential, Interviewee N outlined several challenges to widespread MBSE adoption. A major barrier is the organisational and cultural change required across the sector. He cited cases where asset owners, despite being provided with advanced models and simulations, opted to rely on traditional documents—highlighting persistent resistance to change.

Another challenge is the issue of risk allocation in large infrastructure projects. Interviewee N described how, in complex projects like a major sea lock or tunnel corridor, contractors were forced to make assumptions due to ambiguous or incomplete requirements. These assumptions sometimes turned out to be incorrect, leading to cost overruns and project delays. In one case, a sea lock project suffered severe financial losses due to such misaligned expectations.

He argued that MBSE can help mitigate these risks by providing a clear, shared model that reduces ambiguity. By using a common modelling language (such as SysML), MBSE helps ensure explicit agreement on key requirements and system behaviour. While MBSE does not eliminate all uncertainty, it significantly narrows the scope of what remains undefined, thereby reducing the likelihood of errors. Nonetheless, he noted that not everything can or

should be captured in a model, and effective MBSE practice must also manage the boundary between modelled and non-modelled elements.

The Future of MBSE and the Role of Digital Twins

Interviewee N discussed Digital Twins as a logical extension of MBSE. He described them as digital representations of real-world assets, useful for monitoring performance, simulating scenarios, and anticipating maintenance. However, he warned that the term is often used loosely and can become a buzzword. In his view, a true Digital Twin must emerge from a robust MBSE process—where the digital model accurately reflects the physical system and supports real-time decisions.

He added that within INCOSE, SysML is seen primarily as a common language to facilitate collaboration. It standardises communication of complex system designs across diverse domains and disciplines and is particularly useful in projects where a shared understanding among multiple stakeholders is critical.

C.2.14 Interviewee Q (Research Institute A)

Interviewee Q, a senior consultant at Research Institute A, provided an in-depth exploration of the challenges and opportunities in the field of Model-Based Systems Engineering (MBSE) and Linked Data within the infrastructure sector. Throughout the interview, Interviewee Q highlighted the complexities involved in standardising data models, the integration of various technologies such as Building Information Modelling (BIM) and Linked Data, and the evolving role of Digital Twins. His insights underscore the importance of a coordinated and collaborative approach to data management and the integration of different methodologies to achieve successful outcomes in infrastructure projects.

Challenges of Standardisation and Data Integration

Interviewee Q began by addressing a significant challenge facing the industry: the proliferation of data standards. Despite efforts to establish the right standards, the sheer number of existing standards has led to a "data standard problem," causing confusion and inefficiency across the sector. Research Institute A has been actively promoting Linked Data in the Netherlands, particularly among large public entities such as Public Agency A, provincial authorities, and major cities. These entities are increasingly engaging with Linked Data for public space modelling and asset management.

One of the key developments discussed is the creation of application standards like NEN 2660, which focuses on semantic modelling in the built environment using Linked Data. This standard provides guidelines on how to apply existing formats and languages for modelling assets in infrastructure, aiming to reduce fragmentation caused by varying modelling techniques. Interviewee Q emphasised the importance of having common modelling principles, particularly in systems engineering, where diverse elements like planned information, functional requirements, and technical details need to be coherently integrated.

Application of Linked Data and MBSE

Research Institute A's role extends beyond standardisation, actively assisting the industry in applying these standards. Interviewee Q mentioned collaborations with various stakeholders, including water boards, energy operators, and construction firms, where Linked Data is used to develop ontologies—structured frameworks for organising information. He highlighted the importance of integrating spatial and physical elements in models, a pattern that emerges across various projects, from urban areas to road networks.

A practical example of Linked Data's application is a proof of concept developed for Public Agency A, focusing on a major bridge. This project involved integrating data from multiple sources into a single system, allowing users to access comprehensive information through a unified interface. The aim is to streamline asset management by linking structured data with documents, thereby making it easier to maintain and access vital information.

The Role of Digital Twins

Interviewee Q also touched on the current trend of Digital Twins, acknowledging that while the term is often used as a buzzword, it essentially refers to a sophisticated form of data integration. In their project with Public Agency A, Research Institute A created a Digital Twin of a bridge, not for predictive maintenance but to centralise and unify data from different sources. This integration allows for more efficient asset management and lays the groundwork for more advanced applications in the future.

He also discussed the potential of integrating real-time data into these models, such as strain measurements from sensors on bridges, which could eventually lead to more dynamic and responsive infrastructure management. However, Interviewee Q pointed out that while real-time data integration is possible, it is not always necessary or feasible, depending on the specific needs of the project.

BIM and Linked Data Integration

Interviewee Q discussed the ongoing efforts to bridge the gap between Building Information Modelling (BIM) and Linked Data, highlighting the importance of the Industry Foundation Classes (IFC) model in this integration. IFC is a widely used standard in the construction industry, especially in projects involving infrastructure like bridges and tunnels. Given its broad adoption by various software vendors, Research Institute A is working to ensure that IFC can be seamlessly integrated with Linked Data.

He mentioned that while IFC originated in the building sector, it is now being extended to infrastructure projects. However, there is still a significant challenge in obtaining sufficient software support for this integration due to the current lack of developers focused on these technologies. Research Institute A is addressing this by creating tools that can automatically convert Object Type Libraries (OTLs) into models compatible with IFC. For instance, plugins are being developed for software like Revit, allowing end users to directly incorporate these models and access the specific properties needed for various infrastructure components. This approach aims to provide robust support for ontologies within widely-used BIM tools, ensuring that industry standards are met and that the integration between BIM and Linked Data is both practical and efficient.

Limitations of Linked Data and IFC Integration

Interviewee Q also highlighted several limitations in the integration of Linked Data with IFC and its broader application in the infrastructure sector. One significant challenge is the lack of sufficient software support for integrating IFC with Linked Data, largely due to a shortage of developers focused on these technologies. This limitation complicates the implementation and scaling of effective solutions. Additionally, while Linked Data offers robust capabilities for modelling and integrating data, its complexity can hinder widespread adoption. Extensive training and the development of new tools are required to overcome these challenges.

The integration between BIM and Linked Data, particularly when using IFC, is not straightforward. The process is still in development, with ongoing technical hurdles related to standardisation, data consistency, and coordination between different standards and technologies. Furthermore, Linked Data, especially when handling large or dynamic datasets, can face performance issues. Traditional relational databases or other data storage technologies might be more efficient in some cases, posing challenges to the scalability of Linked Data solutions. However, Interviewee Q noted that there are new developments in Linked Data technology that are improving scalability. For example, certain advancements in database technologies are enabling Linked Data to handle larger datasets more efficiently, suggesting that these scalability issues may be mitigated in the future.

Future Directions and Industry Adoption

Looking ahead, Interviewee Q expressed optimism about the future of Linked Data and MBSE in the infrastructure sector but also highlighted the significant challenges that remain. He stressed the need for more training and education in the industry to build the necessary skills and knowledge for effectively implementing these technologies. Moreover, he acknowledged the presence of sceptics and the need to demonstrate the practical benefits of Linked Data to encourage broader adoption.

Interviewee Q also pointed out that while Linked Data offers powerful capabilities for data integration and management, it is not without its limitations. The challenge lies in balancing the theoretical strengths of Linked Data with practical applications that are both feasible and beneficial for industry stakeholders.

C.2.15 Interviewee C (Engineering Consultancy A)

Application of MBSE and SysML in Practice Projects

Interviewee C shared their experience with Model-Based Systems Engineering (MBSE) in a major Dutch infrastructure project involving a moveable bridge. MBSE (based on the SysML modelling language) was successfully applied to the electrical installations, in part due to the reuse of existing models. This approach enabled a structured and efficient restart after a temporary pause in the project. MBSE proved quickly applicable when the need arose, and the reuse of earlier models enabled a flying start. The interviewee highlights benefits such as traceability and achieving consensus between parties. However, they observe that MBSE is

still often used mainly to generate consistent documents, rather than to support real content-driven design or simulation.

Problems in System Integration in Large Projects

Interviewee C explained that many infrastructure projects fail early on due to a lack of essential systems thinking. There is a strong tendency to move directly into detailed design, without first creating an integrated system design. This often leads to difficulties in system integration in later stages. They referenced the North/South metro line in Amsterdam and the Oosterweel link in Antwerp as examples where components were developed in isolation, without a unified systems architecture. The result is that complex interactions between components only surface during integration, leading to delays and costly rework.

Limitations in the Sector and the Need for Systems Thinking

They emphasised that the full potential of MBSE remains underutilised in the civil engineering sector. Tools such as Relatics are mainly used as light modelling platforms, where interface definitions are rarely made explicit in time. Interviewee C noted that many engineers in the infrastructure sector are trained in domain-specific design and struggle with thinking in terms of higher-level systems. They compared this to the difference between designing small-scale structures and coordinating large, interdependent systems: many professionals are well-equipped to engineer components or subsystems but lack the tools or mindset to integrate them into a coherent whole. This poses a significant barrier to effective MBSE deployment.

Importance of Abstract Formal Descriptions

They argued that formal system models at higher abstraction levels can help manage and control complex system interactions. These models, while abstract, enable precise specification and verification. The problem is not the feasibility of this approach, but rather the lack of awareness and support. Budget constraints, perceived investment risks, and the absence of a long-term vision all contribute to this challenge. They also pointed to the lack of a 'collective memory' in the sector, as contractors regularly change and reorganise across different projects. Interviewee C added that while SysML has benefits for system integration and traceability, its static character may limit its effectiveness for civil or mechanical applications. Tools like Enterprise Architect provide little semantic validation, increasing the risk of inconsistency.

Opportunities for New Tooling and Digital Twins

Interviewee C sees promising opportunities in adopting textual system modelling and software-oriented version control tools such as Git. These approaches could be more transparent and maintainable than many of the current graphical MBSE tools. They also discussed the future role of digital twins, where models remain linked to the evolving physical system throughout its lifecycle. With properly structured models, failures can be simulated and analysed using the original system specifications.

Capturing Interdisciplinary Interfaces

A critical pain point highlighted by Interviewee C is the lack of formally recorded interfaces between disciplines. While intra-disciplinary collaboration typically functions well, coordination between, for example, civil and electrical engineering is often informal or delayed. MBSE can address this by explicitly capturing and managing interface agreements, reducing the risk of integration problems down the line.

Shifting to the System Level for Growing Complexity

Finally, Interviewee C emphasised that the true value of MBSE becomes evident when organisations move beyond discipline-specific modelling and embrace system-level design. Only then can complex infrastructures, such as tunnels with integrated installations or bridges with control systems, be described and managed coherently. They argue that MBSE is especially valuable in contexts involving increased system complexity, such as systems-of-systems, but that this potential remains insufficiently realised in current practice. Moreover, the application often remains superficial and bottom-up, reflecting a sector that is still conservative and hesitant to adopt formalised methods.

Appendix D: SysML Case Study Notes

D.1 SysML Example Input

Block Definition Diagram

Top-Level System Block	Subsystem Block	Property	Data Type	Input Values	Interfaces
SwingBridge	BridgeDeck	MaterialType	String	Steel, Concrete, etc.	
		DeckLength	Double	Meters	
		LoadCapacity	Double	Tonnes	
		DeckWidth	Double	Meters	
	PivotMechanism	MotorType	String	Hydraulic, Electric	Transfers mechanical energy to 'BridgeDeck'
		RotationSpeed	Double	RPM	
		Torque	Double	Newton-meters	
		PivotType	String	Center, Offset, etc.	
	ControlSystem	ProcessorType	String		Directs operational commands for bridge movement and safety
		OperationMode	String	Automated, Manual	Specifies the capability for both automated processes and manual intervention
		SoftwareVersion			
	SensorSystem	SensorType	String	Load, Position, Motion, Temperature, etc.	Provides raw operational data to the Data Collection System
		DataResolution	String	High, Medium, Low, etc.	
	SafetyMechanism	NumberOfSensors	Integer	Number	
		ActivationRequirement	String	Manual, Automatic	Required to activate in response to specific conditions

Top-Level System Block	Subsystem Block	Property	Data Type	Input Values	Interfaces
		Barriers	Type	Manual, Automatic	Operates as physical control for access and safety
	CommonDataEnvironment	AccessType	String	Read, Write	Provides and manages access to all subsystems, incorporating data flows and storage functionalities
		UpdateFrequency	String	Real-Time, Hourly, Daily, etc.	Determines the frequency of data updates and synchronisation across the system
		DataIntegrationCapabilities	String	Semantic analysis, Cross-project querying	Facilitates integration, analysis, and retrieval of data, supporting program-level analyses and enabling cross-project insights
		SecurityFeatures	SecurityFeatures	Encryption, Access Control, Hashing	Ensures data integrity, confidentiality, and secure access, protecting sensitive information and system operations
	DataCollectionSystem	DataAggregationCapabilities	String	Data cleaning, Aggregation	Processes raw sensor data for operational use and comprehensive analysis

Internal Block Diagram

Subsystem Block	Internal Components	Ports and Interfaces	Connectors	Function and Role	Data Flows
PivotMechanism	Motor	Control Input Port	From Control System	Powers the pivot mechanism for bridge movement.	Receives: Operational commands from Control System.
	Gear Assembly	Power Input Port	From Motor	Transfers motor power to the pivot joint for movement.	Transfers: Mechanical energy to Pivot Joint.
	Pivot Joint	Mechanical Output Interface	To BridgeDeck	Enables bridge to open/close by allowing rotation.	Sends: Status feedback to Control System.
BridgeDeck	Deck Surface	Structural Monitoring Ports	To Sensor System	Monitors weight distribution across the bridge with integrated sensors.	Sends: Load data and structural integrity metrics to Data Collection System.
	Support Structures	Safety Monitoring Sensors	To Safety Mechanism, To Data Collection System	Monitors the structural health of the bridge, detecting potential risks and maintaining ongoing status reporting.	Sends: Structural health data and emergency alerts to Data Collection System; Initiates safety protocols to Safety Mechanism.
SafetyMechanism	Barriers	Safety Control Input Port	From Control System	Manages access through barrier deployment, ensuring safety.	Receives: Commands for barrier activation/deactivation from Control System.
	Control Module	Independent Control Interface	Direct Link to Control System	Responds to safety alerts, operates independently, communicates with Control System for coordinated actions.	Exchanges: Alerts and status updates with Control System.

Subsystem Block	Internal Components	Ports and Interfaces	Connectors	Function and Role	Data Flows
Common Data Environment	Semantic Data Storage	Data Input/Output Ports	From/To all subsystems	Central repository for storing and managing semantically enriched data, facilitating strategic planning and insights at project and program levels.	Receives and Stores: Data from all subsystems for integration and enrichment.
	Software Tools Integration	Software Tools Data Exchange Port	Connection to various modeling and software tools	Enhances system analysis and operational optimizations by integrating diverse modeling and analytical tools.	Facilitates Exchange: With analytical and calculation tools for enhanced system analysis and decision-making.
Data Collection System	Data Aggregators and Preprocessors	Data Aggregation Ports	From Sensor System; To Control System, To CDE, To Safety System	Acts as the intermediary for processing raw sensor data, preparing it for operational decisions and comprehensive analysis.	Receives: Raw data from Sensor System. Sends: Processed data to Control System, CDE, and Safety System.
SensorSystem	Environmental and Structural Sensors	Data Collection Ports	To Data Collection System	Gathers real-time data on environmental conditions and structural integrity.	Sends: Raw environmental and structural data to Data Collection System.
ControlSystem	Processor	Input/Output Ports	From Data Collection System, To Pivot Mechanism, To Safety Mechanism, To CDE	Analyzes data to guide system operations and ensure safety, supporting both automated and manual operational adjustments.	Receives: Processed data from Data Collection System. Sends: Operational commands to Pivot Mechanism and Safety Mechanism; Submits data to CDE for strategic analysis.

State Machine Diagram

Subsystem Block	States	Transitions
Pivot Mechanism	Initial Node (Operation): The system is in its normal operating state, ready to execute commands.	Operation to Close/Open: Based on commands from the Control System, the system transitions to either the Close or Open states.
	Close (Static): The bridge is fully closed, allowing vehicle and pedestrian traffic. No active movement of the swing mechanism.	Close to Opening: Triggered by a command from the Control System, signaling the start of the bridge opening process.
	Open (Static): The bridge is fully open, allowing passage for vessels. No active movement of the swing mechanism.	Open to Closing: Triggered by the Control System once the passage is clear, signaling the bridge to close.
	Opening/Closing (Dynamic): The bridge is in transition, either opening or closing. This involves active physical movement.	Opening to Open: Completes when the bridge is fully open. Closing to Close: Completes when the bridge is fully closed.
	Malfunction or Emergency Detection (Dynamic): Detection of any malfunction or emergency situation via sensors or monitoring systems.	Detection to Fault Response: Initiates emergency protocols or safety measures.
	Fault or Emergency Respons (Dynamic) e: Active response to malfunctions or emergencies.	Fault Response to Reset System: After resolving the issue, the system prepares to return to normal operations.
	Reset System (Dynamic): Resets the system to return it to the normal operating state after an emergency or fault has been resolved.	Reset to Operation: Restores the system to its initial operational state, ready to resume normal activities.

Sequence Diagram

Sequence	Actor	Action
0	SensorSystem	Detects approaching water traffic and notifies the Data Collection System.
1	DataCollectionSystem	Aggregates and analyses the detection data; sends notification to the Control System.
2	ControlSystem	Initiates the bridge opening protocol based on the signal from the Data Collection System.
3	ControlSystem	Sends 'ActivateBarriers' signal to Safety Mechanism to secure the bridge.
4	SafetyMechanism	Activates barriers in response to the 'ActivateBarriers' signal.
5	ControlSystem	Sends 'OpenBridge' signal to Pivot Mechanism once barriers are confirmed active.

Sequence	Actor	Action
6	PivotMechanism	Begins the opening process upon receiving the 'OpenBridge' signal.
7	SensorSystem	Monitors Pivot Mechanism's movement and structural responses during the opening process.
8	DataCollectionSystem	Processes opening data from Sensor System; sends data to Control System.
9	SensorSystem	Detects that water traffic has passed and notifies the Data Collection System.
10	DataCollectionSystem	Confirms water traffic has passed and notifies Control System that bridge can be closed.
11	ControlSystem	Sends 'CloseBridge' signal to Pivot Mechanism based on confirmation that water traffic has passed.
12	PivotMechanism	Begins the closing process upon receiving the 'CloseBridge' signal.
13	SensorSystem	Continues to monitor Pivot Mechanism's movement and structural responses during the closing process.
14	DataCollectionSystem	Processes closing data from Sensor System; updates Control System.
15	ControlSystem	Sends 'DeactivateBarriers' signal to Safety Mechanism once the bridge is confirmed fully closed.
16	SafetyMechanism	Deactivates barriers, allowing vehicle and pedestrian traffic to resume.
17	ControlSystem	Logs the data into the CDE for future analysis and reporting.
18	DataCollectionSystem	Sends data regarding the Pivot Mechanism's status (mechanical integrity and operational status) to the CDE as demanded by the ControlSystem after bridge closure.

Parametric Diagram

Parameter	Description	Unit	Related System Block	Equation/Constraint	Rationale
θ	Angular Position of Bridge Deck	Degrees (°) or Radians (rad)	PivotMechanism	$\theta = \frac{\Delta t \cdot \omega}{60}$	Describes the rotation of the bridge deck from its closed position.
ω	Rotation speed of Pivot Mechanism	Revolutions per Minute (RPM)	PivotMechanism	Provided by system specs	The speed at which the bridge deck rotates to open or close.
τ	Torque Required by Pivot Mechanism	Newton-meters (Nm)	PivotMechanism	$\tau = I \cdot \alpha$	The torque needed to achieve desired angular acceleration, considering bridge mass and distribution.
I	Mass Moment of Inertia of Bridge Deck	Kilogram Square Meters (kgm ²)	BridgeDeck	$I = \frac{1}{12} m(l^2 + w^2)$	Measures resistance to rotational acceleration based on the bridge's mass and geometry.
α	Angular Acceleration of Bridge Deck	Radians per Second Squared (rad/s ²)	PivotMechanism	$\alpha = \frac{\omega}{\Delta t}$	The rate of change of angular velocity, crucial for controlling bridge movement.
m	Total Mass of Bridge Deck	Tons (t)	BridgeDeck	Calculated or provided by design specs	Overall mass, including the variable deck weight and any additional loads.
L, w	Length and Width of Bridge Deck	Meters (m)	BridgeDeck	Provided by design specs	Dimensions of the bridge deck, essential for calculating the moment of inertia and load distribution.
Δ	Time to Open/Close	Seconds (s)	ControlSystem	Defined by operational requirements	The desired or required time for the bridge to fully open or close, influencing motor selection

Parameter	Description	Unit	Related System Block	Equation/Constraint	Rationale
WearRateSensorOutput	The output from the wear tolerance sensor attached to the pivot mechanism.	Millimeters (mm)	PivotMechanism, SensorSystem	WearToleranceSensorOutput < WearToleranceThreshold	and energy requirements. Ensures the wear of the pivot mechanism remains within acceptable limits.
SensorAlertThreshold	The threshold value at which the sensor output triggers a maintenance alert or other action.	Millimeters (mm)	SensorSystem	SensorAlertThreshold = 0.5	Set based on the wear tolerance specification to ensure alerts are generated before exceeding limits.

Requirement Diagram

Requirement ID	Description	Associated Object	SMART Criteria	RDF/RDFS Ontology	OCL (SysML) Constraint	SHACL (Semantic Technology) Constraint
R1	The bridge deck must support a distributed load of up to 500 kg/m ² to accommodate heavy vehicular traffic.	BridgeDeck	Specific (500 kg/m ²), Measurable (load capacity per square meter), Achievable (based on construction materials and design), Relevant (to usage and safety standards), Time-bound (permanent requirement)	:DesignPhase :contains :TechnicalProcessExample . :TechnicalProcessExample :managesRequirements :ReqManagementSystem . :ReqManagementSystem :hasRequirement :R1 . :R1 :appliesTo :BridgeDeckExample . :BridgeDeckExample rdfs:type :BridgeDeck ; :hasLoadCapacity "500 kg/m ² ".	context BridgeDeck inv: self.loadCapacity >= 500	bridge:BridgeDeck sh:property [sh:path bridge:loadCapacity ; sh:minInclusive 500 ; sh:datatype xsd:decimal ; sh:message "Bridge deck load capacity must be at least 500 kg/m ² ."] ;
R2	The pivot mechanism's components shall have a wear tolerance of 0.5mm to ensure longevity and reduce maintenance frequency.	PivotMechanism	Specific (0.5mm wear tolerance), Measurable (wear tolerance), Achievable (through engineering and material selection), Relevant (to longevity and reduced maintenance frequency), Time-bound (throughout component lifetime)	:DesignPhase :contains :TechnicalProcessExample2 . :TechnicalProcessExample2 :managesRequirements :ReqManagementSystem2 . :ReqManagementSystem2 :hasRequirement :R2 . :R2 :appliesTo :PivotMechanismExample . :PivotMechanismExample rdfs:type :PivotMechanism ; :hasWearTolerance "0.5 mm".	context PivotMechanism inv: self.wearTolerance >= 0.5	pivot:PivotMechanism sh:property [sh:path pivot:wearTolerance ; sh:minInclusive 0.5 ; sh:datatype xsd:decimal ; sh:message "Wear tolerance must be 0.5 mm or greater."] ;

Requirement ID	Description	Associated Object	SMART Criteria	RDF/RDFS Ontology	OCL (SysML) Constraint	SHACL (Semantic Technology) Constraint
R2.1	Derived from R2: The pivot mechanism requires annual maintenance to ensure reliable operation and to prevent wear and tear, accommodating the wear tolerance specification.	PivotMechanism	Specific (annual maintenance), Measurable (maintenance intervals), Achievable (through regular maintenance schedule), Relevant (to ensure reliability, longevity, and adherence to wear tolerance), Time-bound (annually)	:ReqManagementSystem2 :hasDerivedRequirement :R2_1 . :R2_1 :appliesTo :PivotMechanismExample . :PivotMechanismExample :requiresMaintenance "Annually".	This constraint checks if the maintenance interval is within a certain limit, potentially one year. If the maintenance interval is specified in years, using OCL might not be suitable due to the temporal nature. Semantic languages or temporal logic tools could handle this better.	pivot:PivotMechanism sh:property [sh:path pivot:maintenanceInterval ; sh:maxInclusive 1 ; sh:datatype xsd:integer ; sh:message "Maintenance must occur at least annually."] ;
R2.2	The pivot mechanism must be equipped with a sensor to measure wear tolerance, enabling real-time monitoring and adjustments to the maintenance schedule as necessary.	PivotMechanism, SensorSystem	Specific (equipped with a wear tolerance measuring sensor), Measurable (real-time monitoring of wear tolerance levels), Achievable (implementation of sensor technology), Relevant (to maintenance schedule adjustments), Time-bound (continuous monitoring)	:ReqManagementSystem2 :hasMonitoringRequirement :R2_2 . :R2_2 :appliesTo :PivotMechanismExample . :PivotMechanismExample :equippedWith :WearToleranceSensor . :WearToleranceSensor rdf:type :Sensor ; :measures "Wear Tolerance" ; :enables "Real-Time Monitoring" ; :supportsAdjustment :MaintenanceScheduleExample	This constraint involves the presence of a sensor and its status. While SysML can represent the presence of components, expressing status and operational conditions might be better suited for semantic languages or specialised tools. However, SysML diagrams can visually communicate the presence and status of components, aiding stakeholders' understanding.	pivot:PivotMechanism sh:property [sh:path pivot:hasWearToleranceSensor ; sh:hasValue true ; sh:message "Pivot mechanism must be equipped with a wear tolerance sensor."] ; sensor:WearToleranceSensor sh:property [sh:path sensor:isEnabled ; sh:hasValue true ; sh:message "Wear tolerance sensor must be enabled for real-time monitoring."] ;
R2.3	The sensor system must activate emergency protocols if abnormal readings are detected during operation.	SensorSystem, SafetyMechanism, ControlSystem	Specific (Equipped with a wear tolerance measuring sensor), Measurable (Real-time monitoring of wear tolerance levels), Achievable (Implementation of sensor technology), Relevant (To maintenance schedule adjustments), Time-	:DesignPhase :contains :TechnicalProcessExample . :TechnicalProcessExample :managesRequirements :ReqManagementSystem2 . :ReqManagementSystem2 :hasMonitoringRequirement :R2_3 . :R2_3 :appliesTo :SensorSystemExample . :SensorSystemExample rdf:type :SensorSystem ; :requiresActivationOfEmergencyProtocols "if abnormal readings are detected during operation"	context SensorSystemExample inv: self.abnormalReadingsDetected implies self.emergencyProtocolsActivated	sensor:SensorSystemExample sh:property [sh:path sensor:abnormalReadingsDetected ; sh:datatype xsd:boolean ; sh:message "If abnormal readings are detected, emergency protocols must be activated." ; sh:minCount 1 ; sh:maxCount 1 ; sh:severity sh:Violation] ;

Requirement ID	Description	Associated Object	SMART Criteria	RDF/RDFS Ontology	OCL (SysML) Constraint	SHACL (Semantic Technology) Constraint
			bound (Continuous monitoring)			
R3	Maintenance records for the pivot mechanism must be updated following each scheduled maintenance.	PivotMechanism	Specific (updates after maintenance), Measurable (record updates), Achievable, Relevant (to pivot mechanism's operational integrity), Time-bound (after each maintenance activity)	:TechnicalProcessExample3 :managesRequirements :ReqManagementSystem3 . :ReqManagementSystem3 :hasRequirement :R3 . :R3 :appliesTo :PivotMechanismExample . :PivotMechanismExample :MaintenancePerformed :MaintenanceRecordExample . :MaintenanceRecordExample rdf:type :MaintenanceRecord ; :updatedAfter "Each Scheduled Maintenance".	This constraint specifies a temporal relationship between maintenance activities and record updates. Expressing temporal relationships like "after each" might be better suited for semantic languages or temporal logic tools. However, the maintenance process can be visually represented using SysML activity diagrams, aiding stakeholders in understanding the sequence of events.	maintenance:MaintenanceSubsystem sh:property [sh:path maintenance:recordUpdate ; sh:hasValue true ; sh:message "Maintenance records must be updated after each scheduled maintenance."] ;
R4	Safety barriers must be activated before any maintenance activity on the pivot mechanism to ensure the safety of personnel and the public.	SafetyMechanism, ControlSystem, PivotMechanism	Specific (activation before maintenance), Measurable (activation confirmed), Achievable, Relevant (to safety during maintenance), Time-bound (prior to maintenance activity)	:TechnicalProcessExample4 :managesRequirements :ReqManagementSystem4 . :ReqManagementSystem4 :hasRequirement :R4 . :R4 :appliesTo :SafetyMechanismExample . :SafetyMechanismExample rdf:type :SafetyMechanism ; :activation "Before Pivot Mechanism Maintenance".	This constraint involves a temporal relationship between the state of safety barriers and the start of maintenance. Semantic languages or temporal logic tools might handle this better. However, SysML state machine diagrams can visually represent state transitions, helping stakeholders understand safety protocols.	safety:SafetyMechanism sh:property [sh:path safety:barriersState ; sh:equals "active" ; sh:message "Safety barriers must be active before any pivot mechanism maintenance activity begins."] ;
R5	Maintenance personnel and RAMS specialists must collaboratively review CDE data post-maintenance to recommend system improvements.	MaintenanceSubsystem, RAMSSpecialists	Specific (collaborative review), Measurable (improvement recommendations), Achievable, Relevant (to continuous improvement), Time-bound (post-maintenance review)	:TechnicalProcessExample4 :managesRequirements :ReqManagementSystem5 . :ReqManagementSystem5 :hasReviewRequirement :R5 . :R5 :involvesCollaboration "Maintenance Personnel and RAMS Specialists" . :CollaborativeReview :focus "CDE Data Post-Maintenance" ; :aims "System Improvements".	This constraint also involves temporal relationships related to maintenance activities. Semantic languages or temporal logic tools could handle these better. Still, SysML diagrams can visually represent review processes, aiding stakeholders in understanding the sequence of post-maintenance activities.	maintenance:MaintenanceSubsystem sh:property [sh:path maintenance:reviewCompleted ; sh:equals true ; sh:message "Review must be completed after maintenance."] ; sh:property [sh:path maintenance:recommendationsMade ; sh:equals true ; sh:message "Recommendations must be made after maintenance."] ;

Activity Diagram

Step	Activity	Subsystem	Output	Type
1	Detect Approaching Water Traffic	Sensor System	Signal for bridge opening	Activity
2	Data Collection System Processes Signal	Data Collection System	Processed signal data	Activity
3	Determine if bridge can open	Control System	Decision on bridge opening based on current status	Decision Node

Step	Activity	Subsystem	Output	Type
4	Send Condition Data to CDE	Data Collection System	Condition data updated in Semantic CDE	Activity
4	Evaluate Detected Condition	Control System	Decision on bridge opening	Decision Node
5	Send Condition Data to CDE	Control System	Condition data updated in Semantic CDE	Activity
6	Determine Operation Scenario	Control System	Decision on operation scenario	Decision Node
6a	Emergency Detected	Control System	Decision on emergency protocol activation	Activity
6a1	Activate Emergency Protocols	Safety Mechanism Control Module	Emergency protocols activated, notifications sent	Activity
6b	Maintenance Requirement Detected	Control System	Decision on maintenance activation	Activity
6c	Other Problem Detected	Control System	Decision on handling other problems	Activity
6d	Bridge can Open	Control System	Decision on bridge opening	Activity
7	Activate Safety Barriers (if opening)	Safety Mechanism	Barriers activated	Activity
8	Send 'OpenBridge' Signal (if opening)	Control System	Bridge opening initiated	Activity
9	Open Bridge (if opening)	Pivot Mechanism	Bridge deck in open position	Activity
10	Bridge Fully Open	Sensor System and Data Collection System	Confirmation of open position	Activity
11	Is bridge closing required?	Control System	Decision on bridge closing	Decision Node
12	Send 'CloseBridge' Signal (if closing)	Control System	Bridge closing initiated	Activity
13	Close Bridge (if closing)	Pivot Mechanism	Bridge closed, traffic resumed	Activity
14	Sensor System Confirms Bridge Closure	Sensor System and Data Collection System	Confirmation of bridge closure	Activity
15	Data Collection System Processes Closure Confirmation	Data Collection System	Closure confirmation processed	Activity
16	Deactivate Safety Barriers (after closure confirmation)	Safety Mechanism	Barriers deactivated	Activity
17	Bridge Secured and Traffic Resumed	-	Bridge secured, normal traffic flow resumes	Final Node
18	Resume Normal Operations (after problem resolution)	Control System, Safety Mechanism	Emergency protocols deactivated, bridge operations normalized	Activity
19	Update CDE with Post-Operation Summary	Data Collection System, Control System	Comprehensive operational summary and condition data from incident onset to resolution updated in Semantic CDE	Activity

Step	Activity	Subsystem	Output	Type
1	Detect Maintenance Requirement	Maintenance Personnel/Safety Mechanism	Maintenance alert generated	Activity
2	Activate Safety Barriers	Safety Mechanism, Control System	Barriers activated, bridge secured	Activity
3	Perform Maintenance on Pivot System	Maintenance Personnel, Pivot Mechanism	Pivot system maintained	Activity
4	Manual Request for Barrier Deactivation	Maintenance Personnel	Request sent to Control System for barrier deactivation	Activity
5	Confirm Safe Status	Safety Mechanism	Confirms safe status and approves deactivation request	Activity
6	Deactivate Safety Barriers	Control System	Barriers deactivated, bridge reopened for traffic	Activity
7	Bridge Secured and Traffic Resumed	Control System	Bridge secured, normal traffic flow resumes	Final Node
8	Automated Post-Operation Status Update	Data Collection System, Control System	Status of bridge post-maintenance updated in Semantic CDE	Activity
9	Update Maintenance Records in CDE	Maintenance Personnel, Semantic CDE	Maintenance records updated	Activity

Step	Activity	Subsystem	Output	Type
1	Scheduled or Event-Triggered CDE Data Evaluation	Program Managers, Maintenance Personnel	Initiation of data review process	Activity
2	Collaborative Data Review for System Improvement (Incorporating Cross-Project and Asset Data Analysis)	Maintenance Personnel & RAMS Specialists	Recommendations for system improvements	Activity
3	Conduct New RAMS Calculations	RAMS Specialists	Updated RAMS analysis and recommendations	Activity
4	Identify Necessary System Changes	Designers & Engineering Team	Proposed system changes based on RAMS recommendations	Activity

Step	Activity	Subsystem	Output	Type
5	Update SysML Model and Other Documentation	Engineering Team	Revised SysML diagrams and all associated project documentation updated	Activity
6	Plan, Schedule, and Implement System Changes	Maintenance Personnel, Engineering Team, CDE	Combined planning, scheduling, and implementation of changes	Final Node

Use Case Diagram

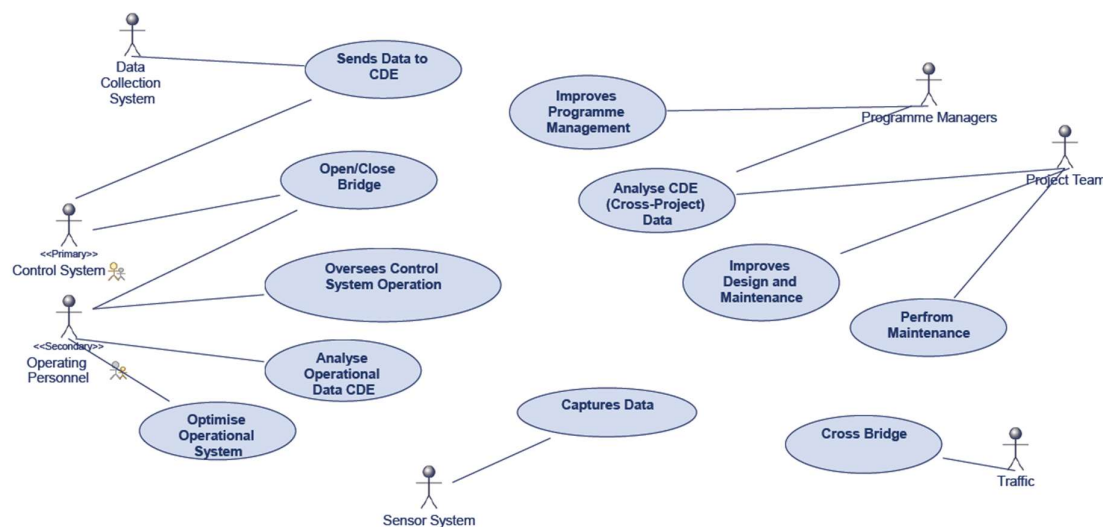
Actor	Use Case	Description
Control System & Operating Personnel	Open Bridge	Initiates the opening of the bridge upon detecting the need, such as for allowing water traffic. Operating personnel oversee and ensure the operation's success.
Control System & Operating Personnel	Close Bridge	Closes the bridge after ensuring the passage is clear, resuming normal traffic. Personnel oversee the operation and address any issues.
Control System & Operating Personnel	Activate/Deactivate Safety Barriers	Engages barriers to secure the bridge for operation and disengages them after operations to resume normal traffic flow. This process is automated but monitored by operating personnel.
Sensor System & Monitoring Personnel	Monitor Bridge Operation	Gathers and analyses data on bridge status and environmental conditions. Operating personnel review and analyse this data to inform decisions and interventions.
Maintenance Personnel	Perform Maintenance	Conducts routine and emergency maintenance to ensure bridge integrity and functionality. Also analyses data from mechanical and structural sensors to plan maintenance activities.
Operating Personnel	Analyse Operational Data	Operating personnel use system and sensor data to optimise bridge operations and maintenance schedules, ensuring efficient and safe bridge functionality for all users.
Maintenance Personnel	Analyse Data for Maintenance	Maintenance personnel analyse data from operations, including mechanical, structural, and operational data, to inform maintenance decisions, improving safety and efficiency.
User (Vehicular and Pedestrian Traffic)	Cross Bridge	Uses the bridge once it's deemed safe, relying on the efficient and safe operation of the system facilitated by both automated and human oversight.
Programme Managers	Prioritise Infrastructure Projects	Programme managers analyse the CDE's operational, maintenance, and user data to prioritise infrastructure projects. This analysis supports strategic planning and resource allocation to address critical needs and enhance bridge functionality.
Maintenance Personnel & RAMS Specialists	Collaborative Data Review for System Improvement	Maintenance personnel and RAMS specialists collaboratively review CDE data post-maintenance to recommend system improvements. This process aims to optimise bridge operations and identify patterns that may indicate the need for maintenance or system adjustments.

D.2 SysML Case Study

Use Case Diagram

The use case diagram, as shown in Fig. D.1, is key a component of SysML within the MBSE framework. This diagram provides a high-level overview of the system's functionalities and the interactions between various actors and the system. In the context of the renovation and replacement programme for movable bridges, it illustrates the roles and responsibilities of different stakeholders and their interactions with the system. The primary purpose of a SysML use case diagram is to describe the system's functional requirements in terms of use cases and the actors involved. It provides a graphical overview that helps stakeholders understand the system's scope and the top-level system requirements. Additionally, it enables discussions about the setup and functionalities of the system for improvements. The diagram serves as a more flexible and easily adaptable form of documentation compared to traditional text documents. The use case diagram enhances understanding by clearly defining the roles and interactions within the system. It allows different disciplines to see how their activities fit into the larger context of the bridge's operation and maintenance. This holistic view is essential for improving coordination and communication among various teams, leading to more efficient and effective project execution.

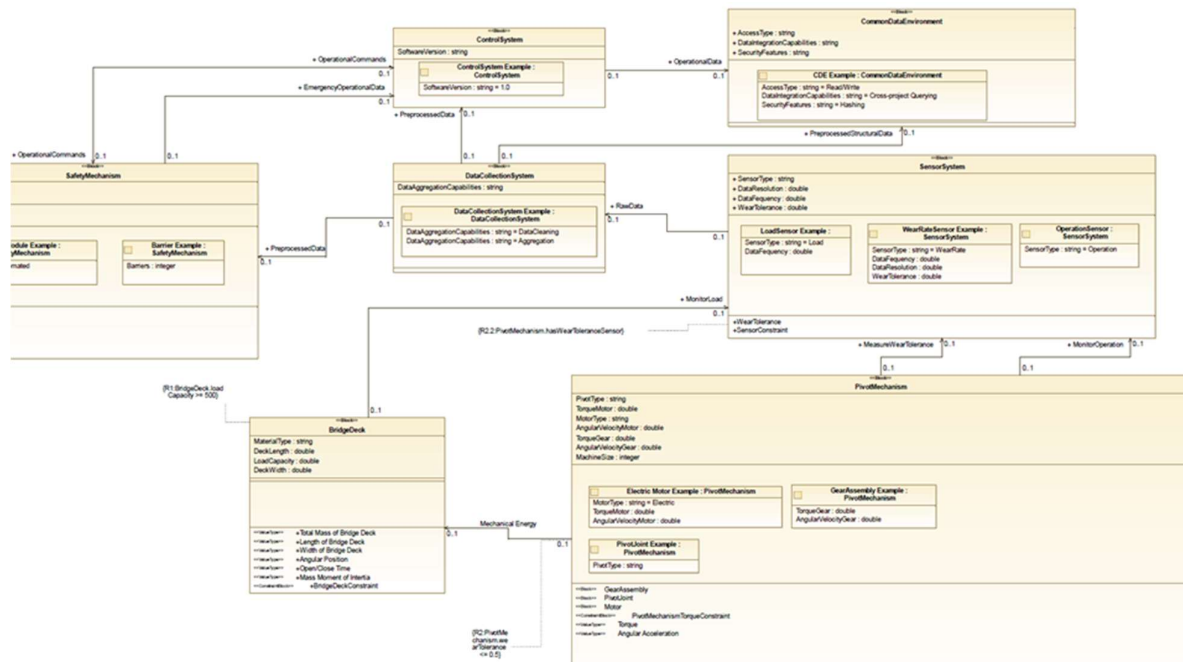
In this use case diagram, actors represent external entities that interact with the system. These include the Control System, which manages the opening and closing of the bridge; Operating Personnel, who oversee the control system's operation and capture data; the Sensor System, which detects conditions and captures operational data; the Project Team, which analyses data and performs maintenance; Programme Managers, who use the data to improve programme management and design; Traffic, representing vehicles and pedestrians that cross the bridge; and the Data Collection System, which captures and sends data to the Common Data Environment. Key use cases in this diagram include Open/Close Bridge, managed by the Control System; Capture Data, performed by the Sensor System; Send Data to CDE, conducted by the Data Collection System; Analyse Operational Data, performed by the Project Team; Perform Maintenance, conducted by the Project Team; Optimise Operational System, an ongoing improvement by the Project Team; and Cross Bridge, which involves interaction with the Traffic actor. This diagram is an example to show how to use the use case diagram in the renovation and replacement programme. The system therefore encompasses the programme management and the movable bridge, integrating both aspects instead of merely applying SysML to the bridge alone.



Appendix D Figure 1 – Use Case Diagram

Block Definition Diagram

The strategic application of Systems Modeling Language SysML within the MBSE framework is further exemplified through the Block Definition Diagram (BDD), see Fig. D.2. This diagram is essential for visualising the placement and interaction of various sensor systems within the architecture of a movable bridge. It offers a comprehensive view of how different components are interconnected, illustrating how these connections support data capture and management through the CDE. Crucially, the alignment between the SysML model and the Semantic CDE is fundamental, as it ensures that data exchange is seamless and adheres to a structured taxonomy. This alignment facilitates the consistent application of data standards across the programme, enhancing the integrity and usability of data across different systems and stakeholders.



Appendix D Figure 2 – Block Definition Diagram

The BDD serves a pivotal role in illustrating the interconnections between the bridge's physical components and the integrated sensor systems. This diagram not only maps out the relationships and data flows between components but also acts as a blueprint for system design, guiding the structuring and integration of sensor systems within the broader infrastructure. As operations become increasingly complex with the integration of automation and advanced sensor technologies, the BDD becomes even more crucial. By clearly depicting these relationships, the BDD facilitates a multidisciplinary understanding of system configuration and operational dependencies, enabling stakeholders to make informed decisions about the design and maintenance of the assets. Moreover, it functions as a dynamic tool that assists project teams in evaluating and refining system interactions to meet evolving operational demands. This adaptability ensures that the sensor systems remain relevant and effective, aligning with the changing requirements of the project. Importantly, the BDD utilises its advantageous use of abstraction to avoid unnecessary complexity, focusing on the most essential and useful level of detail. This strategic approach in determining the abstraction level ensures that the diagram serves as an efficient, practical tool for both designing and understanding the infrastructure system. Additionally, the BDD is instrumental as a communication tool, bridging gaps between different disciplines and enhancing collaborative discussions by providing a visual reference that aligns team perspectives and fosters consensus on system design and operation.

Internal Block Diagram

The Internal Block Diagram (IBD) plays a crucial role in the systems engineering of movable bridges by illustrating how subsystems such as sensors, control systems, and mechanical components like pivot mechanisms are interconnected within the bridge's architecture. This comprehensive depiction ensures seamless interaction among all subsystems, highlighting

crucial pathways and dependencies that are vital for both the initial design phase and sustained operational efficacy. Engineers use the IBD to design an integrated system where components work synergistically, enhancing system integration and coordination.

By detailing the flow of data and control signals, the IBD helps enhance operational efficiency. It supports the effective function of monitoring and automated control systems, allowing for the rapid adjustment and refinement of operations to enhance responsiveness and minimise operational delays. Additionally, the diagram serves as a vital guide for maintenance teams, providing clear visibility into the relationships among components, which aids in quick diagnostics and effective maintenance. This clarity is invaluable for identifying critical interfaces and potential failure points, simplifying maintenance and troubleshooting processes.

For example, in a scenario where a movable bridge experiences unexpected mechanical stress during operation, the IBD can provide immediate visual insights into how the sensors monitoring structural integrity are connected to the central control system. It shows the direct communication paths that alert the control system to initiate preventive measures or to shut down the bridge movement temporarily. This proactive management is critical to preventing potential failures and ensuring the safety and longevity of the bridge infrastructure. Similarly, the IBD is invaluable in scenarios involving environmental stress factors such as high winds or rising water levels, where it details how environmental sensors interface with the control systems to adapt operations dynamically. Furthermore, the diagram aids in managing traffic loads effectively by illustrating how weight sensors trigger system adjustments to prevent overloading. Each of these scenarios benefits from the IBD's ability to map out not only the mechanical and electrical connections but also the operational protocols that govern the system's response to diverse conditions. Thus, the IBD acts as a comprehensive visual tool that supports intricate decision-making processes, enhancing the bridge's operational resilience and responsiveness to any given situation.

As technological advancements or operational requirements evolve, the IBD can be updated to accommodate new integrations or modifications, ensuring these enhancements are seamlessly incorporated without disrupting existing operations. The diagram's role as a powerful communication tool is indispensable, bridging the gap between various disciplines and aligning engineers, project managers, and maintenance staff with a shared understanding of the system's architecture and operational dynamics.

Furthermore, while the BDD establishes the foundational components and their properties, the IBD adds a layer of dynamic interaction, illustrating how these components operate together in real-time. This dynamic perspective is crucial for simulating operational processes and testing potential responses to hypothetical scenarios, providing a functional view that complements the static nature of the BDD. Together, the BDD and IBD offer a comprehensive visual framework that enhances the understanding and management of complex systems.

It is essential for project teams to determine which operational processes are valuable to be detailed in the SysML language, deciding which components to involve and the level of detail necessary for the IBD. This strategic decision-making ensures that the diagrams effectively

support the project's specific needs and objectives, without overcomplicating the model or diluting its focus.

Integrating the IBD into the Semantic CDE further amplifies its utility. This integration maintains all system information in a structured and accessible format that supports robust data management and immediate implementation of changes. Importantly, the use of a consistent semantic CDE taxonomy and terminology is crucial for ensuring that the SysML IBD works in synergy with other models within the framework. The CDE can facilitate changes through data exchanges, such as updating requirements, which in turn can lead to adaptations in the IBD and subsequent system modifications. While the goal is not to achieve full automation between models, using them as separate but complementary tools enhances the systems engineering processes, allowing for a dynamic and responsive management framework. In high-risk or special operational scenarios, such as emergency responses or unusual operational conditions, the IBD is indispensable. It enables teams to quickly comprehend and manage complex interactions and dependencies, facilitating prompt and effective responses to ensure system integrity and safety.

Additionally, the standardised use of SysML within the MBSE framework allows for models like the IBD to be shared across different projects within the programme. The consistent application of a unified semantic CDE taxonomy and terminology ensures that SysML models are understandable by other project teams and asset managers. This interoperability is crucial for leveraging existing models to inform new projects, enabling asset managers to conduct cross-project queries within the CDE. Such queries can reveal insights and solutions applicable to similar assets in different projects, enhancing the efficiency and effectiveness of asset management across the entire programme. Furthermore, it is vital for programme-level guidance to ensure that project teams share their problem-solving strategies and model references through the CDE. This practice promotes a culture of knowledge sharing and collaborative problem-solving, enhancing the overall effectiveness of the programme's systems engineering efforts.

State Machine Diagram

The state machine diagram, see Fig. D.3, provides a standardised representation of the various operational states of a movable bridge and the transitions between these states. It models states such as "Start Point Operation," "Close State," "Opening/Closing State," "Malfunction or Emergency Detection," "Fault or Emergency Response and Reset," and "Open State," allowing for a comprehensive visualisation of the system's dynamic behaviour.

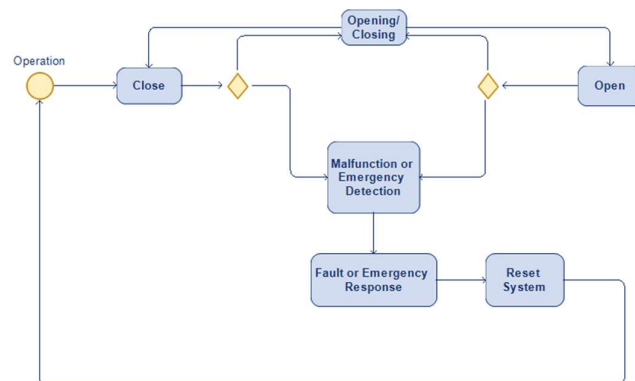
In complex infrastructure projects like movable bridges, understanding the dynamic behaviour of systems is paramount. The state machine diagram offers a clear and structured method to represent operational scenarios and state transitions, providing several key benefits.

The state machine diagram creates a standardised framework for representing the various operational states of movable bridges. This standardisation ensures that all project teams have a consistent understanding of the system's states and transitions, facilitating better coordination and communication. By using a common set of states and transitions, the

diagram helps maintain consistency in how different movable bridge projects are modelled and managed. This is crucial for maintaining data integrity and comparability across the programme's lifecycle.

The state machine diagram provides a visual and intuitive way to understand the operational behaviour of the bridge, making it easier for engineers and project managers to grasp complex interactions and dependencies. By detailing states like "Malfunction or Emergency Detection" and "Fault or Emergency Response and Reset," the diagram helps in planning and analysing various operational scenarios, including emergency situations. This enhances the preparedness and resilience of the system.

The state machine diagram helps identify and optimise transitions between states, ensuring smooth and efficient operations. By explicitly modelling emergency states and responses, it enhances the reliability and safety of bridge operations. This comprehensive approach allows for the design of robust control mechanisms and fail-safe procedures. Practically, the state machine diagram is used to model and manage the behaviour of movable bridges under various conditions, such as transitioning from a "Closed State" to an "Open State," including emergency detection, fault response, and system reset. This detailed modelling supports the planning and execution of renovation and replacement activities, ensuring all potential states and scenarios are accounted for.



Appendix D Figure 3 – State Machine Diagram

Sequence Diagram

The sequence diagram, see Fig. D.4, provides a detailed visualisation of the interactions between various components of the system over time, illustrating how these components collaborate to achieve specific functionalities. It is instrumental in understanding the temporal sequence of events, data exchanges, and control flows that occur during the operation of a movable bridge. By facilitating a clear representation of system interactions, the sequence diagram significantly contributes to multidisciplinary development, ensuring that engineers, project managers, and stakeholders from various fields can collaborate effectively.

In the context of complex infrastructure projects like movable bridges, the sequence diagram is essential for capturing the dynamic interactions between system components. This detailed view of component interactions helps in identifying and optimising communication pathways, ensuring that the bridge operates efficiently and reliably. The sequence diagram creates a

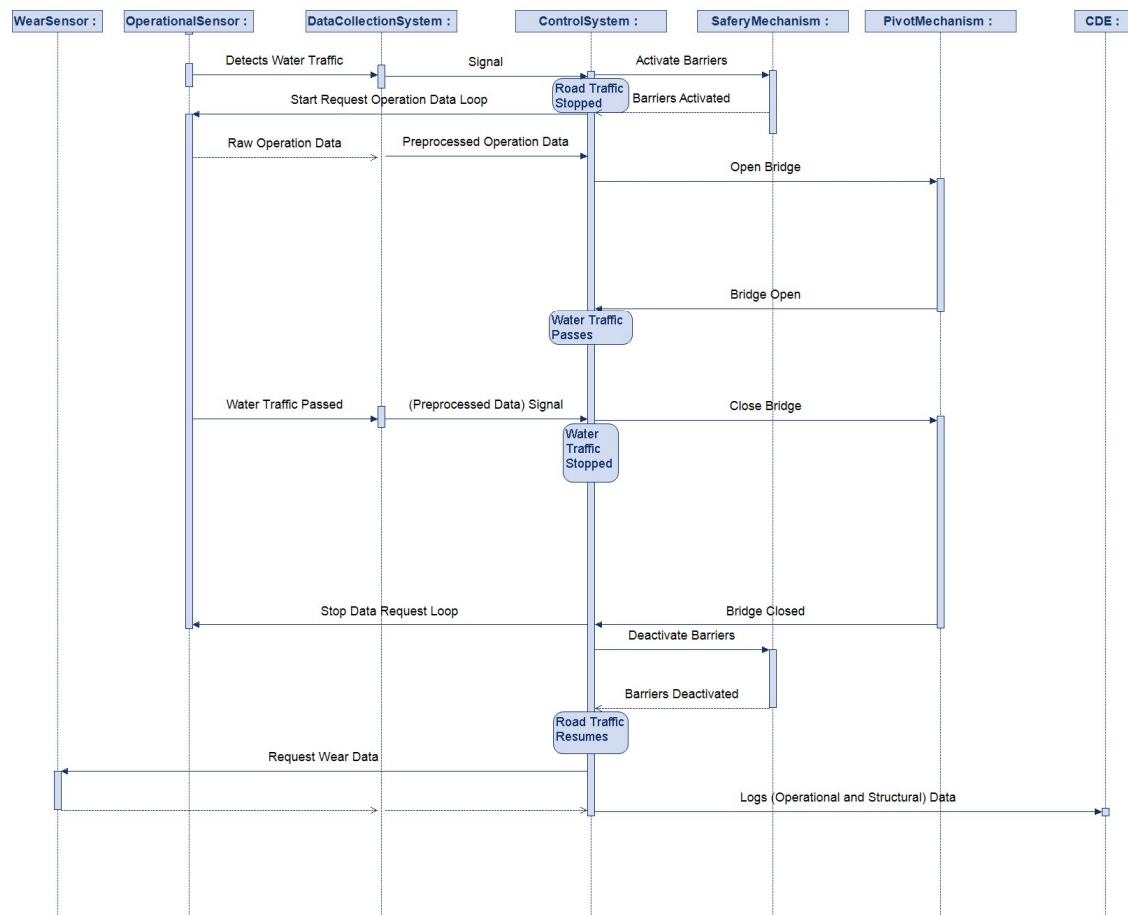
standardised framework for representing the interactions between different components of movable bridges. This standardisation ensures that all project teams have a consistent understanding of the system's interaction sequences, facilitating better coordination and communication. By using a common format for sequence diagrams, the diagram helps maintain consistency in how different movable bridge projects are modelled and managed. This is crucial for maintaining data integrity and comparability across the programme's lifecycle.

The sequence diagram provides a visual and intuitive way to understand the operational interactions of the bridge, making it easier for engineers and project managers to grasp complex communication patterns and dependencies. By detailing interactions such as "Detects Water Traffic," "Activate Barriers," "Open Bridge," and "Log Data," the diagram helps in planning and analysing various operational scenarios, including emergency situations. This enhances the preparedness and resilience of the system. The sequence diagram helps identify and optimise the interactions between components, ensuring smooth and efficient operations. For example, it can highlight potential communication delays or inefficiencies in the command and feedback loops of the bridge's control system. By explicitly modelling interaction sequences, the diagram contributes to the reliability and safety of bridge operations. It ensures that all possible interactions are considered, allowing for the design of robust communication protocols and error-handling mechanisms.

Moreover, the sequence diagram facilitates understanding across different disciplines, enabling engineers, project managers, and stakeholders to quickly comprehend how various components interact. This shared understanding is essential for indicating improvements and making necessary adaptations over time, ensuring the system remains efficient and effective. It also aids in maintaining the consistency of systems throughout the project, allowing teams to quickly analyse and ensure system interactions are consistent and aligned with the overall project objectives. For maintenance teams, the sequence diagram is particularly useful as it provides a clear overview of the system's communication structure, enabling quick diagnostics and efficient troubleshooting. It helps maintenance personnel to understand the flow of commands and data, making it easier to identify and address issues in the system. For long-term planning, the sequence diagram allows project teams to quickly analyse the functioning of different bridges, facilitating necessary adaptations to various operational scenarios and ensuring the system's robustness and flexibility.

In practical terms, the sequence diagram is used to model and manage the interactions of movable bridges during their operation. For instance, in the provided sequence diagram, the process begins with the detection of water traffic by the OperationalSensor, triggering interactions such as starting the data collection loop, activating barriers, opening the bridge, and logging data. Specific operational data, such as sensorID, timestamp, value, and status, are precisely defined within SysML diagrams using Block Definition Diagrams and Internal Block Diagrams. This detailed specification ensures consistent data management and accurate representation, supporting efficient data analysis and integration.

This modelling supports the effective planning and execution of renovation and replacement activities, ensuring all potential interaction scenarios are accounted for. The sequence diagram in SysML is an useful tool for the renovation and replacement programme of movable bridges, providing a standardised and detailed representation of the system’s interaction sequences. By integrating with other SysML diagrams, such as state machine diagrams and block definition diagrams, it ensures a comprehensive and cohesive approach to systems engineering. This approach not only standardises system interaction understanding and data practices across projects but also allows for tailored adaptations to meet specific project needs, maintaining the overarching data structure and integrity. Additionally, it facilitates quick understanding and analysis of the system, enabling stakeholders to see how different components communicate and interact effectively.



Appendix D Figure 4 – Sequence Diagram

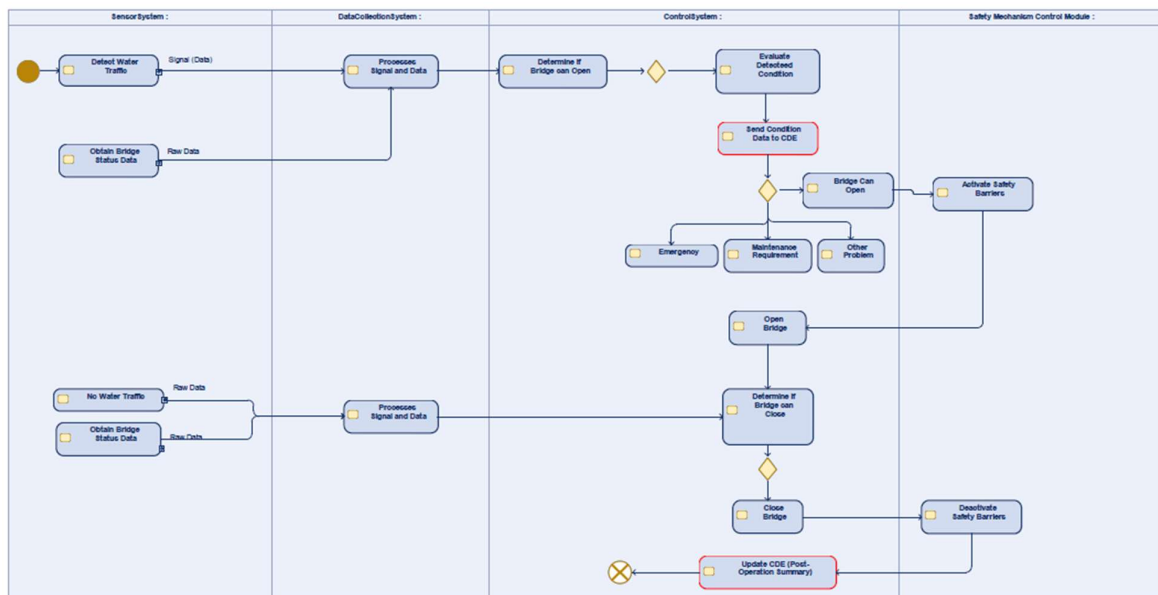
Activity Diagram

Activity diagrams are a crucial element of the SysML within the MBSE framework. They can be used to model the flow of control and data within a system, illustrating the sequence of activities and their interdependencies. In the context of movable bridges, activity diagrams provide a detailed representation of the operational workflows and processes, ensuring

efficient operations. These diagrams enable different disciplines to understand the complex system at various levels, from high-level inter bridge operational sequences to detailed component bridge-specific system interactions. The activity diagrams contribute to a better understanding of the system, especially when the use of data is integrated to control situations and coordinate different bridges simultaneously. This integration helps manage the complex mechatronic systems involved, making the activity diagrams essential for visualising and optimising the interactions within the movable bridge's components and overall system. This comprehensive visualisation facilitates effective communication, coordination, and decision-making across various engineering and project management teams.

This activity diagram in Fig. D.5 focuses on the detection of water traffic and the subsequent actions required to operate the bridge. The process begins with the SensorSystem detecting water traffic and obtaining bridge status data. The DataCollectionSystem processes the signal and data, determining if the bridge can open. The ControlSystem sends condition data to the Common Data Environment and evaluates the detected condition. If the bridge can open, the ControlSystem activates the safety barriers through the Safety Mechanism Control Module and opens the bridge. Post-operation, the bridge is closed, safety barriers are deactivated, and a summary is updated in the CDE.

This detailed workflow ensures that all necessary steps are followed for safe and efficient bridge operation, from traffic detection to data logging, contributing to the reliability and safety of the bridge.

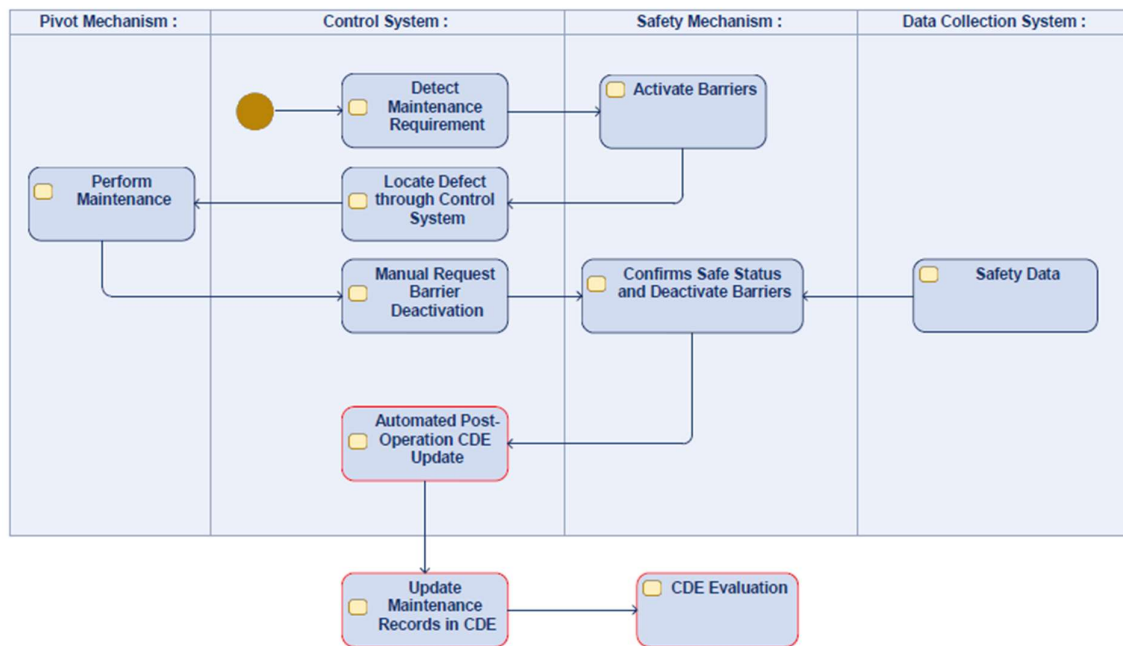


Appendix D Figure 5 – Activity Diagram 1

The second activity diagram, see Fig. D.6, illustrates the maintenance process for the pivot mechanism of the movable bridge. The Control System detects maintenance requirements and locates defects. A manual request for barrier deactivation is made, followed by the activation of safety barriers by the Safety Mechanism to ensure a safe maintenance environment. The Pivot Mechanism performs the necessary maintenance, and post-operation updates are made

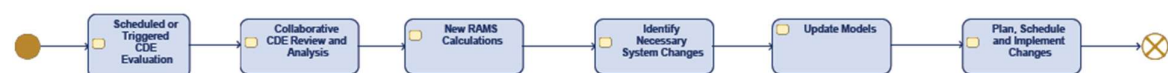
in the CDE. Safety data is collected, maintenance records are updated, and the CDE is evaluated for further analysis.

This diagram highlights the importance of a structured maintenance workflow, ensuring that maintenance activities are performed safely and efficiently, with all actions documented and evaluated.



Appendix D Figure 6 – Activity Diagram 2

The third activity diagram, see Fig. D.7, focuses on the evaluation and updating of the system based on scheduled or triggered events. The process starts with the CDE evaluation, followed by a collaborative review and analysis. New RAMS (Reliability, Availability, Maintainability, and Safety) calculations are performed, and necessary system changes are identified. Models are updated, and changes are planned, scheduled, and implemented. This diagram emphasises the continuous improvement of the system, ensuring that it remains up-to-date with the latest evaluations and calculations, contributing to the overall integrity and reliability of the bridge operations. Additionally, this diagram illustrates the standardised workflow of a socio-technical procedure within the system, demonstrating how human and technical aspects interact and complement each other through SysML.



Appendix D Figure 7 – Activity Diagram 3

Activity diagrams clearly document and communicate workflows, making it easier to train new personnel, troubleshoot issues, and implement process improvements. They support maintenance teams by offering a visual overview of the system's operational sequences, facilitating quick diagnostics and efficient troubleshooting. Unlike sequence diagrams, which detail interactions between components over time, activity diagrams focus on the flow of

activities, highlighting decision points and parallel processes. This distinction makes them particularly useful for evaluating the efficiency and effectiveness of the system's operational procedures. Additionally, they can inform different disciplines working on the bridge, enabling efficient and effective training of personnel. They facilitate discussions about the workings of the bridge, allowing for continuous improvement and quick analysis to identify opportunities for enhancement.

Moreover, activity diagrams have the additional value of visually demonstrating how processes are interconnected or interwoven, something that can be challenging to convey in textual documents. This visual representation helps in understanding the complex relationships and dependencies within the system, making it easier to grasp the overall process flow and identify potential areas for optimisation.

For long-term planning, activity diagrams allow project teams to swiftly analyse the functioning of different bridges, facilitating necessary adaptations to various operational scenarios and ensuring the system's robustness and flexibility. They provide a clear visualisation of the operational flow, making it easier to assess the need for changes or additions to the system. This capability also enables teams to observe differences between various bridges, identifying possibilities for standardising systems across different assets and situations, thereby improving programme management.

Requirement and Parametric Diagram

SysML parametric diagrams are specialised internal block diagrams that focus on modelling and analysing mathematical relationships and constraints within a system. They use constraint blocks to represent equations and relationships between system parameters, allowing for detailed engineering analysis and performance evaluations. These diagrams illustrate mathematical relationships among system components and define constraints and equations that govern the system's behaviour, such as performance, reliability, and other physical properties.

For example, requirements such as R1 (Requirement): `BridgeDeck.loadCapacity >= 500`, R2.2: `PivotMechanism.hasWearToleranceSensor`, and R2: `PivotMechanism.wearTolerance <= 0.5` can be translated into parametric diagrams. These requirements define specific constraints and performance criteria that must be met by the system. By incorporating these requirements into parametric diagrams, engineers can ensure that the system design adheres to these critical parameters, providing a clear and quantitative basis for evaluating system performance.

Additionally, parametric diagrams can be used to model and analyse different scenarios by defining constraints and relationships for various conditions. Different load conditions or environmental states can be represented by setting conditions in the parametric diagrams and incorporating these into the equations. This helps in evaluating how the system performs under different scenarios, ensuring that all possible conditions are considered and managed effectively.

Similarly, requirement diagrams in SysML provide a mechanism to capture, analyse, and manage requirements. These diagrams show the relationships between requirements, other

model elements, and test cases. They help ensure that all system requirements are accounted for and traced throughout the design and development process. It is possible to load these requirements into the SysML software; however, it is important to select the right requirements to include in the diagrams to verify and show traceability. By integrating requirements with other SysML diagrams, teams can maintain consistency and traceability, ensuring that all design elements meet specified requirements.

Thus, some requirements can already be verified at a higher abstract level through SysML, while deeper verification can be performed using specialised tools such as mCRL2. This layered approach ensures that initial validation and verification can be conducted efficiently at a high level, with more detailed analysis reserved for later stages or specific critical requirements.

SysML is also effective for validation at a high abstract level. By creating visual models that represent the system's requirements and behaviours, stakeholders can validate that the system meets its intended goals and functions as expected. This high-level validation is crucial for ensuring that the system design aligns with stakeholder needs before delving into more detailed design and verification processes.

While SysML is highly effective for communication and ensuring that all stakeholders have a common understanding of the system's requirements and constraints, it is not the best tool for formal verification. For formal verification, specialised tools such as mCRL2 are more appropriate. However, SysML can still support formal verification efforts by clearly documenting requirements and constraints. This documentation can then be used to support and explain decisions in the system, ensuring that everyone understands the limits and conditions defined by the requirements.

Both parametric and requirement diagrams play crucial roles in system engineering. Parametric diagrams focus on the quantitative aspects of system behaviour, ensuring that the system performs as expected under various conditions. Requirement diagrams ensure that all stakeholder requirements are captured and satisfied, providing a comprehensive view of system needs and constraints.

By combining these diagrams, engineers can achieve a holistic understanding of both the functional and performance aspects of the system, ensuring that the system is not only built to specifications but also optimised for performance and reliability. This integrated approach enhances the robustness of the system design and supports continuous improvement throughout the system's lifecycle. Maintaining the right level of abstraction in SysML is important to avoid delving too deeply into details, which can diminish the tool's effectiveness.

Appendix E: Qualitative Evaluation of MBSE Framework

E.1 Assessment of MBSE against Needs and Key Quality Metrics

This section examines how MBSE aligns with core project and programme requirements using a structured evaluation based on key quality metrics (KQMs). These metrics are divided into three categories: Technical Metrics (collaboration, adaptability, accuracy, and traceability), Organisational and Sector-Wide Metrics (organisational readiness, leadership support, and collaboration within the sector), Strategic and Long-term Metrics (standardisation, user satisfaction, and financial viability).

E.1.1 Technical Metrics

Collaboration and Communication

An application of Linked Data and Semantic Technologies significantly improves interdisciplinary collaboration and communication by enabling seamless data exchange between different engineering disciplines. Unlike fully document-based Systems Engineering, this approach allows disciplines to easily share data and information with timestamps and cryptographic links to specific decision-makers, ensuring transparency in design changes and improvements.

The goal of this MBSE setup is not to replace document-based systems engineering entirely but to enhance data processing efficiency for both programme members and machine-readable systems at project and programme levels. While contextual documentation remains essential for project teams, MBSE accelerates data exchange and processing, reducing delays caused by excessive document handling.

During project execution, teams progressively transition from linked data models to final documentation, ensuring flexibility. Rather than repeatedly producing static documents, teams can modify information dynamically through the model, improving collaboration across disciplines. On a programme level, this approach strengthens the integration of knowledge from different projects, creating a more connected and data-driven improvement cycle instead of treating projects as isolated entities.

Over time, the Linked Data model can also be leveraged to automate interoperability between different tools and systems, further improving efficiency. Even at early stages, simply using the model to input and structure data enhances collaboration. Additionally, all project and programme members can access data and information through queries, allowing accumulated data to be analysed or specific information to be retrieved as needed. Through queries, disciplines can also identify who made the latest requirement update and trace its origin, enabling direct communication with the responsible individual. This reduces the dependency

on systems engineers as intermediaries and encourages direct engagement among project team members, improving efficiency and reducing unnecessary steps in the workflow.

Flexibility and Adaptability

The ability to efficiently manage design changes and evolving requirements is a key strength of MBSE. Traditional document-based systems engineering (DBSE) struggles with adaptability, as modifying requirements often requires extensive document revisions, which increases the risk of inconsistencies and miscommunication between stakeholders. MBSE, by contrast, enables flexible system updates by leveraging Linked Data and a Semantic Common Data Environment (CDE).

A case study demonstrates how changes in requirements, when connected to a requirement management system, are automatically reflected in the Semantic CDE. This means that once a requirement is updated, it is instantly linked to associated components, allowing project teams to view and analyse the direct impact of the change without additional manual steps. In a DBSE approach, or when using a standalone requirements management tool, multiple additional steps would be necessary to manually propagate changes across disciplines. With MBSE, the project team can immediately see the follow-up impact of a requirement change within the CDE, facilitating quicker decision-making.

The Linked Data model ensures that human and machine-readable data and information are managed in a way that can be exploited throughout the entire lifecycle of the project. During the maintenance stage, teams can trace back decisions made during the design phase, identifying the rationale behind changes and the individuals responsible.

As long as project teams consistently adhere to defined ontologies and a Reference Data Library, the system architecture remains consistent, adaptable and dynamic. Changes within the CDE can occur without causing workflow disruptions, provided that relevant disciplines actively follow updates relevant to their domain. By combining the knowledge embedded in the Linked Data model with the expertise of project teams, MBSE enhances both technical decision-making and organisational adaptability.

Error Reduction and Accuracy

The MBSE framework supports error reduction by tackling root causes such as design errors, omissions, rework, and miscommunication. The Semantic Common Data Environment (CDE) acts as a central repository where project teams can access and query stored information and data, enabling better design coordination and reducing reliance solely on systems engineers. By providing access to updated and accurate information, the CDE helps mitigate errors that lead to variations, as observed in studies showing significant reductions in project variations through improved coordination and communication.

A major challenge in infrastructure projects is the interpretation of requirements, often resulting in discrepancies between specification and implementation. The Semantic CDE addresses this by enabling teams to log significant errors and lessons learned, creating a feedback loop for continuous improvement. Systems engineers can access previous similar

projects to analyse how requirements were made unambiguous, improving standardisation and reducing errors. The CDE also serves as a management tool, facilitating structured reviews and ensuring design checks are conducted by registering them with an audit trail.

By integrating statical, functional, and behavioural models, the CDE ensures consistency across disciplines, improving risk management and reducing contradictions. The Semantic CDE also enhances risk management by providing insights into known unknowns and unknown known risks. This is achieved by offering interdisciplinary and inter-project access to data and information, allowing teams to better anticipate and mitigate potential risks. Information from these models is stored and retrievable through queries, enabling teams to efficiently access validated design data and avoid redundant rework.

The Semantic CDE further enables the realisation of a Reference Data Library (RDL) and facilitates the structured use of ontologies to standardise data across disciplines. By aligning information models, ensuring consistency in terminology, and supporting structured data management, the RDL improves traceability and interoperability. This consistency in systems engineering information storage across projects accelerates project delivery by reducing errors, avoiding misalignment between disciplines, and minimising time spent on data consolidation.

Furthermore, the Semantic CDE enhances information flow between disciplines, addressing gaps in traditional design error management approaches. Teams can track changes, review rationales, and ensure effective communication across all project phases. Over time, automated verification capabilities could be implemented to further streamline compliance checks and reduce manual errors.

Traceability

Traceability within MBSE ensures that requirements, design changes, and project updates are consistently tracked across all stages of development. Unlike DBSE, where tracking modifications relies on manually updated documents, MBSE leverages a Semantic CDE to maintain a structured, centralised record of all changes, reducing the risk of inconsistencies and loss of information. The CDE enables a machine-readable system, allowing users to query specific information directly, which is not possible in traditional document-based approaches. Additionally, the connections between components are clearer and more unequivocal, eliminating the ambiguity often present in text-based relationships. The application of audit trails and cryptographic techniques within the CDE further ensures that records remain unchangeable and traceable.

A key advantage of MBSE is its ability to track changes over the lifecycle – such as a load capacity requirement change or a safety standard update – across all project stages. In DBSE, verifying whether all disciplines have incorporated a change often requires extensive cross-referencing between documents and stakeholder communication. In contrast, the Semantic CDE centralises the process by replacing documentation-based references with a semantic model, which provides a single source of truth and central visibility. Since the model is machine-readable, it enables software applications to provide automated notifications,

ensuring that all relevant stakeholders are promptly informed of updates and changes. This improves traceability and reduces the risk of overlooked modifications.

MBSE supports end-to-end traceability (Digital Thread) by integrating requirements, design decisions, and implementation details within a single structured model. The Semantic CDE enables inter-tool data exchange by storing data and information in a structured way, allowing traceability in tools that do not inherently support it. Ontologies and the Reference Data Library (RDL) ensure standardisation across systems and projects, enabling all stakeholders to work with consistent and clearly defined relationships. This consistency not only improves the quality of design outputs but also accelerates project delivery.

Additionally, the CDE ensures that traceability extends beyond project execution to long-term asset management. By maintaining a digital record of decisions, justifications, and updates, project teams and asset owners can retrieve historical data, verify compliance with original requirements, and make informed decisions about future modifications or maintenance activities. This integration supports proactive risk management by allowing potential conflicts or non-compliance issues to be detected early. Moreover, the traceability within the CDE informs future upgrades, redesigns, and lifecycle decisions, strengthening programme governance and long-term sustainability.

E.1.2 Organisational and Sector-Wide Metrics

Organisational Readiness and Culture

The successful adoption of MBSE within an organisation requires an assessment of the current readiness and cultural adaptability on the work floor. Shifting from traditional systems engineering to MBSE is not just a technological transition but a fundamental change in how teams collaborate, share knowledge, and contribute to programme-wide improvements. To create support for MBSE and the Semantic CDE, it is essential to raise awareness among project teams about why this transformation is necessary and how it improves programme governance. Without a clear understanding of its purpose and benefits, resistance to change may hinder adoption.

A key factor in readiness is motivation and willingness to progress. Organisations must cultivate a collective drive to embrace innovation, ensuring that MBSE is seen as an enabler rather than a disruption. While MBSE can support predictive projects, it thrives in incremental and iterative approaches where flexibility and continuous learning are prioritised. Encouraging experimental projects within selected initiatives allows organisations to refine their MBSE practices before broader implementation. This requires allocating resources to test new methodologies without forcing immediate sector-wide adoption.

Currently, resistance to change is prevalent in the infrastructure industry, but with increasing complexity in renovation programmes and asset management, delayed adoption will result in greater setbacks in the future. A significant cultural shift is needed to transition from isolated project thinking to a programme-based mindset, where information, data, and knowledge are shared across projects to improve long-term infrastructure outcomes. Instead of treating

projects as standalone efforts, organisations must see them as interconnected contributions to a broader programme vision.

This transition also leads to the creation of new roles and job specialisations, such as data managers and ICT-related roles. Combining these roles with general knowledge about the infrastructure sector will be valuable for ensuring the structured management of information within organisations and enabling the successful integration of MBSE practices. Furthermore, it is crucial that organisations position themselves as pioneers in MBSE methods to keep up with rapid technological changes and remain competitive. Failing to adapt may leave organisations at a disadvantage as the industry evolves.

Management and Leadership Support

The successful adoption of MBSE hinges on strong and committed management support. Leaders play a critical role in driving the transition by allocating resources, setting strategic priorities, and fostering a vision for innovation. Without clear leadership and sufficient resource allocation, efforts to adopt MBSE often fall short, leaving organisations reactive to market changes rather than proactive.

Currently, not all organisations prioritise MBSE adoption equally. Some opt to follow the market trends, which risks falling behind as complexity in infrastructure management and renovation programmes increases. In contrast, organisations that position themselves as pioneers in MBSE innovation require leadership with the foresight to take initiatives, allocate budgets for development, and enable experimentation with new methods. This is particularly true for the Renovation and Replacement Programme, where strong initiatives must come from programme managers and asset owners to ensure sufficient resources are allocated for piloting MBSE methods, such as implementing a Semantic CDE.

To institutionalise MBSE adoption, contractual mechanisms can be established. Contracts should outline specific efforts and deliverables related to the development of a Semantic CDE or other MBSE applications, ensuring accountability and alignment with programme objectives. Additionally, during the tendering phase, organisations can evaluate potential contractors based on their capability to implement MBSE and contribute to programme-level improvements. By selecting contractors with proven expertise in MBSE and Semantic CDE development, programme managers can ensure that projects not only meet their immediate goals but also contribute to the broader improvement of the programme.

To further enhance the success of programme ICT applications, establishing a consortium can be a critical step. Such a consortium would bring together programme managers, asset owners, and other stakeholders to collaborate on the development and application of MBSE methods at both the project and programme levels. The consortium would take responsibility for developing and maintaining the Semantic CDE, ensuring that the structure can store data and information indefinitely, even if specific software providers disappear. This independent approach ensures long-term accessibility and reliability of programme data. Additionally, the consortium could focus on fostering interoperability through partnerships with software

providers and serve as a centralised knowledge hub by facilitating collaboration, training, and capacity-building across programme members.

Leadership must also encourage cross-disciplinary collaboration and foster a culture of innovation to address potential resistance to change. By clearly communicating the long-term benefits of MBSE and ensuring sufficient resources, management can drive the transition forward. Strong management commitment is not only essential for project-level success but also for achieving the overarching goals of programme improvement and modernisation.

Sector- Wide Collaboration and Model Sharing

Sector-wide collaboration and model sharing are essential for the Renovation and Replacement Programme. This collaborative approach is particularly critical in infrastructure renovation and replacement, where the complexity and interdependencies of systems require efficient information flow between project stages, individual projects, and programme-level management. To foster sector-wide collaboration, it is essential that organisations look beyond the boundaries of individual projects and actively contribute to the broader programme by sharing information. MBSE, supported by a Semantic CDE, provides the interoperability required to exchange information, models, and data across different organisations, disciplines, and software platforms. This capability allows stakeholders to access and share information directly through the model, improving coordination and alignment. The Semantic CDE acts as the glue between various sector-wide collaboration initiatives, bringing them together into a cohesive ecosystem that enhances collective progress. These initiatives are essential for building a culture of knowledge sharing and collaborative problem-solving across the sector. Furthermore, this approach is software-independent, ensuring that the framework can be developed and maintained without reliance on a single software provider, promoting long-term sustainability and flexibility. However, for this to be successful, certain conditions must be in place, such as the adoption of standardised ontologies, clear protocols for data exchange, and a shared mindset that recognises the value of information sharing for overall programme success.

A key advantage of MBSE is its ability to integrate data from various tools and systems, creating a unified environment where stakeholders can access comprehensive information with greater context than is often available in separate tools. Beyond enabling inter-tool data exchange, the Semantic CDE serves as a central repository for data and supplementary information, offering programme teams working on different projects a shared platform that enhances collaboration and decision-making. This centralised structure ensures that relevant data is easily accessible, reducing reliance on fragmented systems and enabling a more coherent understanding of project and programme relationships. By promoting a culture of information sharing, the Semantic CDE allows stakeholders to contribute to and retrieve data, breaking down silos and fostering collective expertise. Organisations can collaborate more effectively, leveraging each other's insights to address common challenges. Additionally, the Semantic CDE serves as a digital representation of the asset, which must be maintained and passed on as the asset evolves. Asset owners play a crucial role in ensuring that the Semantic

CDE is shared between different teams involved in renovation, replacement, and maintenance activities, ensuring continuity and informed decision-making throughout the asset lifecycle.

Establishing industry standards for collaboration, model, and data sharing is crucial for ensuring interoperability across projects. Standardised data formats, shared ontologies, and agreed-upon communication protocols enable different organisations to work together without compatibility issues. Ensuring data security and intellectual property protection is essential when sharing sensitive information between organisations. The Semantic CDE must include robust security measures, such as access controls, encryption, and audit trails, to safeguard data integrity and restrict access to authorised users. Clear agreements on data ownership and usage rights further help to maintain trust and encourage open collaboration.

Crucially, this data structure also lays the foundation for future advancements in technology. By storing data in a structured, interoperable format, the Semantic CDE enables the application of emerging technologies, such as machine learning and artificial intelligence, to process and analyse data. This forward-looking approach ensures that the infrastructure sector remains adaptable, improving both current project outcomes and long-term asset management capabilities.

E.1.3 Strategic and Long-term Metrics

Strategic Alignment and Standardisation

MBSE plays a crucial role in aligning infrastructure organisations with their long-term strategic goals, including innovation, risk reduction, and sustainability. By integrating a Semantic CDE into infrastructure projects, organisations can standardise data management, enhance collaboration, and improve decision-making, ensuring that their infrastructure development is both future-oriented and sustainable. This alignment is particularly critical in the Renovation and Replacement Programme, where the efficient management of ageing assets requires a forward-looking approach that supports long-term performance and resilience.

A key advantage of MBSE is its ability to drive innovation by enabling data-driven decision-making and facilitating the integration of emerging technologies, such as machine learning and digital twins. By storing structured data within the Semantic CDE, organisations can analyse data – such as performance trends, maintenance needs, and system behaviours – to optimise asset management strategies and enhance both asset operational efficiency and long-term programme sustainability and efficiency.

MBSE contributes to risk reduction by improving the accuracy and consistency of project data. The Semantic CDE acts as a single source of truth, reducing the likelihood of errors caused by miscommunication or outdated information. By providing access to data from current and past projects, teams can learn from previous challenges and apply those lessons to improve processes, reducing the risk of design errors and ensuring reliable project outcomes. Additionally, the CDE supports the application of RAMS (Reliability, Availability, Maintainability, and Safety) principles by enabling teams to analyse performance data, predict potential failures, and ensure compliance with safety and reliability standards. Tracking

changes through an audit trail further enhances transparency and accountability throughout the project lifecycle.

Preventing vendor lock-in is another strategic advantage of MBSE. By using a software-independent approach based on open standards and shared ontologies, organisations avoid reliance on proprietary tools, ensuring long-term accessibility and interoperability as software platforms evolve. This flexibility safeguards the value of data stored within the Semantic CDE, supporting ongoing collaboration and data reuse across different systems and technologies.

Promoting standardisation in systems engineering is essential for increasing the capacity and efficiency of renovation and replacement projects. By using shared design models, standardised processes, and a Reference Data Library (RDL), organisations can ensure consistent application of components, terms, and data definitions across projects. This standardised framework enhances the reusability of data, models, and components, ensuring consistency within the programme. The Semantic CDE further supports this by ensuring that data is reusable across different projects and at various project stages, from initial design and construction to maintenance and long-term asset management. This continuity allows insights and knowledge from one project to be applied to future projects, creating a cumulative improvement cycle.

User Satisfaction and Experience

MBSE plays a vital role in improving the experience and satisfaction of those who interact with infrastructure assets, including project teams, programme managers, operators, and maintenance teams. By leveraging a Semantic CDE, MBSE ensures that infrastructure systems are designed, constructed, and maintained with greater accuracy, consistency, and reliability, operational efficiency, and long-term performance. This leads to increased trust in infrastructure assets and improved satisfaction levels among stakeholders.

For **operators**, MBSE provides access to structured data related to system performance, maintenance schedules, and operational parameters, reducing the likelihood of unexpected issues and improving operations. By integrating RAMS principles into system design and management, MBSE helps ensure that infrastructure assets are reliable, easy to maintain, and safe to operate. The Semantic CDE supports this by storing structured data and information that can be used for RAMS calculations, performance monitoring, and trend analysis, including the application of machine learning techniques for predictive maintenance and anomaly detection. For example, reliability assessments can be performed using historical failure rates stored in the CDE, while availability calculations can leverage real-time operational data to increase uptime. Maintainability is improved by tracking past maintenance actions, enabling better preventive planning and informing design improvements based on real-world performance data. Safety enhancements are achieved through the analysis of stored risk assessments and incident reports.

Compared to DBSE, where such analyses require manual data collection from fragmented reports, linked-data MBSE enables centralised and automated access to relevant data,

significantly improving decision-making. For example, operators can leverage stored data and insights from standardised bridge operations to continuously refine control systems, enhancing performance and efficiency based on past operational experiences.

For **maintenance teams**, the Semantic CDE acts as a comprehensive digital record of system components, design specifications, and maintenance history. This centralised access to accurate, information enhances problem solving, reduces maintenance time, and minimises the risk of errors caused by outdated documentation. Additionally, all maintenance-related information, including maintenance schedules, is centrally accessible within the linked data model, allowing for optimised maintenance planning and scheduling. By tracking historical performance data, maintenance teams can identify recurring issues, optimise preventive maintenance schedules, and extend the lifespan of infrastructure assets, improving both performance and cost-efficiency.

In DBSE, maintenance records are often scattered across different files, requiring manual effort to retrieve relevant information. With MBSE, maintenance teams can instantly query the latest system configurations, retrieve previous maintenance records, and assess component health. Additionally, they can access maintenance records and problem findings from other bridges, allowing them to identify recurring issues, compare failure patterns, and apply lessons learned. This approach reduces errors and allows teams to respond to issues faster, ultimately improving infrastructure availability and reliability.

For **project teams**, MBSE facilitates cross-disciplinary collaboration by providing a shared platform where different engineering disciplines can access, share, and integrate design data. Through the Semantic CDE, teams can query project-specific and cross-project data, gaining insights from previous projects to improve current designs and processes. This interconnected approach enhances communication between disciplines, reduces the risk of design conflicts, and fosters a collaborative environment where teams can leverage collective expertise.

By using a standardised ontology, including predefined breakdown structures and a Reference Data Library (RDL), project teams can avoid repetitive rework and inconsistencies that often arise when starting from scratch with each new project. This standardisation ensures that core components, terms, and relationships are consistently applied across different projects, improving design efficiency and reducing the time required to develop new systems.

Additionally, the Semantic CDE improves interconnectivity by allowing teams to attach more contextual information and structured data directly to system components, enhancing traceability and searchability within the model. This enables engineers to efficiently retrieve specific, relevant information linked to components, such as requirement justifications, risk assessments, past design decisions, or maintenance records. As a result, systems engineering capabilities are significantly enhanced, allowing teams to navigate complex models more effectively, track dependencies, and ensure consistency throughout the project lifecycle.

Moreover, the interconnectivity between different models within a single Semantic CDE model enables impact analyses by allowing teams to assess how changes in one part of the system affect related components across multiple disciplines. This capability ensures that

modifications, whether in requirements, functional models, or structural designs, can be evaluated holistically, reducing unintended consequences and improving decision-making throughout the engineering process.

Under DBSE, design changes and interdisciplinary coordination require manual document updates, meetings, and email exchanges, increasing the likelihood of miscommunication and delays. In contrast, the Semantic CDE ensures that changes are immediately and centrally visible to all disciplines, allowing teams to adapt efficiently while improving traceability, supporting impact analyses, and preventing outdated information from circulating within the organisation.

For **programme managers**, the Semantic CDE offers a comprehensive overview of project performance and infrastructure condition, enabling them to monitor current asset performance, track programme-wide progress, and make informed decisions. By accessing cross-project data, programme managers can assess the overall health of the programme, ensure consistency across projects, and strengthen governance by leveraging structured, interlinked data. Through the interconnected data and information available within the Semantic CDE, programme managers can evaluate past actions, build programme-wide knowledge, and refine strategies in iterative cycles to enhance future decision-making.

Additionally, at the programme level, the Semantic CDE allows managers to determine which bridges or assets should be prioritised for renovation or replacement based on chosen factors derived from data analysis. The availability of structured, inter-project information enhances governance capabilities by providing insights into resource allocation, risk assessments, and compliance with overarching policies. This ability to process and analyse infrastructure data at multiple scales ensures that renovation and replacement decisions are data-driven and aligned with strategic programme objectives.

In DBSE, programme managers must manually compile reports from various projects to extract relevant insights, leading to delays in strategic decision-making. MBSE eliminates this inefficiency by automating data aggregation, ensuring that programme managers can evaluate the current performance of infrastructure assets, track key programme metrics, and prioritise projects based on objective, real-time indicators.

Essential Factors for Adoption

A user-friendly front-end interface is essential to ensure that all stakeholders can effectively interact with the Semantic CDE. Developing an intuitive interface that aligns with the needs of different user groups enhances usability and encourages engagement. By involving users in the interface design process, organisations can ensure that the system is accessible, easy to navigate, and tailored to the specific workflows of each discipline, maximising both efficiency and satisfaction.

The adoption of advanced technologies like MBSE and the Semantic CDE does not necessarily reduce the overall workload within infrastructure projects. Instead, it shifts the

nature of work, creating new roles within project teams, such as data managers, CDE specialists (programmers), and digital integration coordinators, ensuring interoperability, and maintaining the digital infrastructure. Technological advancements do not always result in reduced workload, but rather enable achieving the desired results of the programme, ensuring that projects are executed with higher precision, efficiency, and long-term sustainability.

The Role of a Consortium in Sustaining Engagement

Continuous engagement with stakeholders, including project teams, programme managers, operators, and maintenance teams, is essential to maintaining high levels of satisfaction and ensuring that the Semantic CDE meets evolving needs. By gathering feedback throughout the design, construction, and operational phases, organisations can identify areas for improvement and refine system models to better align with user requirements. The Semantic CDE facilitates this process by providing a platform for capturing, structuring, and analysing feedback, enabling a data-driven approach to continuous improvement.

Additionally, a consortium of stakeholders, including asset owners, programme managers, software providers, and engineering teams, plays a key role in maintaining ongoing engagement. This consortium should take responsibility for the structured development and implementation of the Semantic CDE MBSE framework at the programme level. To ensure continuous improvement, feedback must be collected systematically across all projects and incorporated into the iterative refinement of the framework. Within individual projects, project teams can document structured feedback on the Semantic CDE itself, capturing insights on usability challenges, data integration issues, and necessary improvements. The consortium can then analyse feedback across projects, ensuring that enhancements align with both project needs and broader programme objectives.

Currently, no such MBSE consortium exists in the Netherlands, meaning there is no coordinated direction for the development and implementation of MBSE applications in the infrastructure sector. As a result, the progress of MBSE adoption remains fragmented, with companies often focusing on their own internal software solutions rather than contributing to programme-wide improvement efforts. Unlike a fully open market, Dutch infrastructure projects are primarily government-financed, with strict budget controls limiting opportunities for technological development. As companies are not incentivised to invest in sector-wide MBSE advancements, the required systematic progress to improve programme performance remains unrealised. To foster further development, it is essential that other MBSE applications are also explored and tested, which requires clients and asset owners to allocate resources for experimentation and innovation. Establishing a dedicated consortium would provide the strategic direction, coordination, and investment framework needed to accelerate MBSE adoption and enhance infrastructure programme efficiency.

Financial Implications and ROI

The successful implementation of MBSE and a Semantic CDE requires long-term financial commitment and strategic investment. Establishing a dedicated and responsible consortium is crucial to coordinating development, ensuring standardisation, and driving adoption across the

infrastructure sector. This consortium could secure financial resources from investors, industry partners, and companies interested in advancing MBSE and data-driven programme governance through Linked Data. Additionally, funding must be allocated for experimentation within projects, allowing organisations to test and refine MBSE applications before scaling them across the programme.

The main goal of investing in MBSE and the Semantic CDE is to make the Renovation and Replacement Programme more efficient, increase capacity, and improve governance. By reducing inefficiencies, eliminating redundant work, and enhancing collaboration, programme organisations can manage more projects within the same timeframe and budget. The Semantic CDE supports this by enabling structured data storage, ensuring collective knowledge is built up and retained rather than being lost between projects.

Investing in MBSE and the Semantic CDE will also increase infrastructure availability by improving programme-wide prioritisation and proactive decision-making. With data-driven insights, asset owners can allocate resources more effectively, prioritising projects based on actual infrastructure needs rather than incomplete information and reactive maintenance. By preventing design errors and reducing miscommunication, organisations can lower unnecessary costs and extend asset lifespans. Thus, the programme's capacity increases in three key ways: through better governance, asset management, and design improvements.

The return on investment is realised through cost savings in project execution, reduced lifecycle costs, and improved long-term asset management. The Semantic CDE ensures future-proof data storage, aligning with existing standardisation efforts such as ontologies and Reference Data Libraries (RDLs). This guarantees that stored data remains accessible and reusable, allowing future technologies such as machine learning, AI, and digital twins to further enhance efficiency, decision-making, and ultimately programme capacity.

Without a structured financial commitment, MBSE development will remain fragmented, and the sector will miss the opportunity to establish a scalable, internationally leading infrastructure management approach. Strategic investment now will position the Netherlands at the forefront of programme-based infrastructure digitalisation, creating a model that can be exported and applied globally.

E.2 Validation Interviews

E.2.1.1 Validation Interview List

Interviewee Code	Organisation Label
O	Engineering Firm C
D	Technology Provider A
B	Public Agency A
L	Engineering Firm B
F	Engineering Firm A
N	Contractor B

E.2.1.2 Interviewee O (Engineering Firm C)

Sector-Wide Replacement and Renovation Challenge: Interviewee O confirmed that the problem analysis is accurate and comprehensive. He agreed that incomplete documentation, miscommunication between disciplines, repeated mistakes, integration difficulties between old and new systems (both technical and managerial), and inconsistent terminology are key challenges in infrastructure renovation programmes. He stressed the importance of clearly distinguishing between technical challenges and project management issues in the analysis.

Recognition of Linked Data as a Suitable Approach: Interviewee O supported the conceptual direction towards using Linked Data within a Model-Based Systems Engineering (MBSE) framework. He agreed that establishing a common data structure with ontologies, taxonomies, and a Reference Data Library (RDL) would greatly enhance programme-level insights and interdisciplinary collaboration across projects.

Implementation and Organisational Challenges: Interviewee O pointed out that the biggest hurdle is not the technical feasibility but the organisational transition. He emphasised that the adoption of semantic data frameworks is primarily a change management issue. Transitioning from traditional methods to semantic information management frameworks requires significant organisational alignment and strategic commitment.

Sector Initiatives and Standardisation Trends: Interviewee O highlighted that open standards are becoming increasingly mandatory, supported by initiatives like the Dutch Forum Standaardisatie and sectoral organisations such as DigiGo. He encouraged referencing these movements as underlying drivers for adopting Linked Data principles.

Cross-Project Knowledge Exchange and Long-Term Vision: Interviewee O endorsed the vision of cross-project knowledge sharing, linking Digital Twins to semantic frameworks, and using the approach for predictive analysis and programme-level decision-making. He noted that these possibilities would greatly benefit from a consistent and scalable data structure.

Human and Organisational Factors: Interviewee O stressed that long-term benefits are enormous if properly implemented, but warned that without human and organisational adoption, the benefits would not materialise. He urged strong attention to organisational change, stakeholder engagement, and practical accessibility of the frameworks for end-users.

Problems Identified: Interviewee O found the identified problems realistic and confirmed that they represent the main pain points in practice, both at technical and project management levels.

Proposed Solution Approach: He fully endorsed the solution framework conceptually, provided that validation with technical specialists is completed and that strong attention is paid to the organisational implementation strategy.

Implementation Recommendations:

- Clearly distinguish between technical problems and project management/organisational challenges.
- Validate the technical accuracy of RDF, SPARQL, SHACL, and related examples with specialists.

- Highlight the shift towards open standards driven by government and sector initiatives.
- Recognise that successful adoption requires strong organisational change management.
- Emphasise the long-term scalability and cross-project benefits but temper expectations around short-term implementation speed.
- Propose future research or follow-up work focusing specifically on organisational implementation strategies.

E.2.1.3 Interviewee D (Technology Provider A)

Sector-Wide Replacement and Renovation Challenge: Interviewee D confirmed that the problems identified – such as repeated mistakes, incomplete documentation, miscommunication between disciplines, and lack of project integration – are realistic and critical issues that hinder capacity and efficiency in infrastructure renovation programmes.

Recognition of Linked Data as a Suitable Approach: He strongly supported the conceptual approach of using Linked Data within a Model-Based Systems Engineering (MBSE) framework. According to Interviewee D, Linked Data is currently the only solution that can systematically address these data fragmentation and knowledge-sharing challenges across asset life cycles.

Need for Step-by-Step Implementation: Interviewee D agreed that starting small, for example at project level, and gradually scaling up the use of Linked Data across multiple projects and asset lifecycles, is the correct approach. This includes building a shared ontology, taxonomy, and Reference Data Library (RDL).

Importance of Standards Development: He noted that standards development (such as for taxonomies and data structures) is ongoing but progressing slowly. Although important, such initiatives often suffer from slow decision-making and limited momentum.

Organisational Challenges: Interviewee D emphasised that the technical solution is clear and valuable, but the main bottleneck lies in the lack of organised collaboration across the sector. Currently, there is no consortium or structured initiative to build a true semantic Common Data Environment (CDE) for infrastructure projects.

Tooling and Market Readiness: Interviewee D explained that broader adoption will depend heavily on the availability of accessible, user-friendly tools. Many innovative technologies struggle because they are not sufficiently embedded into practical software environments yet. However, he observed that this is now starting to improve.

Vendor Lock-in Issues: He warned that many current software vendors (such as Relatics) have a business interest in keeping their systems closed, limiting interoperability. This could delay broader application of Linked Data principles, although he believes market pressure will eventually force change.

Validation of Example Models and Codes: The technical examples shared (such as RDF/Turtle, SPARQL queries, timestamping, and SHACL validation) were confirmed to be correct and well-chosen to explain the practical application of Linked Data in asset management.

Cross-Project Knowledge Exchange: Interviewee D saw strong potential in the proposed approach to facilitate the re-use of lessons learned, risk information, and asset models across projects, making project execution more efficient and improving programme-level insights.

Long-Term Perspective: He confirmed that future integration with Digital Twins, predictive maintenance, and data-driven governance is a realistic and promising direction, although reaching that vision will require persistence and sector-wide coordination.

Problems Identified: Interviewee D found the list of challenges accurate and comprehensive, and recognised them from his own work in the field. He noted that the problems around tool integration, data silos, and inefficient interdisciplinary collaboration are particularly critical.

Proposed Solution Approach: Interviewee D strongly endorsed the outlined solution of using a semantic Linked Data CDE framework within MBSE. He agreed that this offers a technically sound and highly promising pathway to tackle current sector-wide challenges.

Implementation Recommendations:

- Start small at project level and expand incrementally across assets and organisations.
- Continue to develop standards (ontology, taxonomy, RDL) but manage expectations regarding slow progress.
- Form a sector-wide consortium (e.g., involving Rijkswaterstaat and major contractors) to drive semantic CDE adoption.
- Push for more interoperable tooling to make Linked Data principles usable in day-to-day engineering practice.
- Address vendor lock-in issues by promoting open standards and creating market incentives for open interoperability.
- Leverage opportunities to improve processes in large infrastructure programmes by embedding semantic technologies.

E.2.1.4 Interviewee B (Public Agency A)

Sector-Wide Renewal Challenge: Interviewee B emphasised that the replacement and renovation challenge is not limited to Public Agency A but affects the entire sector (municipalities, provinces, water boards). Much of the Netherlands' infrastructure was built during the post-war reconstruction period, meaning that many assets are now ageing simultaneously. At the same time, demographic shifts (an ageing workforce) are causing a capacity problem: the outflow of technical personnel exceeds the inflow, which means productivity must increase significantly.

Inefficiencies in Tender Processes: He pointed out significant inefficiencies in traditional tendering practices, where multiple engineering firms design competing solutions but ultimately only one design is realised. This process wastes valuable engineering hours and ideas that are never implemented.

Insufficient Insight into Asset Conditions: Prioritisation within replacement programmes often happens in an ad-hoc manner because the actual condition of many assets is poorly known. Although inspections yield condition scores, sudden failures or unexpected deterioration often force changes in priorities. Better monitoring and data-driven decision-making are urgently needed.

Potential for Data-Driven Governance: Interviewee B supported the idea that improved data structures (such as semantic models and Digital Twins) could enhance insight and prioritisation. He stressed that a clear, high-level dashboard is essential for programme-level steering without overwhelming decision-makers with unnecessary detail.

Need for Uniformity and Aggregation: A critical success factor is the uniform recording of condition assessments and failure mechanisms across all assets. Only by standardising object definitions, inspection methods, and scoring systems can meaningful aggregation and cross-comparison occur.

Changing Nature of Asset Management: Asset management must increasingly be based on three key parameters: costs, risks, and performance. Future replacement designs should be evaluated early on according to these criteria to ensure better long-term outcomes regarding reliability and life cycle costs.

Sector-Wide Collaboration: Interviewee B noted that collaboration with contractors and engineering firms is essential to ensure that models and data standards are maintained throughout the life cycle of infrastructure assets. Open standards and interoperability between different software tools are critical to this effort.

Digital Skills and Training Needs: A barrier to broad adoption is the current lack of digital skills among both clients and contractors. Interviewee B stressed that systematic investment in training and the hiring of new, digitally skilled professionals is necessary to future-proof the sector.

Problems Identified: Interviewee B confirmed that the challenges identified in the research were accurate. However, he added that the overall productivity of the sector must be improved and that the lack of uniform asset condition information is a critical limitation for effective replacement and renovation management.

Proposed Solution Approach: Interviewee B saw clear potential in using a semantic data model and Linked Data for better governance, knowledge sharing, and long-term monitoring. He highlighted that practical success depends on developing an easy-to-use dashboard and reliable data input processes.

Implementation Recommendations:

- Develop uniform standards for inspections and condition scoring across all asset types.
- Build an aggregated dashboard to support programme-level governance and prioritisation.
- Standardise data structures to enable practical use of Digital Twins and Linked Data.
- Start with small pilot projects and demonstrate tangible benefits early.
- Strengthen collaboration between clients and contractors based on open standards.
- Invest systematically in training and recruiting personnel with digital skills.
- Use data insights to support replacement design decisions based on cost, risk, and performance.

E.2.1.5 Interviewee L (Engineering Firm B)

Sector-Wide Replacement and Renovation Challenge:

Interviewee L confirmed that the challenges outlined (such as incomplete documentation, repeated mistakes, integration issues between old and new systems, limited tool integration, and siloed information) were accurate and relevant. He added that these issues are widely recognised and slow down project execution across the sector.

Need for Better Data-Driven Collaboration:

Interviewee L agreed that data-driven collaboration across projects and organisations could significantly accelerate and improve the replacement and renovation programme. He supported the idea of using semantic models and Linked Data to create a shared information environment and reduce the current fragmented approach.

Potential of Linked Data:

He acknowledged the strong conceptual value of Linked Data for improving knowledge sharing, traceability, integration with Digital Twins, and long-term asset management. However, he stressed that while the technical solution is promising, organisational implementation would be the true challenge.

Organisational and Sectoral Complexity:

A key point raised was that the main difficulty lies not in the technology itself, but in aligning stakeholders, overcoming competing interests, and organising collaboration effectively across clients, contractors, and engineering firms.

Importance of a Strong Client Role (e.g., Rijkswaterstaat):

Interviewee L stressed that the client must take the lead. Without proactive leadership from large public organisations (like Rijkswaterstaat), it is unlikely that private companies will invest the necessary resources, since they operate under tight margins and must carefully prioritise their innovations.

Balance Between Investment and Return:

He pointed out that private companies will participate if the expected return justifies the cost and effort. Therefore, concrete benefits, such as reuse of risks and lessons learned across projects (low-hanging fruit), must be clearly demonstrated.

Necessity of Incremental Implementation:

Rather than implementing a full semantic framework immediately, he advised starting with small, manageable steps (for instance, sharing risk libraries between projects) and expanding gradually, similar to a 'snowball effect' to build momentum and demonstrate value.

Examples of Existing Collaborative Structures:

Interviewee L mentioned organisations like COB (Centrum Ondergronds Bouwen) as good examples where sectors organise themselves to jointly tackle challenges. Such network organisations could be models for how Linked Data initiatives might be developed collaboratively.

Risk of Overcomplicating:

He warned that previous initiatives (e.g., CB-NL) suffered because they remained too abstract

and disconnected from practical use. Any new approach must keep direct usability and integration with practical tools in mind.

Training and Digital Skills Development:

He stressed that for broader adoption, companies will need to invest in developing digital skills among their employees. The future system engineers must be familiar with tooling and data-driven methods to ensure long-term success.

Problems Identified:

Interviewee L found the list of challenges accurate and well-supported by both literature and interviews. He confirmed that each challenge represented a recognised barrier to faster and more efficient asset replacement and renovation.

Proposed Solution Approach:

Interviewee L agreed that using a semantic Linked Data framework could be a valuable solution. He saw a roadmap and stepwise implementation plan as crucial for success but noted that further research would be needed to explore practical governance, funding, and sector-wide cooperation models.

Implementation Recommendations:

- Start with small, visible wins (e.g., linked risk databases across projects).
- Develop a sector-wide consortium, led by a strong client like Rijkswaterstaat.
- Use open standards and shared ontologies to ensure interoperability.
- Provide financial incentives or demands through tenders to drive participation.
- Create accessible tools for practical use to encourage adoption.
- Structure pilot projects to validate the approach incrementally.
- Invest in digital skills training for both clients and contractors.
- Integrate lessons learned from previous initiatives (like CB-NL) to avoid repeating mistakes.

E.2.1.6 Interviewee F (Engineering Firm A)

Fragmented Communication and Double Work: Interviewee F emphasised the problem of fragmented communication between different management layers and organisations, particularly within asset owners like Rijkswaterstaat. He illustrated that different branches, such as PPO (maintenance projects) and GPO (major projects), often operate independently, leading to duplicate studies and inefficiencies. This fragmentation at both the technical and managerial levels underscores the need for better integration.

Legacy Systems and Integration Issues: It was confirmed that integrating new systems into ageing infrastructure brings unforeseen consequences. Interviewee F agreed that current renovation projects often underestimate the complexity of aligning old and new technologies, reinforcing the importance of upfront integration planning.

Data Silos and Interdisciplinary Miscommunication: Interviewee F supported the identification of persistent "information silos" where different disciplines and organisations work with isolated data sources, causing rework and delays. He highlighted that even within

the same owner organisation, the lack of shared data structures leads to inefficiency and knowledge loss.

Potential of Linked Data and Standardised Ontologies: Interviewee F found the proposed use of Linked Data combined with shared ontologies and reference data libraries a promising solution. He stressed that ensuring a standard object tree (where, for example, a pillar or a bridge is always defined consistently across projects) would allow structured reuse of information and enable easier querying across projects.

Importance of Cross-Project Knowledge Sharing: The idea of creating project libraries that store verified data, lessons learned, and standard configurations was considered valuable. Interviewee F highlighted that true programme-level improvement depends on cross-project learning, which requires secure and structured data-sharing agreements between different parties.

Programme Governance and Consortium Approach: The need for a programme-wide consortium was discussed. Interviewee F noted that collaboration between competing engineering firms is traditionally difficult, but crucial for realising sector-wide improvements. He suggested that strong leadership from major clients like Rijkswaterstaat is necessary to enforce shared standards and drive alignment between contractors and engineers.

Scalability and Practical Implementation: Interviewee F supported a stepwise, practical implementation approach. He recommended starting with small, visible successes to build momentum and demonstrate early value. He warned against trying to implement too much at once, particularly given the sector's traditional and fragmented working practices.

Flexibility versus Standardisation: A critical point raised was the balance between flexibility and standardisation. While structured data input is important for systematising knowledge, Interviewee F warned that over-rigid frameworks could stifle creativity and engineering insight, especially in complex infrastructure projects. The framework must allow engineers to retain enough freedom to apply professional judgement.

Long-Term Asset Management and Lifecycle Perspective: Interviewee F underlined that future client demands are shifting from one-off project deliveries to long-term asset stewardship, including real-time monitoring with sensors and predictive maintenance. The proposed framework should therefore anticipate supporting continuous lifecycle data collection and management, not just project handovers.

Challenges for Smaller Clients: Interviewee F warned that smaller asset owners (e.g., municipalities) often lack the resources to manage advanced data-driven approaches. Cooperation between smaller municipalities, or external support structures, may be needed to make these concepts viable beyond large clients like Rijkswaterstaat.

Implementation Recommendations:

- Early user engagement and development of intuitive user interfaces.
- Long-term client–contractor collaboration models that reflect lifecycle thinking.
- Organising pilots across multiple projects to unlock true programme-level insights.

- Ensuring that data collection supports ongoing engineering reflection, rather than replacing critical professional judgement.

E.2.1.7 Interviewee N (Contractor B)

Domain-Specific Language Problem: Interviewee N stressed the problem of domain-specific language, where technical jargon alienates management teams. He pointed out that MBSE implementations must bridge the communication gap between technical experts and non-technical decision-makers. If management does not understand the language or models, MBSE adoption risks failure.

Semantic Layer and Management Accessibility: A solution was discussed where Linked Data and a structured semantic framework (including ontologies and reference data libraries) could facilitate different user views. Inspired by a "cube" concept Interviewee N had developed, it was suggested that depending on the perspective (e.g., HR, finance, procurement, technical), users should be able to query the shared data environment and receive answers tailored to their roles without needing deep technical knowledge.

Lessons from Infrastructure Projects: Interviewee N referenced his experience with a tunnel project, where a model-driven approach enabled both technical depth and simplified outputs for operators. He emphasised that MBSE models should serve different stakeholders without overwhelming them with unnecessary complexity.

Importance of Consistent Data Structures: A critical success factor is having a strict and standardised definition of system elements across projects. Interviewee N warned that cross-project queries and model reuse are only possible if elements are consistently defined. Otherwise, semantic chaos undermines the model's usability.

Hardware, Software, and Operations Decoupling: Interviewee N advised that MBSE and semantic structures must distinguish between hardware, software, and operational logic. Good interface definitions are essential for future-proofing systems, allowing upgrades and replacements without major disruptions.

Lifecycle Perspective: Beyond technical integration, Interviewee N highlighted the importance of addressing both the physical and digital lifecycle of systems. Models must evolve over time to capture changes not only in the physical assets but also in software and operational procedures. He stressed the need for strong configuration management to support this.

Organisational Challenges and Stakeholder Dynamics: The interview touched upon the political and economic forces that could resist sector-wide MBSE adoption. For example, advisory firms might oppose a common semantic structure because it threatens their business models. Interviewee N emphasised the importance of mapping stakeholder interests and resistance factors early in the transition strategy.

Need for Executive-Level Buy-In: Broader MBSE adoption requires convincing not just engineers but also executive leadership (CEOs, CFOs) of its value. Interviewee N pointed out

that many technical initiatives fail because they are not communicated in terms that resonate with business leadership.

Reflections on Broader Adoption: Interviewee N noted that in the Netherlands, organisations like INCOSE still struggle to involve top executives, whereas international examples show stronger strategic involvement. For systemic adoption, MBSE benefits must be made visible at the programme and portfolio management levels.

Problems Identified: Interviewee N confirmed that the sector challenges identified in the research were accurate and aligned with practice.

Proposed Solution Approach: The semantic integration concept and programme-level knowledge sharing approach were validated as promising. However, Interviewee N stressed the importance of a strong, shared semantic foundation and flexible, stakeholder-specific data visualisations.

Implementation Recommendations:

- Ensure strict definition and standardisation of system elements (ontology and RDL).
- Decouple hardware, software, and operations clearly in models.
- Map and address stakeholder resistance proactively.
- Focus on usability and accessibility across different user groups.
- Integrate lifecycle thinking into both physical and digital asset management.
- Secure early buy-in from senior executives by speaking their language and focusing on business value.

Appendix F: Documents

F.1 Avans Hogeschool Interviews

F.2 Leo van Ruijven INCOSE Presentation