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Improving Information Requirements Management in Complex Rail Transport Projects

by Yu Chen

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under the supervision of
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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, *Yu Chen*, declare that this thesis is submitted in fulfilment of the requirements for the award of *Doctor of Philosophy* in the *School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology* at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Abstract

The infrastructure construction industry is undergoing a digital transformation, shifting from traditional engineering practices and services to new digital and model-based approaches. Digital engineering is widely regarded as a significant enabler of this digitisation trend. Throughout the digital delivery of transport infrastructure, the elicitation, specification, implementation and verification and validation of the asset information requirements to support the development of the physical and digital assets are crucial to establishing the golden thread and harmonising data in support of the digital twin. High levels of integration in complex project environments present significant challenges for traditional requirements management practices. Existing approaches to requirements management in the rail transport sector lack a whole-of-system and whole-of-life methodology and have lower levels of maturity regarding the traceability and management of both physical system and asset information requirements, impacting effective and efficient creation of a digital twin. To address this gap, this thesis implemented a design science research methodology to explore the improvement of asset information requirements management capability in the rail transport sector in three cycles: *relevance cycle*, *rigour cycle* and *design cycle*.

In the relevance cycle, a systematic and cross-domain literature review was conducted to better understand requirements management capabilities, initiatives and challenges in digital delivery across similar domains. As a result, 22 requirements management capabilities were identified, covering *process*, *technology* and *people* related areas. Initiatives and methods used across different domains were analysed. Finally, challenges in requirements management were identified and categorised into the same areas as capabilities.

In the rigour cycle, a multiple-case study was undertaken to investigate the contemporary requirements management practices in Australian transport projects. Key requirements management capabilities, initiatives in real projects, and challenges to requirements management practices were identified. A deeper investigation was conducted focusing on the status of requirements management and digital engineering standards, the maturity levels of requirements management practices, and the significance of challenges in the complex infrastructure sector.

In the design cycle, a Capability Improvement Framework was developed based on findings from earlier research steps and then revised according to feedback from professionals in the industry. This framework had four maturity levels and identified 82 information requirements management activities across seven project stages. Each activity is linked to one or more information requirements management capability areas. This framework can be used at the organisational and project levels to assess capability maturity and provide a basis for potential improvements.

Chapter 1 Introduction

This chapter presents an introduction to the area of inquiry and the problem of requirements management in complex rail transport projects addressed in this thesis. The aim, objectives, research questions and scope of this research are presented. The chapter ends with an outline of this thesis.

1.1 Research Problem

As a part of a greater whole in a linear network, modern rail transport systems can be characterised as cyber-physical systems (Chen & Jupp, 2021). Cyber-physical systems emphasise the link between computational and physical components, representing a network of interacting elements with physical input and output instead of standalone devices. The integration of computation and physical systems to achieve complex functionalities distinguishes many of today's built assets (Lee & Seshia, 2016). Increasingly, government-funded infrastructure projects are also embracing the development of spatial digital twin platforms in support of more strategic approaches to asset lifecycle management (Infrastructure Australia, 2023). Australian rail transport infrastructure projects are therefore increasingly required to deliver or contribute to the generation of spatial digital twins, providing asset managers with functionalities to monitor and optimise operations and maintenance (Chen & Jupp, 2023a). Consequently, the delivery of complex rail transport systems is increasingly reliant on integrated methods supported by multiple digital construction technologies, including Building Information Modelling (BIM), Geographic Information Systems (GIS) and semantic data management.

Digital engineering (DE) was proposed in the Australian transport sector in 2018 to replace the older concept of BIM. While BIM is defined in International Standard ISO 19650-1 (2018) as the "use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions", DE is defined in Australian Standard AS 7739-1 (Rail Industry Safety and Standards Board [RISSB], 2023, p. 28) as a "collaborative way of working, using semantic data management, to enable more productive methods of project delivery and asset management". More recently, the importance of data integrity and asset data validation in DE is emphasised and challenges to data integrity and validation are identified, particularly in the context of government led DE initiatives. Moreover, the scale and complexity of the interactions that occur on complex rail transport projects present new challenges to requirements management.

During project planning and acquisition phases of complex rail transport projects, the requirements management process is used to identify, control, decompose, allocate, verify and manage changes in requirements, and to handle these tasks across all levels of the work breakdown structure. The main goals of implementing requirements management processes are, therefore, to provide bidirectional traceability, manage changes to established requirement baselines over the system's lifecycle, and verify requirements according to a given lifecycle phase, such as at system concept review, system definition review, or preliminary design review (Transport for NSW, 2017). In complex rail transport projects, requirements management activities span planning and acquisition phases, where tens of thousands of interdependent requirements describing the conditions and capabilities of cyber, physical and virtual assets are handled across various project team disciplines and organisational boundaries, and using diverse approaches (Chen & Jupp, 2023a). A myriad of requirement types must be elicited, specified, developed and verified – ranging from stakeholder expectations and customer requirements to the management of reliability, availability, maintainability and safety (RAMS) requirements, technical system requirements (including interfaces between systems and external entities) as well as software, data architecture and code requirements (supporting the execution of operational functions), and asset information requirements (defining the graphical and non-graphical data, information and documentation needed for the lifetime operation and management of built assets).

Managing the cyber-physical systems development effort relative to this complex of expectations and requirements demands collaborative processes and integrated toolsets. Technical system requirements are normally specified in the scope of works and technical criteria of the asset. Management requirements are specified in an array of management standards, processes and procedures that must be followed. DE has an array of management requirements relating to (primarily) the management of data, information and collaborative information sharing. Systems engineering (SE) also has an array of management requirements relating to (primarily) the management of technical requirements (e.g., via the RTM). Thus, an information requirement is a project deliverable that must be governed by a responsible party following a management process, and upon delivery must also be assured that it meets the requirements set out in the contract.

Research on the requirements management practices implemented on cyber-physical systems projects in manufacturing industries has shown that increased complexity, multiple distributed stakeholders, and the involvement of several disciplines (with their own formalisms and requirements models) present significant challenges to implementing collaborative requirements management processes across organisational boundaries (Wiesner et al., 2014, 2017; Zahid et al., 2022). Requirements in digital engineering enabled rail transport projects not only include the technical system requirements that were decomposed during planning and design phases, but also the information requirements (including project information requirements, asset information requirements and exchange information requirements, see detailed definition in Section 2.5.3) about the digital twin modelling of the rail transport system. Thus, requirements management in complex rail transport projects should not only consider the development and management of these two different types of requirements, but more importantly, the governance structure and governance interface of technical system requirements and information requirements that are overlaid onto and are driven by the different DE and SE management frameworks.

However, due to the fragmented nature of supply chains and project phases of the complex rail transport sector, different actor-groups are involved in specifying and managing different types of requirements. Consequently, the requirements generated in the early planning phase (e.g. the original brief) are neither widely distributed and accessed by all stakeholders throughout subsequent project stages, nor updated to reflect the requirements changes (Jallow et al., 2014; Kiviniemi, 2005). Furthermore, unstructured text-based requirements management tools are inadequate for managing such complexity and distributed stakeholders, resulting in ineffective requirements handling (Broy et al., 2012; Ncube, 2011; Penzenstadler & Eckhardt, 2012). Parallels can be drawn between these existing studies and the deficiencies in requirements management on complex rail transport projects. Without an effective way of capturing, tracking and managing the requirements of physical, cyber and virtual assets, it is difficult to successfully ensure all requirements have been met.

Some DE/BIM standards, such as PAS[1] 1192 series (British Standards Institution, 2013, 2014), NBIMS[2] (National Institute of Building Sciences buildingSMART alliance, 2015) and ISO/DIS 19650 (ISO, 2018a, 2018b), and industry guidelines, such as US National BIM Guide for Owners (National Institute of Building Sciences, 2017), US AIA BIM Protocol Exhibit (American Institute of Architects, 2008), have evolved to embrace the model-based context. However, the specification of information requirements from a whole-of-system and whole-of-life perspective and the necessary requirements management processes, protocols and tools are currently lacking (Chen & Jupp, 2018). The claim of this research is that a more structured, coordinated and systems approach to information requirements management is needed in complex rail transport projects to support the creation of digital twins and, as a consequence, the

[1] Publicly Available Specification

[2] US National BIM Standard

implementation of information requirements management processes demanded by the DE/BIM standard.

1.2 Aim and Objectives

The main aim of this research is to develop a Capability Improvement Framework for information requirements management on complex rail transport projects to support an effective management of technical systems requirements (for physical deliverables) and information requirements (for digital deliverables). This aim has been translated into three measurable research objectives around the processes, protocols and tools applied in systems requirements management, large-scale requirements management, or model-based requirements management practices as documented in the research literature and how they relate to contemporary approaches in the practices of complex Australian rail transport projects. The three objectives are:

Objective 1: Understand contemporary and state-of-the-art requirements management methods supporting the creation of digital twins or cyber-physical systems. This objective focuses on methods reported in the research literature and examines the main challenges relating to the management of both technical system requirements and information requirements.

Objective 2: Describe and analyse contemporary requirements management practices as they occur in complex Australian rail transport projects, and the extent to which they support the governance management process of technical system requirements and information requirements. The goal of representing and analysing contemporary practices aims to identify the:

1) key capabilities of industry-based requirements management practices that support both technical system requirements and information requirements
2) initiatives that have been implemented by organisations to support technical system requirements and information requirements management practices
3) main challenges in current requirements management practices encountered by project teams.

Objective 3: Develop a Capability Improvement Framework for information requirements management in digital engineering enabled complex rail transport projects (see definition provided in Section 2.1). Accordingly, definitions of capabilities, indicators and maturity levels are developed, and capability improvement pathways identified providing a useful diagnostic tool. It is intended that the framework can be used at both organisation and project level to determine the status of information requirements management capability of an organisation, and the capabilities required in a project for effective information requirements management.

1.3 Research Questions

The central research question that this thesis addresses is:

> *How are information requirements managed on complex rail transport projects, especially in terms of the implementation of digital engineering, and how can information requirements management practices be improved from the perspective of the client?*

To achieve the aim and objectives, this research question and the three objectives outlined above are translated into three research questions. These three research questions are developed into 11 sub-questions in Chapter 3.

Objective 1 to Question 1

Q1: In the context of complex project delivery, what is the current status of information requirements management and what capabilities are essential to the efficient and effective management of information requirements?

Objective 2 to Question 2

Q2: In the specific context of complex rail transport projects implementing digital engineering approaches, what capabilities are essential to information requirements management and what is the current status of information requirements management practices in industry?

Objective 3 to Question 3

Q3: In the context of complex rail transport projects, what levels of capability can be identified to assess the relative maturity of information requirements management practices, and what activities are required to support the improvement of information requirements management?

1.4 Thesis Structure

The thesis follows a conventional research methodology and is organised into eight chapters, including this chapter. Table 1.1 shows the relationship between each chapter and the research questions.

Table 1.1 Chapter structure and content of the thesis

Chapter	Research Questions and Sub-questions
Chapter 1	Research Introduction
Chapter 2	Research Background
Chapter 3	Research Methodology
Chapter 4	Research Question 1
Chapter 5	Research Question 2-1 ~ 2-3 (see Chapter 3 for sub-question details)
Chapter 6	Research Question 2-3 ~ 2-6 (see Chapter 3 for sub-question details)
Chapter 7	Research Question 3
Chapter 8	Conclusion

Chapter 1 introduces the thesis. The remaining chapters of the thesis are as follows.

Chapter 2 provides a detailed background of the research domains. This chapter provides a foundation for the research study and identifies key boundaries and gaps in the research domain. It discusses complex rail transport systems and their qualification as cyber-physical systems. The chapter explores digital twin technology implementation in rail transport systems and examines the current state of systems requirements management, including various models and activity domains within this process. Suitable requirements management methods for the rail transport sector are discussed, along with a conceptual framework defining the main characteristics for lifecycle information requirements management in the research context. Various maturity models for capability assessment and enhancement, tailored to requirements management within the broader research context, are also analysed.

Chapter 3 presents the research methodology, beginning with the design science research framework and how it is implemented in this research study. The three cycles of design science research are reflected in three research steps, including desktop-based research, multiple-case study followed by an online survey, and development of a Capability Improvement Framework for information requirements management. Analysis themes for the desktop-based research are briefly introduced before presenting the data collection methods, case identification and participant sampling strategy, approach to data analysis in case studies, and online survey instructions. Findings from the desktop-based research, case studies and online survey form the knowledge base and environment inputs for the development of the Capability Improvement Framework. An outline of the development and validation process of this framework is then presented. Chapter 3 ends with the research management strategies including ethical considerations and risk management strategy.

Chapter 4 addresses research question 1 and focuses on investigating requirements management research in the context of digital engineering enabled projects across various domains, such as architecture, engineering, construction and operational (AECO), infrastructure, and manufacturing. The chapter employs a systematic literature review approach to address research questions related to requirements management capabilities, initiatives supporting information requirements management, and challenges. It identifies 22 requirements management capabilities and outlines initiatives and methods used across different domains. Challenges in general requirements management and information requirements management are identified and categorised into process, technology and people related areas. This chapter lays the groundwork for the study, serving as the knowledge foundation within the design science research framework.

Chapter 5 addresses part of research question 2. In this chapter, a case study approach is used to examine key requirements management capabilities, initiatives and challenges encountered by project teams in complex rail transport projects. The chapter outlines the case studies' scope, introduces the interview themes and participants, and then summarises critical capabilities for efficient information requirements management. Initiatives in specific case studies are analysed for their advantages and limitations. It also explores challenges in general requirements management and information requirements management, and maps the challenges within the Diamond model.

Chapter 6 addresses part of research question 2 through an online survey, investigating the status of requirements management and DE standards in the complex infrastructure sector, the current maturity levels of requirements management practices, and the significance of challenges. Key resources required for effective requirements management practices are identified. Chapter 5 and Chapter 6 form the 'environment' of the design science research methodology.

Chapter 7 presents the core design cycle of the design science research methodology including the development and validation of a Capability Improvement Framework, with the aim of addressing research question 3. The chapter introduces the framework, detailing its key components, including maturity levels, information requirements management activities, and the assessment method. It explains four maturity levels and identifies 82 information requirements management activities across seven project stages. Each activity is linked to one or more information requirements management capability areas. The chapter then outlines the assessment and improvement process, discussing how the framework can be used at the organisational and project levels to assess capability maturity and provide a basis for potential improvements. Industry professionals participated in feedback sessions and the framework was enhanced and refined based on their insights and recommendations.

Chapter 8 summarises the finding of this research project on the study of information requirements management in the complex rail transport sector, and discusses the main contributions and limitations of the approach. Future research plan and recommendations are outlined.

Chapter 2 Literature Review

This chapter focuses on the background of this research study, aiming to identify the relevant boundaries and current gaps in the research field. First, concepts of cyber-physical systems, digital twins and their relationship with complex rail transport systems are investigated. This is followed by an exploration of what is identified as “state-of-the-art” in systems requirements management. Then, related requirements management process models are described and compared, followed by the identification of core activity areas of requirements management. Requirements management methods suitable in the rail transport sector are then investigated. Next, a framework describing the digital engineering backbone for lifecycle information management in the infrastructure construction context is presented and proposed. Finally, different maturity models supporting capability assessment and improvement are explored and analysed, identifying common components of maturity models. Maturity models specific for requirements management are further investigated in the context of this research. Based on findings from the literature review, the last section of this chapter further develops and details the research gaps, research aim and research questions that were presented in Chapter 1 Introduction.

2.1 Introduction

The digitisation of the construction industry has rapidly changed design and delivery practices. Building Information Modelling (BIM) and, to a lesser extent, digital engineering (DE) now dominates the construction information technology literature. The literature exploring digital use cases to improve architecture engineering, construction and operational (AECO) activities continues to grow (Dave et al., 2016; Matarneh et al., 2019; Pasini et al., 2016; Tay et al., 2017). In Australia, the recent release of various state government standards defining DE (e.g., see Transport for NSW DE Standard, 2022a and 2022b) has encouraged higher levels of adoption of Building Information Modelling (BIM), Geographic Information Systems (GIS) and a host of other applications to achieve more integrated approaches to semantic data management in transport infrastructure projects. Similarly, Foster (2019) proposed that “Digital Engineering is a broad term which gathers several other related technologies or processes together, such as Computer-Aided Design (CAD), BIM, GIS and Data Science”, while BIM was viewed as the element of DE used in the design and construction phases. In these definitions, BIM was defined as a subset of a wider DE ecosystem (Hosseini et al., 2020).

The term “digital engineering” was first used in 1975 in the context of electronic and logic circuit design, and further applied in manufacturing including “developing digital concepts and systems” (Kostopoulos, 1975, p. vii) and product lifecycle management (PLM) (Hosseini et al., 2020; Newman et al., 2020). The aim of DE is to create a seamless thread of data and information throughout the product or asset lifecycle, with this achieved through interoperability across heterogeneous systems, as well as integrated information management and data exchange (Kim et al., 2010; McMahon et al., 2005). In response to the challenges faced by the construction industry – such as ineffective communication, inconsistencies in information, loss of data and utilisation by stakeholders of out-of-date or wrong information and data for information decision-making (Hosseini et al., 2018; Jupp & Singh, 2016; Mignone et al., 2016) – the Australian Transport and Infrastructure Council endorsed the National Digital Engineering Policy Principles (Transport and Infrastructure Council, 2016) in November 2019. Since then, Transport for NSW has acted as a driving force promoting the adoption of DE in Australia to maximise quality and efficiency in delivering transport projects (Transport for NSW, 2018).

This thesis applies a similar concept of DE as the Rail Industry Safety and Standards Board (RISSB) and Transport for NSW, identifying DE as “a collaborative way of working, using semantic data management, to enable more productive methods of project delivery and asset management. DE uses data modelling to represent all aspects of physical infrastructure and support all activities over the complete asset lifecycle” (RISSB, 2022, p. 28). Information models under the DE framework are implemented using a “consistent data architecture with semantic interoperability to ensure all datasets are machine-readable, and can be managed, exchanged, federated, and re-used in an ecosystem of linked databased” (RISSB, 2022, p. 28). DE therefore focuses on the integration of all data across systems engineering, survey, design, GIS, asset, document management, schedule, cost, carbon assessment, etc., from a government client or operator’s planning and procurement processes. This approach to integration means that any data relating to an asset is tagged with the same consistent coding throughout all phases of the asset lifecycle, i.e., throughout the plan, design, construction and maintenance phases (Jupp & Griffiths, 2024).

Due to government agencies investing in digital asset management (DAM) and digital twin (DT) platforms, requirements specifications surrounding data and system integration are increasing. Projects with requirements to deliver or contribute to the generation of spatial DTs (reflecting the 3D geometry of the physical components and the current non-graphical information about these components) (Kampczyk & Dybeł, 2021) in complex rail transport systems have also been garnering increasing attention. As a kind of DT, the spatial DT of complex rail transport systems can be frequently and automatically updated using data sampled by a sensor network deployed in the physical environment, also called the physical twin. The virtual spatial DTs can provide infrastructure managers with functionalities to monitor and optimise their asset stock and to make informed and data-based decisions, in the context of day-to-day operative conditions and after extreme events. Studies have shown that spatial DTs enable more strategic approaches to asset information lifecycle management by supporting connected and autonomous transport capabilities (Kampczyk & Dybeł, 2021), managing digital cadastral information (Xia et al., 2022), leveraging the value of digital asset data created during project delivery, e.g., to locate and maintain assets (Zhao et al., 2022), and the modelling of complex relationships in the physical world using sensors, predictive analysis and artificial intelligence to support O&M (Tchana et al., 2019).

The crucial issues explored in this chapter include:

1) What is the complex rail transport system?
2) Is the complex rail transport system a cyber-physical system?
3) What digital twin implementations exist in the complex rail transport sector?
4) What are the core activity areas of the requirements management process and requirements management methods implemented in the complex rail transport sector?
5) What are the existing initiatives in digital engineering that are currently able to support a collaborative information requirements development process for the physical and virtual assets?
6) What are the existing requirements management capability assessment and improvement models?

2.2 What is the Complex Rail Transport System?

A rail transport system refers to the fundamental railway facilities, systems and services necessary for achieving the function and safety of rail transport (Scott et al., 2016). Digital engineering enabled complex rail transport assets can be broken down to include physical products, from trains, to track masts and the rail network, and the cyber and virtual systems supporting the physical operation and services of the physical infrastructure, from the crew and passenger systems to operational and maintenance systems to the software and internet infrastructure and its providers. The rail transport system involves open, rather than closed, systems with interdependencies between the human-built and natural environments. When a new infrastructure is built in the rail network it becomes part of a system of systems (SoS) (Whyte, 2016). Rail transport systems are therefore an SoS and can be characterised by the following six features.

i) Complex SoS. A rail transport system can be considered an SoS where individual lines not only form an independent system that transports people and freight through specified regions but also interact to transfer users between the lines (Shirvani et al., 2020). Other than the function systems, there are civil and infrastructure systems, signalling and control systems, information systems as well as rolling stock systems that form the whole rail transport SoS (Pallipattu, 2022).

ii) Safety-critical system. "The rail transport system has an immutable principle: It is forbidden to degrade the safety level" (Cebulski, 2020, p.1). This means that development, innovations, initiatives and transformations in progress should be closely monitored and assessed regarding their impact on the network global safety level (Cebulski, 2020).

iii) Significant lag in procurement. It may take 10–15 years to fully procure and put new facilities into service. During this period, technologies, standards and other factors may change, leading to modifications of requirements, contracts and financial arrangement (Shirvani et al., 2020).

iv) Phased evolution on large parallel systems. The introduction of new rail facilities in this context needs to be phased for several reasons. First, the size and complexity of the system requires a gradual approach to ensure that all components are properly integrated and tested. Second, this phased approach is crucial to avoid compromising the safety of the system, as introducing multiple changes at once can lead to unforeseen issues and safety concerns (Scott et al., 2016; Shirvani et al., 2020).

v) Environment-specific issues and requirements. Rail transport systems, due to their expansive geographic coverage, are faced with specific challenges in identifying, capturing and tracking region-specific requirements. Additionally, effectively communicating these region-specific requirements to relevant stakeholders is also a notable challenge in the context of complex rail transport systems (Scott et al., 2016; Shirvani et al., 2020).

vi) Multiple stakeholders with various requirements. In the rail transport SoS, each system or sub-system typically has an individual organisation responsible for its operation or a specific part of its operation. This results in a complex group of stakeholders who own aspects of the acquiring system as well as the operating system and may have conflicting requirements (Scott et al., 2016).

In a complex rail transport project, effective requirements management is a critical process that encompasses several key activities. These activities are essential for ensuring that the project successfully meets the needs and expectations of the client and stakeholders. These activities include the elicitation, analysis and prioritisation, negotiation, allocation and documentation of client requirements and then actively managing these requirements. However, the features of complex rail transport mentioned above indicate potential challenges in areas including interface management of different requirement types, prioritisation of requirements, requirements change management, and requirements negotiation among multiple stakeholders. In this research, the scope of investigation focused on the linear infrastructure of the rail transport system. This is further explained in Chapters 4 and 5.

2.3 Is the Complex Rail Transport System a Cyber-Physical System?

The phrase "cyber-physical systems" (CPS) was coined by Gill in 2006 (Gill, 2006). It characterises systems that smoothly integrate computational components and physical elements while facilitating communication with each other (Deka et al., 2018; Wiesner et al., 2014). The CPS approach has a history of adoption in information systems across various sectors, including shipbuilding, automobile, aerospace and healthcare (Akanmu et al., 2013). According to Tao, Qi, et al. (2019), CPSs are multifaced and intricate systems that achieve integration and collaboration between the dynamic physical world and the cyber world through the fusion of three fundamental components, often referred to as the "3Cs": computing, communication and control. A CPS can be characterised by the following five characteristics:

1) Merging of physical and virtual world (Rajkumar et al., 2010)
2) System of systems with dynamic system borders (Colombo et al., 2013)
3) Context-aware, partially or fully self-governed, with active control in real time (Wan & Alagar, 2014)
4) Collaborative systems with distributed and alternating control (Zhou et al., 2013)
5) Comprehensive human–system interaction (Schirner et al., 2013).

In the context of a domain-specific level, where numerous sub-systems function in parallel, the term "cyber-physical *system-of-systems*" (CPSoS) was introduced to depict the multifaceted and intricate network that merges the cyber realm with the dynamic physical world (Broy, 2013; Tao, Cheng, et al., 2018). Complex transport infrastructure projects can be categorised as a CPSoS. For example, a rail CPSoS can be broadly classified into an infrastructure-based CPS, a vehicle–infrastructure coordinated CPS, and a vehicle-based CPS (Deka et al., 2018).

The increasing integration of GIS, IoT, big data, artificial intelligence and cloud-based platforms in support of Construction 4.0 brings opportunities to increase intelligence, innovation, productivity and competitiveness in the acquisition and operation of rail infrastructure. Assets can be broken down to include physical products – from trains, to track masts and the rail network – and the cyber and virtual systems supporting the physical operation and services of the physical infrastructure – from the crew and passenger systems to operational and maintenance systems to the software and internet infrastructure and its providers. Rail infrastructure systems can be considered a CPSoS, where individual lines not only form an independent system that transports people and freight through specified regions but also interact to transfer users between lines (Shirvani et al., 2020).

As a CPS, complex rail transport systems can be characterised by the management of interactions between the dynamic behaviours of physical rail systems and their distinct computational, sensor and actuator components (Levshun et al., 2021). For example, railway CPSs involve interactions between the physical world and the signal controls, and communication networks spanning the operations and maintenance of railway infrastructure and rolling stock. The behaviour of the physical world of a railway CPS is continuously changing with time (e.g., velocity, flow and density), while the process of communication and calculation in a railway cyber system is usually distributed and supported by the smart power grid (Zhou et al., 2013). Digital delivery methods, and spatial DT modelling, in particular, support the accurate representation of the physical components and cyber processes, enabling the application requirements of the DTs (e.g., visualisation, prediction, optimisation, simulation and monitoring) and, therefore the functional services of the asset (Tao, Cheng, et al., 2018).

2.4 Creating a Spatial Digital Twin of a Complex Rail Transport System

2.4.1 What is a Digital Twin?

The "digital twin" (DT) concept was first introduced by Grieves in 2003 (Grieves, 2014). Definitions and explanations of the DT concept have been proposed and refined by various researchers (Grieves, 2014; Negri et al., 2017; Parott & Warshaw, 2017; Tao, Cheng, et al., 2018). For example, Grieves (2014) defines DT as the creation of high-fidelity virtual models of physical objects in virtual space enabling the simulation of the object's behaviours in the real world and providing feedback in real time. Negri et al. (2017) believe that a DT is the virtual and computerised counterpart of a physical system that can be used to simulate it for various purposes, exploiting a real-time synchronisation of the sensed data coming from the field. Parott and Warshaw (2017) consider that DTs make the prediction and detection of physical issues faster and more accurate, supporting the optimisation of manufacturing processes, and producing better products. Tao, Cheng, et al. (2018) summarise that a DT relies on a bi-directional dynamic mapping process and it breaks the barriers in the product lifecycle and provides a complete digital footprint of physical products.

DT technologies were adopted in the spacecraft sector in 2010 and later in complex manufacturing sectors (Glaessgen & Stargel, 2012; J. Lee et al., 2013). The National Aeronautics and Space Administration (NASA) was an early pioneer of DT technologies for remote monitoring, controlling and running simulations of spacecraft from Earth (Shafto et al., 2010). NASA defined a DT as "an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin. It is ultra-realistic and may consider one or more important and interdependent vehicle systems" (Shafto et al., 2010, pp. TA11-7).

In the complex manufacturing sector, a DT was defined as the coupled model "of the real machine that operates in the cloud platform and simulates the health condition with an integrated knowledge from both data driven analytical algorithms as well as other available physical knowledge" (J. Lee et al., 2013, p. 41). Later on, more core characteristics of DT have been added such as the lifecycle view, the check on mission requirements, and the prognostic and diagnostic functionalities (Negri et al., 2017). Siemens (2018) proposed a comprehensive construction industrial version digital twin which comprises three types of digital twins – Product, Construction, and Performance, as illustrated in Figure 2.1. The combination and integration of these three digital twins as they evolve together is known as the "digital lifecycle ecosystem" (Siemens, 2018).

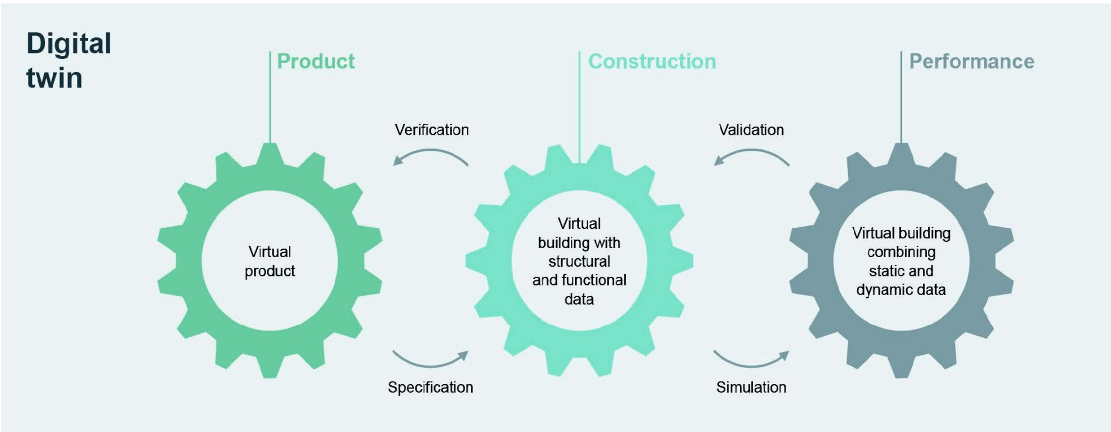


Figure 2.1 Digital twin in construction (Siemens, 2018)

In the built environment, the application of DTs is in the early stages, with few fully-realised examples (Lamb, 2019). In a white paper on applications of DTs in the built environment, the Institution of Engineering and Technology (2019) proposed an industry-agnostic DT maturity spectrum with five maturity elements or levels (Table 2.1) to provide a framework to communicate progress.

Table 2.1 DT maturity spectrum defining principles and outline usage (Institution of Engineering and Technology, 2019)

Maturity element[3]	Defining principle	Outline usage
0	Reality capture (e.g. point cloud, drones, photogrammetry, or drawings/sketches)	- Brownfield (existing) as-built survey
1	2D map/system or 3D model (e.g. object-based, with no metadata or BIM)	- Design/asset optimisation and coordination
2	Connect model to persistent (static) data, metadata, and BIM Stage 2 (e.g. documents, drawings, asset management systems)	- 4D/5D simulation - Design/asset management - BIM Stage 2
3	Enrich with real-time data (e.g. from IoT, sensors)	- Operational efficiency
4	Two-way data integration and interaction	- Remote and immersive operations - Control the physical from digital
5	Autonomous operations and maintenance	- Complete self-governance with total oversight and transparency

According to these definitions, both CPSs and DTs are aimed at achieving systems integration. However, their emphasis on the implementation of functions is where these two concepts differ. CPSs emphasise sensors and actuators, while DTs consider asset data and models as the main modules (Tao, Qi, et al., 2019). Table 2.2 reflects the differences and similarities of CPSs and DTs from perspectives of origins, category, physical-cyber/digital mapping, core elements and control (Tao, Qi, et al., 2019). To some extent, DTs could be regarded as one type of CPSs with a higher degree or level of fidelity (Zheng et al., 2019).

Table 2.2 Comparison of CPS and DT (Tao, Qi, et al., 2019)

Items	CPS	DT
Origins	Coined at the National Science Foundation (NSF) workshop in 2006 (Gill, 2006)	First adopted in the aerospace field in 2010 by NASA in health maintenance (Glaessgen & Stargel, 2012)
Category	Akin to a scientific category	Akin to an engineering category
Mapping between physical and cyber/ digital worlds	One-to-many correspondence	One-to-one correspondence
Core elements	CPSs emphasise sensors and actuator	DTs emphasise models and data
Control	Physical assets or processes affecting cyber representation, and cyber representation controlling physical assets or processes	

[3] Logarithmic scale of complexity and connectedness

Although emphasising different elements, it is necessary to understand DTs in light of CPSs as they share procedural similarity and dependency relative to their creation, where the elicitation, specification, implementation, verification and validation of asset information is essential to their successful delivery (Chen & Jupp, 2023a).

2.4.2 Digital Twin Implementation in the Complex Rail Transport Sector

The rise of IoT, big data, artificial intelligence and cloud-based platforms in support of Industry 4.0 brings opportunities to increase intelligence, productivity and competitiveness for rail infrastructure assets. With the Industry 4.0 movement in rail infrastructure, a range of major projects have been initiated. Examples include digital twinning in heavy rail, connected infrastructure in both commuter and heavy rail, autonomous train systems, and augmented reality for maintenance intervention (Cebulski, 2020). Due to the safety critical nature of the rail infrastructure, all these projects must be assessed, certified and authorised, by demonstrating that they do not reduce the level of safety of the rail networks on which they are implemented and then checked during operations to ensure that safety is maintained (Cebulski, 2020).

In Australia, government-funded infrastructure projects have made a strategic shift to adopt cross-functional DTs. One of several key recommendations from Infrastructure Australia's ambitious five-yearly report in 2021 calls on governments, as regulators, owners, funders and benefactors of public infrastructure, to lead the transition from "digital by exception" towards "digital by default" for infrastructure development (Infrastructure Australia, 2021). In New South Wales, the main government authority, Transport for New South Wales, has already implemented an Open Data Hub and NSW real-time data from intelligent sensors which are aggregated and shared for use by customers, operators and network managers. In support of Transport for NSW's DT vision, a spatial DT, underpinned by a 3D model of cities and communities, is currently being developed to facilitate better planning, design and modelling for future needs.

The application of DTs in transport infrastructure has the potential to improve the overall information flow across the whole lifecycle of the asset. Bado et al. (2022) summarise six aspects of DT implementation in transport infrastructure, including efficient damage detection, better decision-making support, addressing infrastructure managers' scepticism about structure health monitoring, predictive maintenance approach, the potential for automation of infrastructure, and the potential for sustainability. Kampczyk and Dybeł (2021) demonstrate how a spatial DT of railway infrastructure assets can use measurement data from surveying and diagnostics to support the decision-making of operators and infrastructure managers by analysing the effects of different hypothetical scenarios and supporting the selection of the most effective solutions (Kampczyk & Dybeł, 2021). Moreover, the accumulation of information about the transport infrastructure and the features of its operations in connected data environments supports more accurate and efficient decision-making and problem-solving relative to complex technical issues and incidents such as interruptions to power supply, the malfunctioning of interdependent CPSs, and the consequences of control systems failures that arise in operation (Guskova et al., 2020). Callcut et al. (2021) analysed the UK's West Coast Main Line DT (developed by Alstom) and showed that by compiling data from multiple sources and overlaying this on a GIS map, the DT is able to more effectively support maintenance teams via the simulation of various maintenance regimes and running "what-if" scenarios. The ability to analyse maintenance simulations in this way supports the development of predictive maintenance regimes, response plans for emergencies, and responsive timetable updates and their implementation (AnyLogic, 2022; Callcut et al., 2021). The value of rail infrastructure DTs is dependent on the operations and maintenance team's ability to use predictive methods, and thereby anticipate responses to such events (Chen & Jupp, 2023a). To support the creation of DTs of rail transport system, the importance of asset data and the integrity of the asset register at handover cannot be emphasised enough.

2.4.3 Role of Asset Information Requirements (AIRs) in Digital Twin Creation

An enterprise level approach to information requirements and information models is needed to consistently define a digital twin in the context of fixed linear infrastructure assets. The section above described the DE requirements that enable the digital twin and how they map back to ISO 19650 concepts of organisation information requirements (OIRs), asset information requirements (AIRs) and project information requirements (PIRs). This section focuses on exploring the role of AIRs in DT creation.

The creation and verification of a DT of a rail transport system is dependent on the timely definition of AIRs, asset classification and referencing schemas, and asset hierarchy management (Chen & Jupp, 2023a). Asset information needs are predominantly non-geometrical, including specifications of asset performance, uptime, pressure ratings, operating temperatures, set points, manufacturer, asset tag numbers, operating limits and costs. This information is more valuable than having geometrically accurate "twins" of a rail infrastructure asset (Chen & Jupp, 2023a).

As part of the earlier mentioned Transport for NSW DE Framework, the Asset Information Standard Part 1 was issued in June 2023, focusing on the requirements for managing asset information to support "the collection, governance and maintenance of accurate, complete and consistent asset information" (Transport for NSW, 2023, p. 7) for transport assets. It clearly articulated the relationship between AIRs, the asset register and asset information. As described in this standard, "AIRs comprise high level objectives and purposes for the need for different types of asset information that not only support the delivery of new as-built or altered assets, but are required to support the whole-of-life operation and maintenance of the asset" (Transport for NSW, 2023, p. 15). AIRs define not only what information is required (content) but also how it should be delivered (form and accepted formats of deliverables) (Chen & Jupp, 2023a). The asset register serves as a consolidated repository that seamlessly integrates pertinent asset information, offering a comprehensive record encompassing both financial and non-financial information throughout the lifecycle of each asset (Transport for NSW, 2023). This register is meticulously structured and defined to uphold the standards outlined in the AIRs. It functions as a definitive and organised inventory, capturing all relevant details about the assets owned by the client. All data generated within the asset register adheres strictly to the prescribed AIRs, ensuring consistency and conformity with established standards (Transport for NSW, 2023). This structured approach aims to maintain a current and historical record, offering a holistic view of the assets and supporting effective management and decision-making processes.

Consequently, the effective and efficient management of AIRs holds paramount importance in the context of developing a DT for government infrastructure clients. The management of AIRs ensures that the necessary information, conforming to specified standards, is systematically organised and accessible, facilitating the successful implementation of a DT. This strategic approach enhances the development process, contributing to the creation of a robust and functional DT for government infrastructure projects.

2.5 Requirements Management in Complex Rail Transport Projects

In complex rail transport projects, requirement types can include, amongst others, high-level capability requirements defining the system architecture, current and future operations and maintenance (O&M) requirements, definitions of the system-, sub-system-, and unit-level requirements that include functional, performance and physical requirements, as well as business case requirements. Non-functional requirements capture the need for quality, reliability, availability, maintainability and safety (RAMS), and operational constraints, which are paramount in the planning and acquisition of rail transport. Overlaid on this are the DE requirements about the digital twin modelling of the rail transport system (Tao, Xiao, et al., 2022). The DE requirements include information requirements and data requirements.

The development and management of requirement types adhere to the formal methods and processes of systems engineering methodologies (Chen & Jupp, 2023a). In complex rail transport infrastructure projects, implementing digital approaches to requirements management is immature in comparison to manufacturing sectors (Chen & Jupp, 2018; Johnson et al., 2021). These requirements have a long history of being documented inconsistently or inexplicitly on projects (Jupp, 2024). They can often be found in various aspects of the DE execution plan (DEXP) (also known in the building sector as the BIM execution plan, BEP), in the delivery strategy, interdisciplinary design review and model coordination procedures, or in quality management under the quality control strategy, quality checks and processes (Jupp, 2024).

This section introduces requirements management and its relationship with systems engineering, followed by an overview of requirements management methods and tools. This section concludes with an overview of requirements management implementation in the rail infrastructure sector.

2.5.1 Requirements Management as a Sub-discipline of Systems Engineering

Systems engineering (SE) is a discipline that concentrates on the design and application of the whole (system) as distinct from the parts. It is regarded as an iterative process of top-down synthesis, development, and operation of a real-world system that satisfies, in a near optimal manner, the full range of requirements for the system (Eigner et al., 2012). In SE, an essential principle is the focus on requirements traceability throughout the lifecycle of a system to ensure alignment and consistency among components, units, sub-systems and the overall system (Whyte, 2016).

Requirements describe conditions or capabilities needed by organisations, groups or people along with their environment to solve a problem or achieve a goal (Wiesner et al., 2014; Wiesner, Peruzzini, et al., 2015). Their elicitation, documentation, verification and validation, traceability, and maintenance are regarded as the main objectives of requirements management. Requirements management is involved in the SE process as independent activities which are not constrained to a specific development phase (Wiesner et al., 2014).

A number of product development lifecycle models have been proposed and implemented in large-scale system and software development projects in industries and academia. Several of these models are grounded in one of the following seminal models in Figures 2.2 to 2.5: a) Royce's Waterfall model (Royce, 1987), b) Boehm's Spiral model (Boehm, 1988), c) Forsberg and Moog's "Vee" model (Forsberg & Mooz, 1992) and d) Eigner's Model-based systems engineering V-model (Eigner et al., 2012).

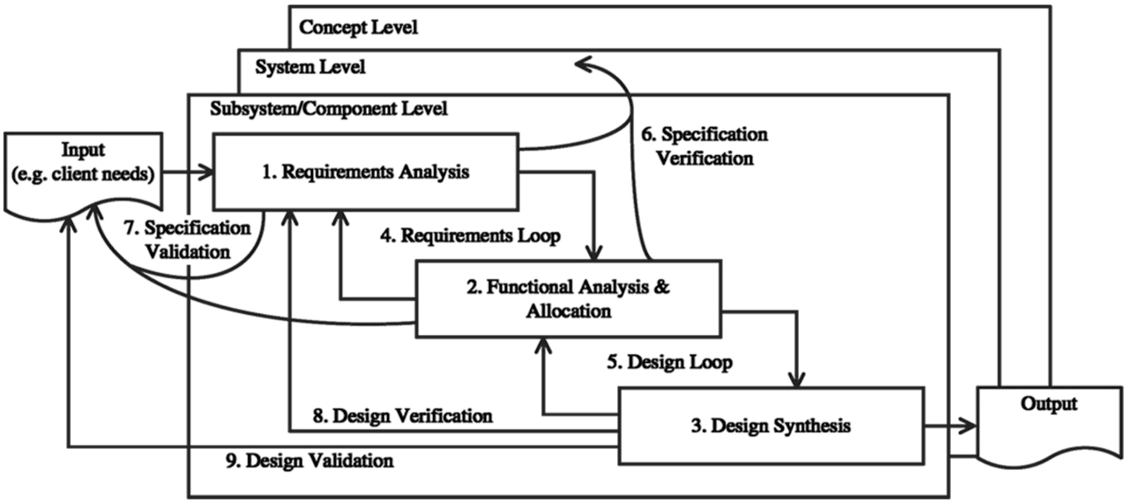


Figure 2.2 Waterfall model (Royce, 1987)

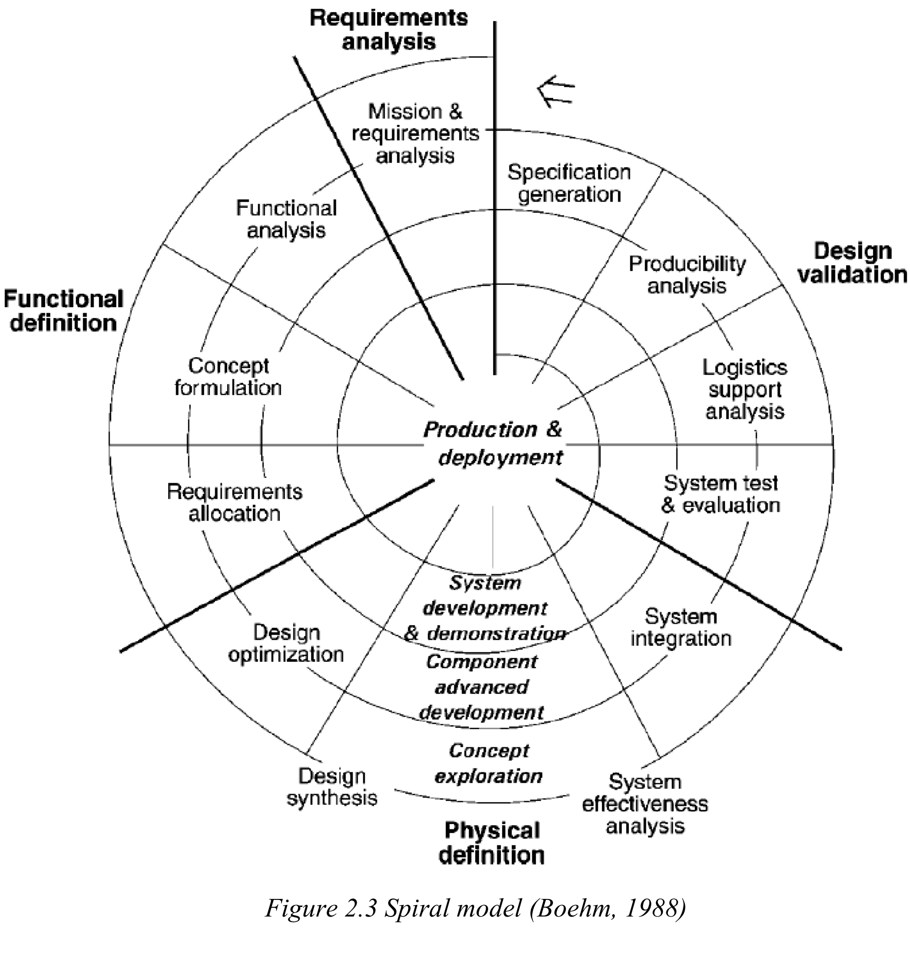


Figure 2.3 Spiral model (Boehm, 1988)

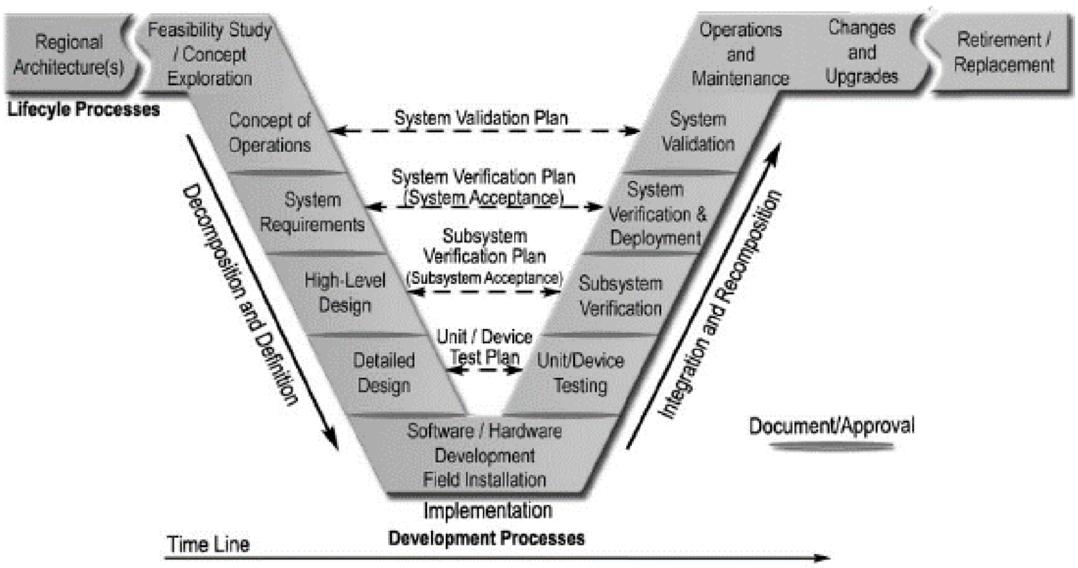


Figure 2.4 Vee model (Forsberg & Mooz, 1992)

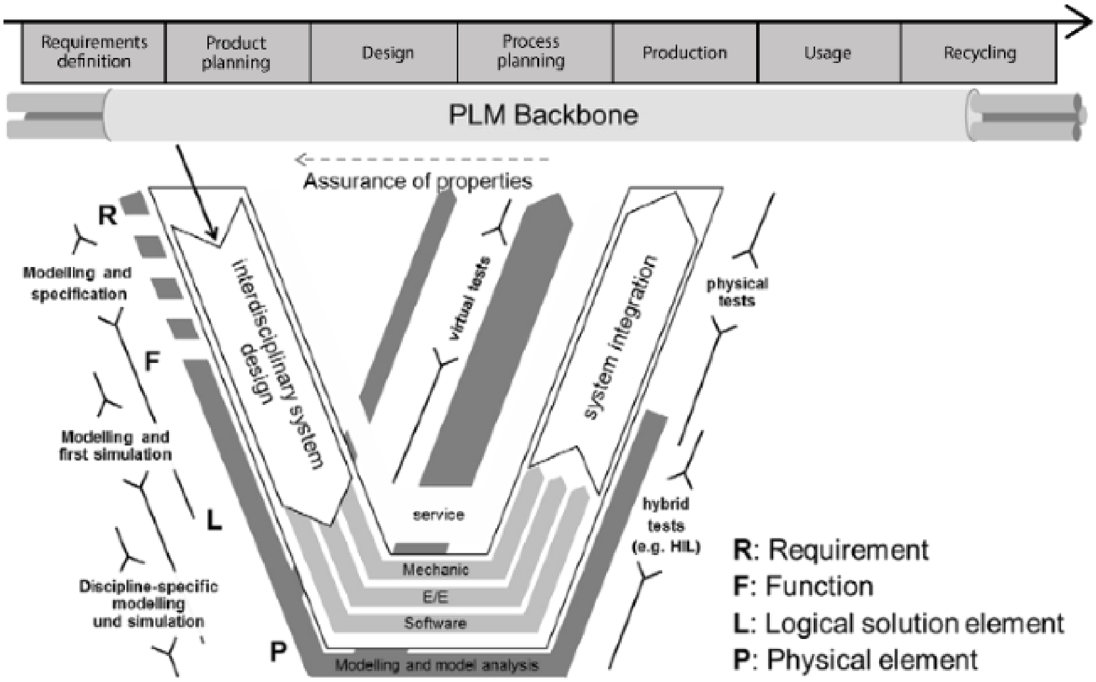


Figure 2.5 Model-based systems engineering V model (Eigner et al., 2012)

Systems requirements management therefore reflects the ongoing interaction between requirements management activities and the development phases in the SE V-model (see Figure 2.6). As shown in Figure 2.6, requirements are vital for all layers in SE. It is essential to validate requirements from lower layers against requirements from upper layers as well as stakeholder requirements to ensure that the requirements represent the original goals (Wiesner, Hauge, et al., 2015).

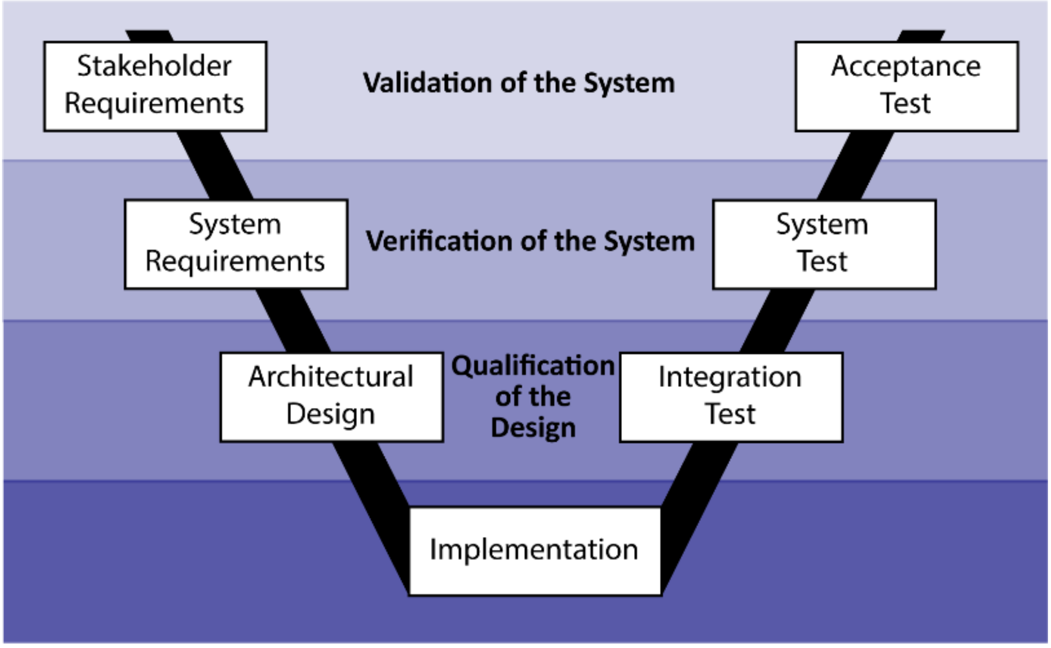


Figure 2.6 Requirements management in the V model (Dick et al., 2017)

The development processes surrounding the physical asset and its virtual replica were described by Boeing using the classic V-model, thereby providing a representation of the development lifecycle and corresponding testing in a “Diamond model” with model-based engineering (MBE) as its foundations (Hatakeyama et al., 2018). The Diamond model addresses the co-development processes of the physical asset and its DT (see Figure 2.7).

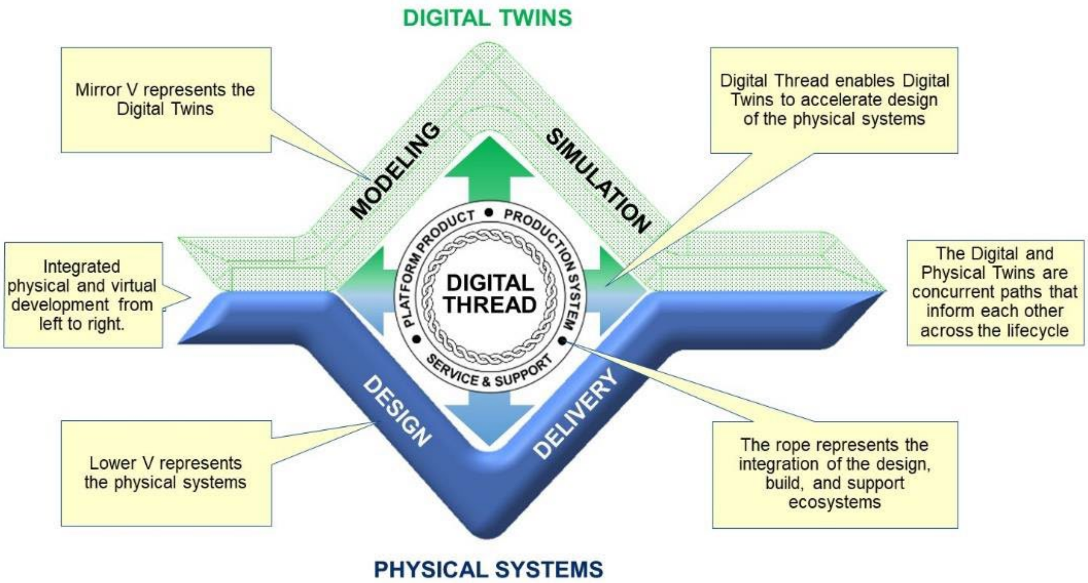


Figure 2.7 Model-based engineering Diamond model (Hatakeyama et al., 2018)

The lower V of this Diamond model reflects the classical SE process of a physical system (both hardware and software), while the mirror reflection of the V above represents the DT’s modelling and simulation (Hatakeyama et al., 2018). The Diamond model takes the classic V-model transformation of product functional requirements to physical systems that are ultimately delivered as a product or service solution and incorporates the DT pathway as separate but integrated activities. The inverted V represents the design and realisation of the behavioural simulations (Hatakeyama et al., 2018). The design and development process of the virtual model correlate exactly to the development of the physical baseline. In other words, the virtual informs the physical during the design, development and simulation phases, and as IoT devices are used, the physical informs the virtual. This interplay between physical and virtual is simultaneous along the lifecycle and between the physical systems and their DTs (Hatakeyama et al., 2018). For example, virtual qualification can simulate actual test conditions and relate to and, in some cases, replace physical testing (Hatakeyama et al., 2018). The creation pathway of a DT is therefore predicated on a lifecycle approach to requirements development and digital information management, highlighting the importance of software tools to support system requirements management processes throughout project delivery.

2.5.2 Requirements Management Process Models and Core Activity Areas

Transport for NSW (2017) describes "requirements management is an active process throughout the duration of a project lifecycle. Requirements management involves identifying, analysing, tracing, prioritising, agreeing and documenting client requirements and then actively managing these requirements. Requirements management processes include controlling and managing changes, communicating any requirements to the relevant stakeholders, and demonstrating compliance". There are three principal requirements management process models that categorise and describe requirements management processes differently that can be identified in the literature (see Figure 2.8). The nature of their structures are differentiated as linear, linear-iterative, and purely iterative (Pandey et al., 2010b).

The **linear** requirements management process model (see Figure 2.8a) was proposed by Linda Macaulay in 1996 (Macaulay, 2012). Five activities including concept, problem analysis, feasibility and choice of options, analysis and modelling, and requirement documentation are arranged sequentially in this model. This is a simple model and applicable for small and uncomplex projects (Shams-ul-Arif et al., 2009).

The **linear-iterative** requirements management process model (see Figure 2.8b) was proposed later by Kotonya and Sommerville in 1998 with some iteration for validation (Kotonya & Sommerville, 1998). This model is applicable for the system where the specifications should be pinpoint accurate and should be validated multiple times through the potential stakeholders (Shams-ul-Arif et al., 2009).

A **purely iterative** requirements management process model (see Figure 2.8c) was proposed by Pandey et al. in 2010 (Pandey et al., 2010a). The requirements elicitation and development, documentation, verification and validation are sequential processes conducted during the early plan and design stages of a development project, while the requirements management and planning process is a lifecycle activity that is closely tied with previous activities, and can therefore be performed concurrently. The requirements management and planning process interacts with and links multiple processes together throughout the lifecycle of the product (Wiesner, Peruzzini, et al., 2015).

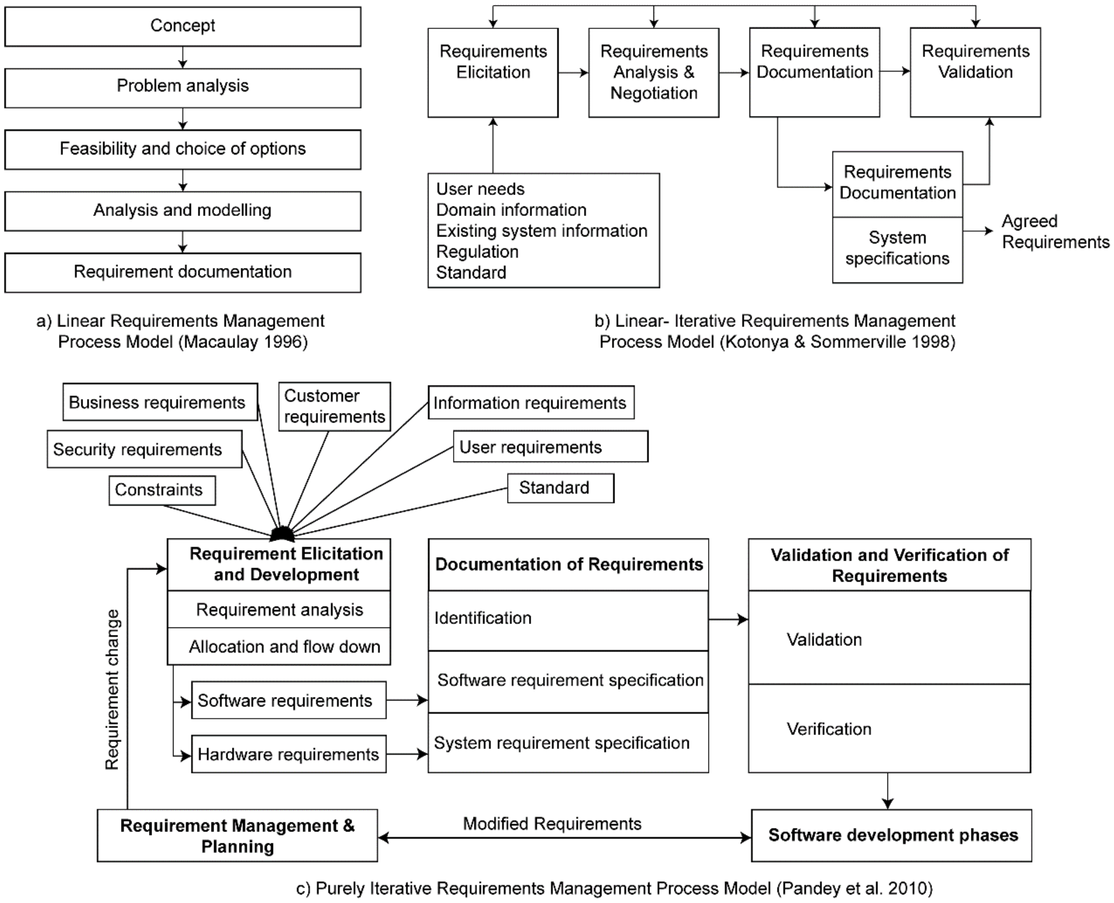


Figure 2.8 Different types of requirements management process models

Existing studies of requirements management processes in industry indicate that the systematic and incremental requirements management models presented in the literature do not reflect the requirements management processes in current practice (Pandey et al., 2010b). For example, Nguyen and Swatman (2003) found that the requirements management process identified in their case study did not occur in a systematic, smooth or incremental way, but was rather opportunistic, with irregular simplification and restructuring of the requirements model when it reached points of high complexity. In other requirements management field studies, conflicting results relative to the status of requirements management process standards in organisations have also been identified. Hofmann and Lehner (2001) have examined the 15 requirements management processes in industry and found that most participants saw requirements management as an ad hoc process, with only some using an explicitly defined requirements management process or customising a company standard requirements management process. In another study by Pandey et al. (2010b), the requirements management processes identified in different companies were shown to have different levels of maturity, where not every requirements management process activity was clearly identifiable.

Despite the different structure of traditional requirements management process models, there are six common activity areas that occur throughout (Pandey et al., 2010b) and are well documented in research literature (Aaramaa et al., 2015; Pandey et al., 2010b; Wiesner, Peruzzini, et al., 2015):

1) requirements elicitation and analysis
2) requirements prioritisation
3) requirements communication and negotiation
4) requirements verification and validation
5) requirements change management
6) requirements traceability.

These six activities are also discussed in the research literature as being essential capabilities of the requirements management process.

RM CAPABILITY 01 – Requirements elicitation and analysis: Gather the relevant requirements of a project by consulting relevant stakeholders, analysing documentation and the domain knowledge. Based on that, categorise different types of requirement, identify risks of technical requirements (Pandey et al., 2010b; Ramos, 2018).

RM CAPABILITY 02 – Requirements prioritisation: Develop prioritisation criteria to support the aspired added values of both internal and external stakeholders (Aaramaa et al., 2015).

RM CAPABILITY 03 – Requirements negotiation and communication: Different stakeholders negotiate and communicate to resolve conflicts between viewpoints or other project constraints (Pandey et al., 2010b).

RM CAPABILITY 04 – Requirements verification and validation: Requirements verification focuses on analysing the agreed requirements to detect ambiguities or conflicts, ensuring their consistency and completeness (de Ataíde Ramos, 2014), while requirements validation was aimed at ensuring that “the final system meets all of the stakeholder and user requirements that were captured at the outset as well as any approved changes or additions to those requirements" (Transport for NSW, 2019, p. 14). The stakeholders have to be involved in the requirements verification and validation process (Wiesner, Peruzzini, et al., 2015).

RM CAPABILITY 05 – Requirements change management: Change management ensures that the modified requirements are fed back into the development process, so that the system can further fulfil its purpose (Wiesner, Peruzzini, et al., 2015).

RM CAPABILITY 06 – Requirements traceability: Requirements traceability links lower-level requirements with the higher-level requirements they originate from, so that requirements management can trace each single requirement to its information source (Wiesner, Peruzzini, et al., 2015) and when a change occurs to a design component, the original requirements can be located (Pandey et al., 2010b).

2.5.3 Configuration Management in Relation to Requirements Management

Another key capability that supports requirements change management and traceability is **configuration management**. Configuration management was developed in the 1950s by the US military to control documentation in the manufacture of missiles (Whyte et al., 2016). This approach has since been extensively used in the software industry, and in safety critical systems such as nuclear and aerospace (Whyte et al., 2016). In the International Council on Systems Engineering (INCOSE, 2007) Handbook, configuration management is described as the means to control and document the evolution of requirements. The objective of configuration management is to ensure that changes that occur in sub-system requirements are checked and analysed in terms of their consequences for system requirements and upper-level business requirements.

In the complex rail transport sector, the benefits of configuration management have been identified by government agencies as a structured approach to control the assets (Transport for NSW, 2022c). In support of the DE capabilities on transport projects, a Configuration Management Framework (CMF) assuring the physical and digital asset has been issued. As a SE process for establishing and maintaining consistency in asset performance, as well as functional and physical attributes, configuration management considers the requirements in design and operational information for managing changes throughout the asset lifecycle. It assists with the management, planning, control, establishment and ongoing maintenance of transport infrastructure assets. It is also important to note the role of Transport for NSW's CMF in the implementation of the DE Standards on projects, which specifies the requirements that apply when planning or undertaking a configuration change at any stage of the asset lifecycle. For assurance of transport projects, the CMF specifies the use of asset lifecycle phases, Configuration Management Framework submission baselines, and Configuration Management Framework Design Review Gates. The requirements for the digital asset assurance are aligned with the physical asset assurance, namely the Configuration Management Baselines and Review Gates which support the effective and efficient delivery of outcomes during multiple phases of the project (Transport for NSW, 2022c).

Due to complex work-share arrangements in transport infrastructure projects and multi-domain common data environments, it is possible to be involved in managing changes across physical systems requirements, digital controls requirements, and their associated asset information requirements (Jupp & Griffiths, 2024). This adds considerable complexity in managing the status of data at any point in time. It is necessary to know exactly what data is available to manage changes to that data effectively. That is one of the greatest challenges in a modern infrastructure construction environment. For most infrastructure clients and engineering and construction companies, configuration management remains a manual, handwritten process, with very few companies having implemented automated or digital change management (Jupp & Griffiths, 2024). Yet, while keeping track of frequent engineering changes during project delivery is a common challenge, it is a particularly onerous one that diminishes efforts to implement asset breakdown codes (Jupp & Griffiths, 2024).

2.5.4 Requirements Management Methods

There are numerous requirements management methods and supporting tools used in the industry. In process manufacturing industries, some of the most widely used requirements management methods include Analytic Hierarchy Process (AHP), a technique for requirements prioritisation, and Quality Function Deployment (QFD), a customer-driven design and manufacturing approach that has been used to transform prioritised requirements into quantitative parameters or specifications (Kubler et al., 2016; Papinniemi et al., 2014). Kano's model (Wang & Ji, 2010) has also been adopted to support the categorisation of different customer requirements based on how well they are able to achieve customer satisfaction (Papinniemi et al., 2014). However, these methods are not widely used in the building and infrastructure sectors, and are not designed to support the co-development of traditional technical system requirements and DT requirements (Chen & Jupp, 2023a). Careful adaptation is required to implement these methods in the context of requirements management workflows supporting DT and CPS development and delivery in the built environment.

Methods specific to the unique context of buildings and infrastructure projects have been developed to support requirements management, with some methods integrating with parametric, model-based capabilities in projects using BIM models. Recent studies have explored the use of BIM models to support requirements management (Baldauf et al., 2020). Two different methods of support for client requirements management have been enabled in BIM-based tools

(Parsanezhad et al., 2016). The first approach facilitates requirements visualisation and communication by using the hierarchical tree structure to store and display physical system requirements for designers while developing 3D BIM models (Baldauf et al., 2020). The second approach facilitates requirements management and verification by translating requirements information into rules for automated checking of 3D parametric design solutions. This second approach is especially useful when checking regulatory and quantitative requirements (Jallow et al., 2014; Parsanezhad et al., 2016).

The development of requirements management methods and tools to support AEC stakeholders in their efforts to better visualise, manage and verify requirements has also been proposed by researchers. Cavka et al. (2017) proposed a BIM requirements framework describing the relationship between the digital (model) and physical (design solution) products with types of owner requirements and organisational constructs to bridge design requirements and facilities management requirements, supporting better traceability between the design information being generated and consumed by various stakeholders at different stages. Jallow et al. (2017) presented an information-centric enterprise architecture framework for managing client requirement information across all phases of a construction project and operational phases of a built asset. Patacas, Dawood, Greenwood, et al. (2016) put forward a framework that combines several technologies and standards to develop asset information models (AIM). This framework integrates the use of Content Management Interoperability Services (CMIS), Construction Operations Buildings Information Exchange (COBie), Industry Foundation Classes (IFC) and Information Delivery Model (IDM). The goal of this framework is to ensure that the client's requirements, known as asset information requirements (AIRs), are met in the AIM through the entire life of a building. By using these technologies and standards in a coordinated manner, the framework helps in effectively managing and delivering the right AIM to meet the client's needs and expectations.

In the sectors of built infrastructure assets, including rail and road, requirements management methods arguably have more in common with those used in process manufacturing than in the buildings sector (Chen & Jupp, 2023a). While the use of specific methods such as Analytic Hierarchy Process and Quality Function Deployment are less common, the recent introduction of model-based systems engineering (MBSE) in Australian government agencies to support complex rail transport projects has improved requirements design and analysis activities during the planning phase (Roodt et al., 2020a, 2020b; Scott et al., 2016). MBSE methods and tools put digital models at the centre of system design and aim to support requirements management through the improvement of communications among the project team members and the reuse of artefacts throughout the project lifecycle (Kaslow, 2015). MBSE captures requirements information in a structured and relational database that can be visualised, unlike unstructured text-based documents or requirements management tools. Thus, in projects that implement DE, MBSE has the potential to provide advantages that document-based systems engineering cannot provide. For example, in a document-based approach, many documents are generated by different authors to capture the system's design from various stakeholder views, such as system behaviour, software, hardware, safety, security or other disciplines. In contrast, when using a digital modelling approach, a single source of truth for the system is built in which discipline-specific views of the system can be created using the same model elements.

In theory, the application of MBSE is well placed to support the requirements management processes on complex transport infrastructure projects. However, in practice, applications of MBSE on complex rail transport projects are not fully implemented, with benefits limited to the planning phase. During the acquisition phase, MBSE digital models and their supporting processes are underutilised or not used at all as they are unable to cover all system development dimensions (Abdelrazik et al., 2019; Subarna et al., 2020). As a result, requirements traceability and requirements change are difficult to manage in highly heterogeneous environments. Requirements traceability connections are essential for managing the interface between physical, cyber and asset information requirements. Requirements management is an increasingly difficult undertaking. Due to the scale, complexity, dynamic interactions and emergent properties, the requirements of complex rail transport systems are increasingly difficult for current requirements management methods to handle.

Tools such as Genesis and Doors Next Generation are growing as the complexity of major infrastructure projects increases (see Section 2.5.1 below for further details). In recognition of the growing maturity of requirements management in infrastructure asset planning and acquisition, researchers have proposed extensions to MBSE approaches. Scott et al. (2016) developed an MBSE Architecture Framework that structures the available data and provides guidance and traceability between the datasets. Similarly, Shirvani et al. (2020) examined how existing MBSE can be employed to enhance the procurement processes and any required evolution of the available languages to develop an architecture framework to support them. Both adopt 'The Rail Architecture frameworK' (TRAK) to support the modelling of all procurement requirements in a standardised knowledge structure for information sharing of case studies. Notably, Fusaro et al. (2017) explore the integration of Quality Function Deployment and MBSE tools in a transport systems project to support the generation of mission scenario alternatives and their prioritisation based on real-world criteria.

In summary, the importance and complexity of effective requirements management is not to be underestimated. The lack of discipline for thorough requirements management is the single biggest cause of risk leading to failure on complex rail transport projects (Chen & Jupp, 2023a).

2.6 Conceptual Framework of Lifecycle Information Requirements Management in Infrastructure Construction Industry

In the manufacturing industry, especially complex discrete manufacturing which focuses on vehicles, aircraft and aerospace, PLM (Product Lifecycle Management) backbone infrastructure is identified as an effective approach for support through model-based delivery processes. By using a PLM platform, organisations can harness three critical information management capabilities to facilitate MBSE (Erasmus et al., 2015):

1) **Integration of product information across the entire lifecycle and associated information**: This capability involves the seamless integration of product-related data and information throughout the entire lifecycle of the product. It encompasses not only the core product data but also any associated information that is crucial for understanding, designing, producing and maintaining the product.

2) **Improved collaboration between practitioners from different disciplines and business functions**: Collaboration is a key component of successful MBSE. The PLM platform allows improved cooperation and information sharing among professionals from various disciplines and business functions within the organisation. This collaboration ensures that different experts work together efficiently to achieve SE goals.

3) **Integration of people, data, processes and business systems**: This capability involves integrating various aspects of the organisation, including its personnel, data, processes and business systems. By doing so, it provides a structured methodology for managing product information across the entire organisation and its extended enterprise, which may include suppliers, partners and other stakeholders. This integrated approach ensures that information flows smoothly and consistently across the organisation and its network.

These capabilities collectively support a product information methodology that benefits the company and its extended enterprise by enhancing information management, fostering collaboration, and streamlining processes for improved system engineering and product development.

In the infrastructure construction industry, the increasing adoption of BIM, GIS, IoT and other construction technologies, commonly referred to as DE, has opened up opportunities for the reuse of information throughout an asset's entire lifecycle (Jupp, 2016). In a digital engineering enabled environment, it is crucial to develop information management processes and protocols that can facilitate the interactions among different participants in the supply chain and their model-based deliverables. This involves enabling the exchange of information that defines the product, its configuration, its intended use, and how it will be maintained (Chen & Jupp, 2018).

To support these requirements, various technologies have emerged, providing the necessary infrastructure, data structuring, cloud provisioning services, and enterprise architectures (Chen & Jupp, 2018). Much effort has therefore been made to support interoperability, where data standards have sought to support the open data exchange across various disciplines (Lai & Deng, 2018; van Berlo et al., 2012; Zhang et al., 2015). These standards play a crucial role in ensuring that information can flow seamlessly between different systems and stakeholders, promoting collaboration, efficiency and accuracy in the infrastructure construction industry.

This section introduces a conceptual framework that attempts to define the main characteristics of lifecycle information requirements management in the context of the infrastructure construction industry. The framework illustrated in Figure 2.9 provides a means of identifying and structuring the problem of implementing a through-life approach to information management in the context of the infrastructure construction industry to highlight the gaps to model-based requirements management, verification and validation, and configuration management processes and infrastructures. The framework consists of five layers: (i) asset lifecycle phases and stages (Transport for NSW, 2022c), (ii) MBSE DE aligned V-model (adapted from Eigner et al., 2012), (iii) model-based and data-driven applications, (iv) data standards supporting data transfer between model-based and data-driven applications, and (v) process standards. Underneath these five layers was the key enabler – the substitute DE "backbone" referred to in Figures 2.10 to 2.12 – as shown on top of the V-model.

In this framework, the Transport for NSW asset lifecycle phases and stages which refer to ISO 55001, ISO 15288 and INCOSE are adopted (Transport for NSW, 2022c). According to *ISO 55001 Asset management – Management systems – Requirements*, there are five main stages for asset and system lifecycle: demand and need, plan, acquire, operate and maintain, and dispose (International Organization for Standardization [ISO], 2014b). According to *AS/NZS ISO/IEC/IEEE 15288:2015* (Standards Australia, 2015) and INCOSE *Systems Engineering Handbook* (INCOSE, 2007), system lifecycle stages include concept, development, production, utilisation and support and retirement. In the Transport for NSW configuration management standard, asset lifecycle stages are further developed into need, concept, specify, procure, design, build, integrate, accept, operate and maintain, evolve and dispose (Transport for NSW, 2022c). The following sub-sections discuss layers (iii) to (iv).

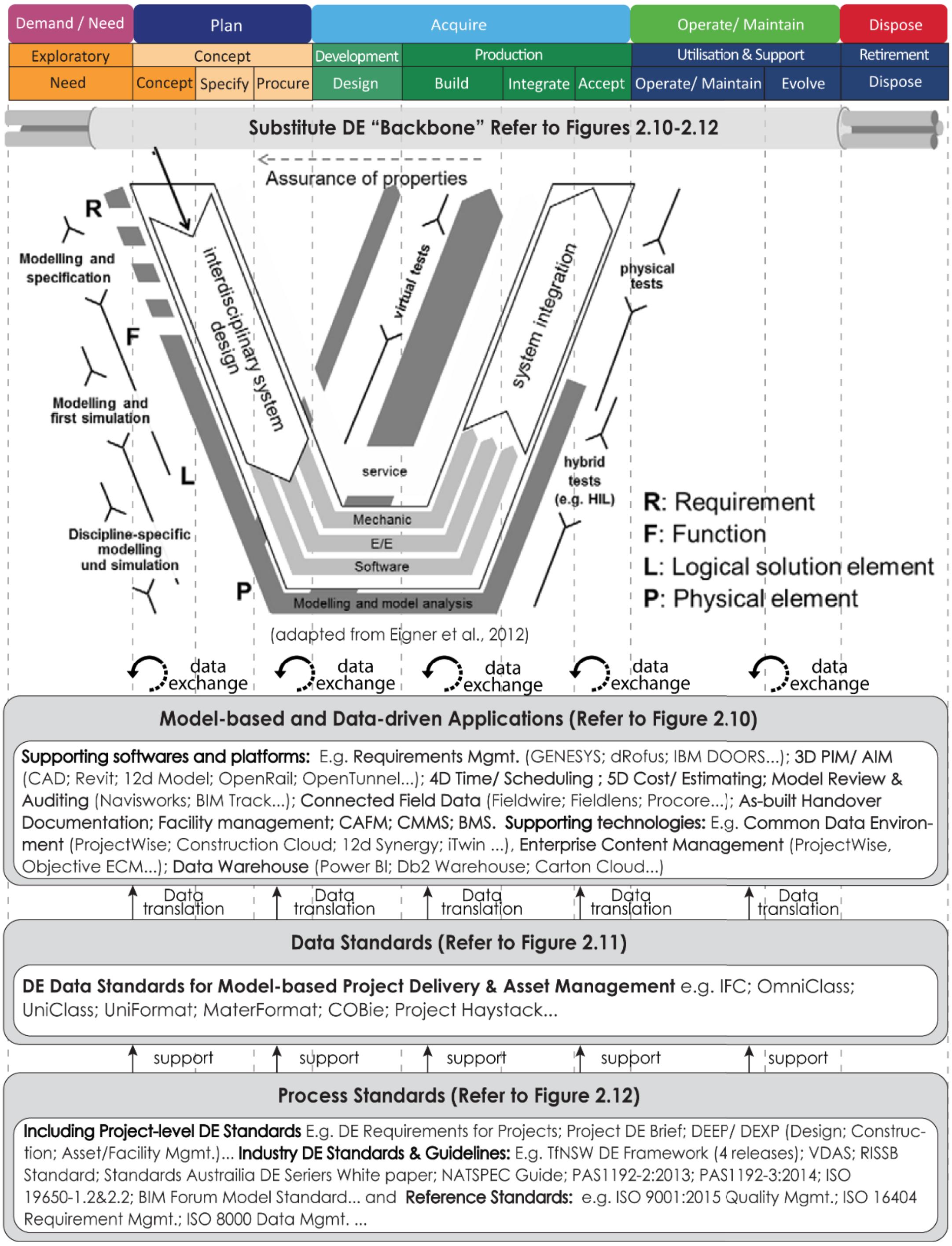


Figure 2.9 Conceptual framework of lifecycle information requirements management in infrastructure construction context

2.6.1 Model-based and Data-driven Applications

Model-based and data-driven applications can be broadly divided into two areas: supporting software and platforms, and supporting technologies (as shown in Figure 2.10). Figure 2.10 lists some typical software adopted in different phases according to their corresponding functions. Some applications span phases, e.g., requirements management; 3D PIM/AIM, 4D time/scheduling and 5D cost/estimating costing have different applications according to the minimum modelling requirements specified at each phase. Applications may also occur across multiple functions based on the multifunctional modules supported. However, this is not an exhaustive list of all software or platforms in the market. During the development of the project, stakeholders should choose the software or platforms according to the collaborative requirements of the client and themselves.

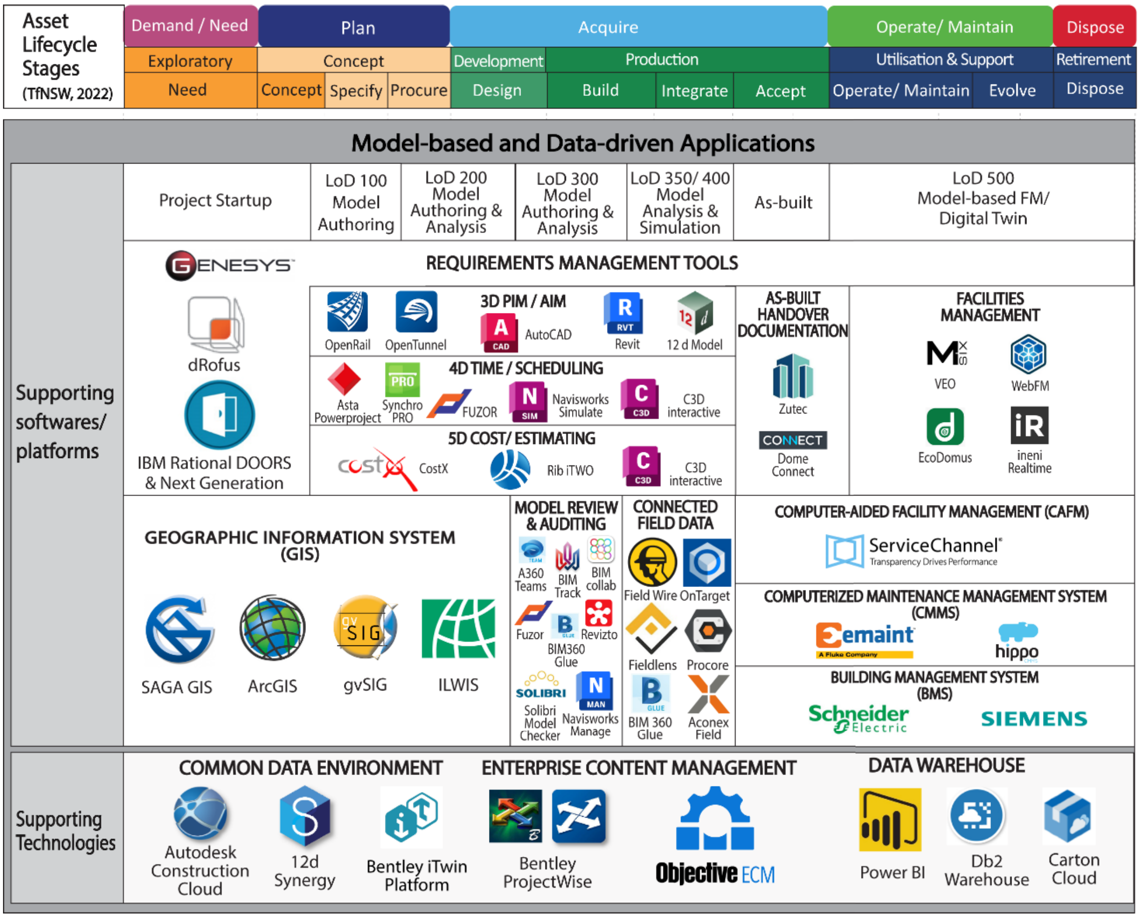


Figure 2.10 Model-based and data-driven applications (adapted from Chen & Jupp, 2018)

The handling of requirements across the life of the asset necessitates the use of digital tools. However, the use of digital requirements management tools or software is often conducted as an independent activity within organisations, leading to silos of disparate information across a project, and does not scale well (Tüzün et al., 2019). Thus, while a growing number of complex rail transport projects are now using software tools (such as GENESYS, IBM Rational DOORS, IBM DOORS Next Generation, dRofus, TRAM, ReqMan) to support requirements modelling, requirements management, configuration management, and verification and validation procedures (Chen & Jupp, 2018), their application has been hampered by the lack of a conscious effort in the establishment, adjustment and reinforcement activities that create an integrated digital ecology of requirements management tools, processes and practices (Chen & Jupp, 2023a). Adoption is largely driven by the need for complex rail transport projects to identify and trace dependencies between requirements, and is not holistic (Shah et al., 2017). In other case studies that centre on DE-enabled complex rail transport projects, researchers have explored the efficacy of various requirements management tools. IBM Rational DOORS (and Next Generation) is a commonly used tool in complex rail transport projects. Yet, despite the use of requirements management software, the interactions between the myriad of interdependent requirements often go unchecked and, as a result, remain independent (Chen & Jupp, 2022a). Linking requirements management software with the information contained in 3D models (or linked databases) to automate traceability and verification processes is therefore rare (Chen & Jupp, 2022a).

To support data integration, common data environment (CDE) platforms, enterprise content management (ECM) system and data warehouses have become essential to facilitate complex transport project delivery. The CDE provides an environment to share geometric information as well as related information such as registers, schedules, contracts, reports and model information (see detail in Section 5.2.4). In the AECO industry, a single environment and enterprise platform across the supply network is not common. However, the use of a CDE in complex rail transport projects is growing. Cloud-based platforms such as Autodesk Construction Cloud, 12d Synergy and Bentley iTwin Platform provide different forms of CDE and interface software, enabling progress towards adopting CDE platforms. ECM systems such as ProjectWise and Objective Enterprise Content Management are adopted as a loading zone for data transfer between client and supply chains.

Due to the complexity of the tool ecologies used throughout complex construction project delivery phases, a variety of data and process standards have been developed. Despite the growing maturity in collaborative modelling software and CDE (Transport for NSW, 2022b), they tend to be bolt-on solutions to the systems integration problem that persist due to construction's fragmented supply chain and typical design, tender and construct delivery methods.

With global lockdowns caused by the COVID-19 pandemic, the demand for digital transformation in rail infrastructure is increasing significantly (Shirowzhan et al., 2020). Initiatives keep emerging in terms of supporting tools and technologies, guidelines and templates. Tools and technologies such as network technology, sensors, artificial intelligence, big data and Lidar technologies are critical for the creation of digital twins (Shirowzhan et al., 2020). Another important innovation in European railways is the creation of a digital ecosystem, as digital technologies change all aspects of transport including the structure of the railway system (Tokody & Flammini, 2017). Although technology is an important enabler for DT creation, the structured processes supporting the information flows across multiple artefacts are essential together with protocols addressing those processes. However, these two aspects are largely lacking in the complex rail transport sector.

2.6.2 Supporting Data Standards

Data standards encompass a range of data exchange and data formats (as shown in Figure 2.11). Data standards reviewed here are based on the classification systems proposed by Sabol (2008). While standards are primarily applied during design and are directed towards supporting the onsite integration of asset equipment, recent data standards such as Project Haystack are designed more for operations (Haystack, 2018).

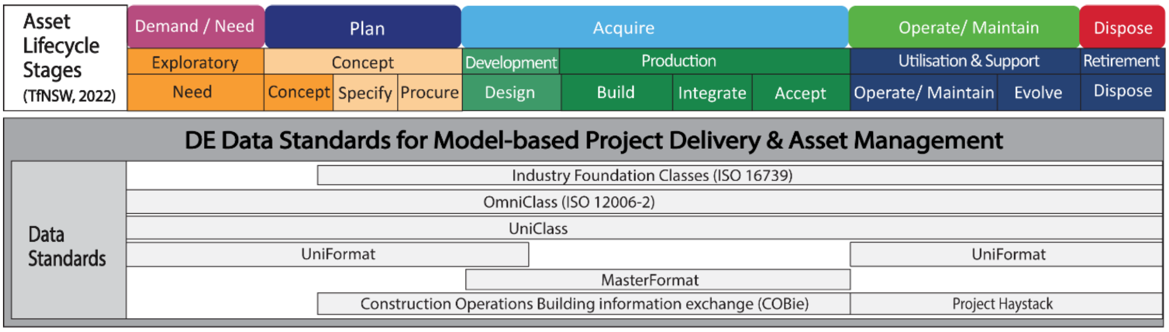


Figure 2.11 Data standards supporting model-based data-driven tool ecologies (Chen & Jupp, 2018)

One of the most commonly used data standards includes Industry Foundation Classes, or IFCs, (ISO16739) which were developed to support data exchanges between different software. Since being specified for the first time in 1996 by the IAI[4], IFC Standards have experienced a number of minor and major revisions with the most recent released version *IFC 4.3 RC1* (buildingSMART International, 2022). IFC schema support model-based interoperability (Boton et al., 2018) and, like the SysML standard modelling language, provide the means to translate different modelling formats. It is the most widely accepted DE data exchange standard and is the basis of PAS 1192-2:2013, PAS1192-3:2014 and BS 1192-4:2014 standards (buildingSMART International, 2018) and ISO 19650 standard.

Uniclass is the main classification system in the UK while the UniFormat and MasterFormat standards are well known and widely used in the North American construction context. The successor classification system, OmniClass (also known as ISO 12006-2), is also used worldwide (Boton et al., 2018). COBie was first proposed by the US Army Corp of Engineers in 2007 (East & Brodt, 2007) and was adopted as a British Standard in 2014 (Pärn et al., 2017). More recent classification systems aimed at the O&M phases are gaining traction in the industry. An example is Project Haystack, which has developed an open set of tags for naming key building automation and energy components (Haystack, 2018).

[4] International Association for Interoperability – now Building SMART International

2.6.3 Supporting Process Standards

The technical processes and technical management processes from the SE domain have the capability to support the development of process standards in the AECO domain supporting a systems approach to CPS and DT in the smart built environment. DE process standards consist of the current developed project-level DE standards informed by industry DE standards and guidelines as well as its reference industry standards (as illustrated in Figure 2.12).

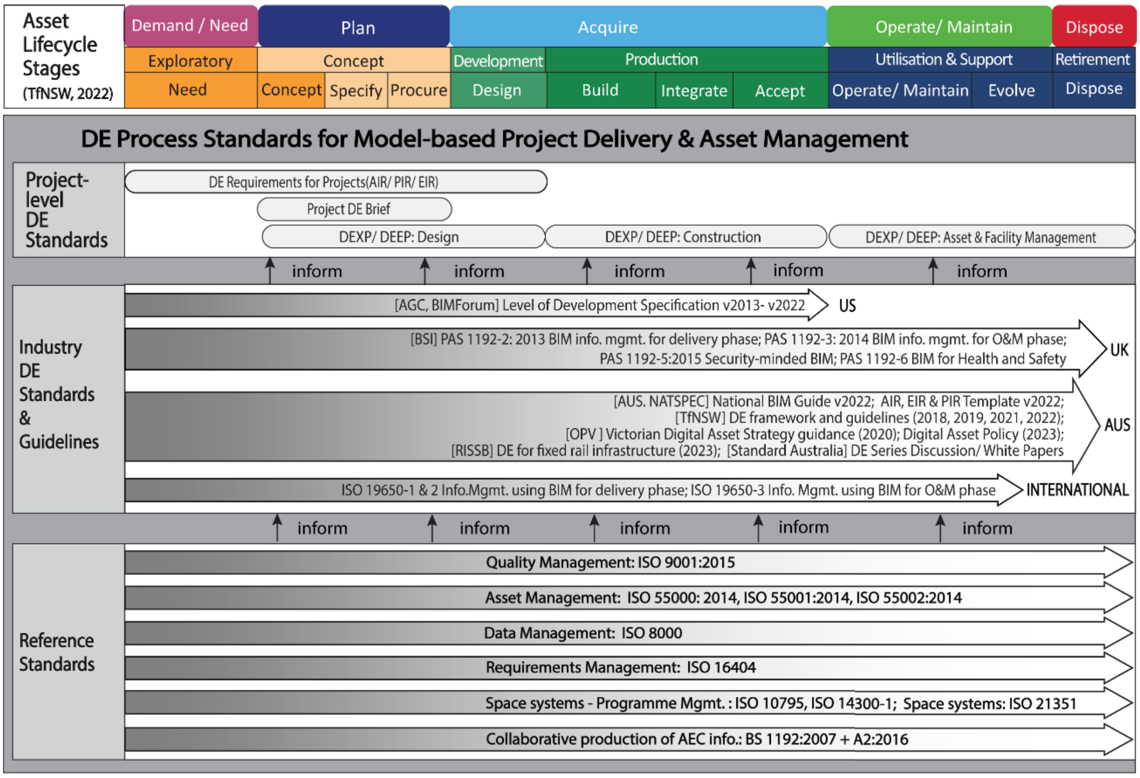


Figure 2.12 Process standards supporting a systems approach to CPS and DT (Chen & Jupp, 2018)

The project-level DE standards include DE requirements for projects, project DE brief, and DE Execution Plan (DEXP/DEEP) for design, construction, and facility/asset management purposes. While a DEXP or DEEP provides the project team members with a general structure covering modelling requirements, modelling responsibilities, discipline-specific modelling architectures and workflows for model coordination, it does not provide adequate levels of control and management capabilities that support processes and process outputs that commence at requirements elicitation and analysis and conclude with commissioning and handover activities.

To support the management of information requirements in building and civil infrastructure projects, the ISO 19650, Parts 1 and 2 (2018a, 2018b) and ISO 55000 (2014a) define general procedures and much needed consistency in the terminology, concepts and principles underpinning the development of asset management strategy and identification of supporting requirements. Together, ISO 19650 and ISO 55000 are able to provide a regulated procedural method for the development of a strategic approach to asset information lifecycle management (Chen & Jupp, 2021).

Prior to the introduction of ISO 19650, projects implementing DE and structured data approaches did not have a consistent information requirements management process across the industry (Chen & Jupp, 2021). Together, *ISO 19650-1:2018* and *ISO 19650-2:2018* describe the processes supporting digital information management, with a focus on information requirements management in the context of buildings and civil engineering works, including DE (ISO, 2018a, 2018b). ISO 19650 provides a procedural method according to four requirement types: i) organisation information requirements (OIRs), ii) asset information requirements (AIRs), iii) project information requirements (PIRs) and iv) exchange (or employer) information requirements (EIRs) of the project team. Information requirements management activities commence with the client's OIRs, which are established in a statement about the information needed by an organisation.

It is critical that the OIRs accurately reflect *what* information is required so as to be able to inform the development of the AIRs and PIRs (Chen & Jupp, 2021). The AIRs and PIRs will in turn inform production of the EIRs, which represent the overall information requirements that span the managerial, commercial and technical aspects of the AIRs and PIRs, with the owner's requirements for asset registers to support spatial referencing, classification, hierarchical management and location referencing as per the nominated schema, such as Uniclass 2015. The EIRs are then primarily concerned with the *who*, *how* and *when* of their delivery, and include the information production processes and procedures, data standards, file formats, timetables for information exchange, and roles and responsibilities of the project team (Australasian BIM Advisory Board, 2018). The EIRs are used to inform the development of the DEXP/DEEP to inform decision-making about high-level strategic objectives (Australasian BIM Advisory Board, 2018).

The development of OIRs therefore forms a critical first step in the procedural method as it supports the capture and mapping of information and deliverables contained in the policies or acts of government transport agencies, including their asset management accountability framework (AMAF), which is an integral component of ISO 55000:2014 implementation (Chen & Jupp, 2021). Australian transport agencies widely use the AMAF to detail mandatory asset management requirements and provide guidance for managing assets. The ISO 55000 series consists of three international standards that provide the terminology, requirements and guidance for implementing, maintaining and improving asset management systems. The ISO 55000 series is widely used by utilities, transport, mining, process and manufacturing industries worldwide, enabling them to streamline their expenditure, strengthen their credentials and future-proof their facilities and assets (International Council on Systems Engineering, 2007; Transport for NSW, 2017).

Together, the ISO 19650 and ISO 55000 standards and the procedural methods play a central role in the development and management of AIRs and the asset information model (AIM), as well as the ongoing management of digital information and digital deliverables supporting asset management (Chen & Jupp, 2022b).

2.6.4 Australian Government Agency Standards for Digital Engineering

The Australian federal government initiated a national BIM effort in 2012 and suggested the mandatory adoption of full 3D collaborative BIM for all Australian government building procurement projects by 1 July 2016 (buildingSMART Australasia, 2012). However, the implementation of this national mandate faced challenges due to the isolated and inconsistent efforts between different states (Jiang et al., 2022). However, some states opted to proceed more quickly with their own initiatives. In 2018, the Queensland government introduced a policy mandating the use of BIM on all government construction projects with a budget over $50 million. This mandate was planned to extend to encompass all built assets by the year 2023 (Queensland Government, 2018). As mentioned at the beginning of Chapter 2, the term "digital engineering (DE)" was introduced to the Australian transport infrastructure sector in 2019 by the Australian Transport and Infrastructure Council (Hosseini et al., 2022). Since then, new DE standards have been developed and implemented by a growing number of state infrastructure agencies, including *Digital Engineering Standard* (Transport for NSW, 2022a, 2022b), *Victoria Digital Asset Strategy* (Office of Projects Victoria, 2020), *Building Information Modelling Mandate Policy* (Queensland Government, 2018) and *Project Controls – Master Specification – PC-EDM5 Digital Engineering* (South Australian Department for Infrastructure and Transport, 2019).

Transport for New South Wales has developed its own DE strategy since 2016 and formed a DE team responsible for development of the DE framework program. Since the launch of the DE framework in September 2018, there have been four releases of documents adding new capabilities and reflecting lessons learned on pilot projects. Transport for NSW's DE Standard was first published in 2018 and updated in 2019, providing minimum requirements for implementation of DE. It details how the Data and Information Asset Management Policy is to be implemented through the application of the DE framework. This standard describes the language and approach to be adopted when implementing DE for Transport for NSW projects.

The Victorian Digital Asset Strategy, also known as VDAS, was released by the Office of Projects Victoria in March 2020. This guidance consists of three parts which provide strategic-level (Part A), organisational-level (Part B) and project-level (Part C) advice for the effective management of digital information and data throughout the life of an asset. It provides detailed guidance on planning, implementing, managing and maintaining an effective digital asset strategy throughout the lifecycle of the organisation's assets. It has been developed in collaboration with industry and is aligned with international standard ISO 19650. Based on VDAS, the Digital Asset Policy describes three levels of capabilities of 14 requirements at organisational and project level throughout the asset lifecycle.

Although the Transport for NSW DE standards and VDAS are not yet mandated for complex rail transport projects, it is clear that Australian state transport infrastructure agencies have started recognising the whole-of-life benefits that DE will bring to complex rail transport projects. These agencies are therefore implementing a complex set of international and organisational standards to achieve a more strategic approach to asset information lifecycle management.

2.7 Requirements Management Capability Maturity Assessment and Improvement

The effectiveness level of an organisation to develop quality products or services is directly related to the maturity of their processes (de Ataíde Ramos, 2014). Brinkkemper et al. (2008) presented a categorisation of two distinct process improvement approaches: the capability-based approach and the problem-based approach. First, the capability-based approach operates under the assumption that a company's capabilities should grow in maturity to enhance performance (Brinkkemper et al., 2008). Through an assessment of the organisation's current capabilities, the maturity level can be determined, and recommendations of implementing capabilities on a higher maturity level can be made (Brinkkemper et al., 2008). Examples of capability-based approaches are Software Engineering Institute's (SEI's) old Capability Maturity Model (CMM) and the relatively new Capability Maturity Model for integration (CMMI) (Software Engineering Institute, 2010). Second, the problem-based approach used the mechanism of solving the underlying problems, or root causes, that cause a certain process to underperform. An example of a problem-based approach is root cause defect analysis (RCA), which has been applied to process improvement and incident prevention in software and non-software industries (Leszak et al., 2000).

Some critique exists on the capability-based approach. For example, it can be considered as too superficial for a small company, and difficult to implement (Brinkkemper et al., 2008). The CMM/CMMI approach is often not adopted by organisations for the following reasons (Brinkkemper et al., 2008): the organisation was small, the services were too costly and the organisation had no time to implement the process improvements.

While following a complete problem-based approach would be too inefficient due to the extensive analysis process required (Brinkkemper et al., 2008), in the context of this research, a capability-based approach is adopted as the main clients of complex rail transport projects are government agencies that develop numerous projects at the same time. It is not efficient to just focus on specific problems encountered by different project teams. Instead, by improving the capability of the organisation to manage requirements, it will benefit all projects in the future.

In complex rail transport projects, measuring the maturity level of requirements management capability offers a solution to organisations who are seeking requirements management capability improvement (Chen & Jupp, 2023b). This section investigates the fundamental component of maturity models, compares existing requirements management-related capability maturity models, and then discusses their applicability in supporting capability assessment and improvement of requirements management in complex rail transport projects.

2.7.1 Common Components of Maturity Models

In the area of process improvement, various maturity models have been put forth (see Table 2.3), all of which have a shared characteristic: the delineation of multiple dimensions or process areas across a number of discrete stages or levels of maturity (Fraser et al., 2002). These models provide descriptions of performance characteristics at various levels of granularity (Fraser et al., 2002).

The fundamental components which may or may not be present in each maturity model consist of (Fraser et al., 2002):

1) multiple levels (usually ranging from three to six)
2) description for each level (e.g., initial, repeatable, defined, managed, optimising)
3) generic description or summary of the characteristics of each level as a whole
4) a number of dimensions or "process areas"
5) a number of elements or activities for each process area
6) a description of each activity as it might be performed at different levels of maturity.

When assessing performance (i.e. maturity), a differentiation is drawn between those models where different activities may be scored to be at different levels, and those in which maturity levels are "inclusive", where a cumulative number of activities must all be performed (Fraser et al., 2002). In the Software Engineering Institute Capability Maturity Model terminology, these are referred to as "continuous" and "staged" maturity level respectively (Fraser et al., 2002).

For the maturity model style, three basic groups are identified.

- Maturity grids: It generally contains textual explanations for each activity at each maturity level. It has a moderate level of complexity, requiring at most a few pages of text to present (Fraser et al., 2002).
- Likert-like questionnaires: It can be viewed as a simple version of the maturity model. The question represents a statement of "good practice" and the respondent is asked to score the relative performance of the organisation on a scale from 1 to n (Fraser et al., 2002).
- CMM style models: This model category holds a higher degree of formality and complexity with a particular architecture. Each process area is organised by common features which specify a number of key practices to address a series of goals (Fraser et al., 2002). While overarching maturity descriptions are provided for each level, there are no individual descriptions for each activity at each maturity level (Fraser et al., 2002).

2.7.2 Components in Requirements Management Specific Maturity Models

Amongst the maturity models listed in Table 2.3, some are specifically designed for requirements management. Existing models supporting requirements management process maturity assessment and improvement include the Requirements Engineering Good Practice Guide (REGPG) (Sommerville & Sawyer, 1997), the Requirements Engineering Process Maturity (REPM) (Gorschek & Tejle, 2002), the Requirements Capability Maturity Model (R-CMM) (Beecham et al., 2003; Beecham, Hall & Rainer, 2005), the Requirements Engineering Process Assessment and Improvement Model (REPAIM) (Solemon et al., 2012) and the Requirements Process Maturity Model (RPMM) (Louie, 2015).

The first three models (i.e., REGPG, REPM and R-CMM) arose in the software industry and were built based on the Software-CMM or CMM which has been retired and unsupported since the release of the new maturity model Capability Maturity Model Integration (CMMI) (Solemon et al., 2012). Combining the strengths of these models and improvement on requirements engineering best practices presented in CMMI, the REPAIM was developed and validated (Solemon et al., 2012). The last model mentioned above (RPMM) was proposed in the SysEne Blog as a general framework consisting of key areas as process, technology, organisation and people (Louie, 2015). However, there are no further details but a general description of each maturity level. In this section, key components of these five maturity models are reviewed and compared in terms of their characteristics, maturity levels, assessment area, assessment process and limitations (Rana et al., 2015; Solemon et al., 2009).

Table 2.3 Overview of different maturity models (adapted from Fraser et al., 2002)

Subject & Reference	Maturity Levels						Approach
Quality Management Process Maturity Grid (Crosby, 1996)	Level 1 Uncertainty	Level 2 Regression	Level 3 Awakening	Level 4 Enlightenment	Level 5 Certainty		Grid 5 issues, captions describing performance at each level
Collaboration maturity model (Fraser & Gregory, 2002)	Level 1 None	Level 2 Partial	Level 3 Formal	Level 4 Culturally embedded			Grid 7 issues, detailed description & captions
ISO 9004 (EN ISO 9004:2000)	Level 1 No formal approach	Level 2 Reactive approach	Level 3 Stable formal system approach	Level 4 Continual improvement emphasised	Level 5 Best in class performance		Global levels defined 5 questions, 11 issues
Digital Asset Policy Requirements (OPV, 2021)	Defined	Managed	Optimising				4 areas, 14 issues
IIMM Asset Management Maturity Assessment (IIMM, 2020)	Aware 0-20	Basic 21-40	Core 41-60	Intermediate 61-80	Advanced 81-100		IIMM
Project Management Maturity	1	2	3	4	5		Likert style questionnaire 15 areas, 85 issues, no descriptions of performance
Software CMM – Staged: Maturity levels (Pautk et al., 1993)	Level 1 Initial	Level 2 Repeatable	Level 3 Defined	Level 4 Managed	Level 5 Optimising		CMM Style
Requirements Engineering Good Practice Guide (REGPG) (Sommerville & Sawyer, 1997)	Level 1 Initial	Level 2 Repeatable	Level 3 Defined				CMM Style 66 practices Continuous
CMMI – Continuous: Capability levels (Shrum, 2000)	Level 0 Not performed	Level 1 Performed	Level 2 Managed	Level 3 Defined	Level 4 Qualitatively Managed	Level 5 Optimising	CMM Style
FREE (Collaboration) Capability Assessment Framework (Wognum & Faber, 2000)	Level 2 Repeatable	Level 3 Defined	Level 4 Managed	Level 5 Optimising			CMM Style
Requirements Engineering Process Maturity (REPM) Model (Gorschek & Tejle, 2002)	REPM 1 Initial (Wood)	REPM 2 Basic (Bronze)	REPM 3 Formulated (Silver)	REPM 4 Developed (Gold)	REPM 5 Advanced (Platinum)		CMM Style 60 actions
Process & Enterprise Maturity Model (PEMM) (Hammer, 2007)	Level 1 Initial	Level 2 Managed	Level 3 Defined	Level 4 Qualitatively Managed	Level 5 Optimising		CMM Style
Business Process Orientation Maturity Model (BPOMM) (MacCormack, 2001)	Level 1 Ad hoc	Level 2 Defined	Level 3 Linked	Level 4 Integrated	Level 5 Extended		CMM Style
Requirements Capability Maturity Model (R-CMM) (Beecham et al., 2003)	Level 1 Ad hoc	Level 2 Repeatable	Level 3 Defined	Level 4 Managed	Level 5 Optimising		CMM Style
Requirements Engineering Process Assessment and Improvement Model (REPAIM) (Solemon et al., 2012)	Level 0 Incomplete	Level 1 Performed	Level 2 Managed	Level 3 Defined			CMM Style 28 processes
Requirements Process Maturity Model (RPMM) (Louie, 2015)	Level 1 Initial (Ad hoc)	Level 2 Managed (Organised)	Level 3 Defined (Structured)	Level 4 Qualitatively Managed (Traced)	Level 5 Optimising (Integrated)		CMM Style General Framework

2.7.2.1 Overview of REGPG

The Requirements Engineering Good Practice Guide (REGPG) (Sommerville & Sawyer, 1997) stands out as one of the earliest process enhancement and evaluation frameworks for requirements management available to the public. It presents three levels of requirements management process maturity that are consistent with CMM's first three levels – Initial, Repeatable and Defined. The REGPG was intentionally crafted to supplement the CMM, as the CMM does not encompass requirements management processes. The decision to incorporate only three levels was influenced by their preliminary efforts in shaping the model, revealing that only a limited number of companies with defined RE processes were included in the higher CMM levels (Solemon et al., 2014).

The three levels of REGPG are described as follows:

Level 1 – Initial. There is no defined requirements management process in the organisation, leading to poor requirements management, late delivery of products, and budget over-runs (Sommerville & Ransom, 2005).

Level 2 – Repeatable. There are explicit standards for requirements documents and requirements management-related policies and procedures in the organisation. Requirements management processes are supported by some advanced tools or techniques (Sommerville & Ransom, 2005).

Level 3 – Managed. Requirements management processes are documented, standardised and integrated into a standard process based on best practices. There is an active process improvement program and objective assessment of the value of new methods and techniques in the organisation (Sommerville & Ransom, 2005).

In terms of assessment area, the REGPG includes 66 practices, also known as guidelines or key practices in CMM. These practices come either from existing standards and reports of requirements practices, or are based on the experience of expert partners. These practices are classified into *Basic*, *Intermediate* and *Advanced* practices, reflecting the extent that requirements practices are used and standardised in an organisation (Solemon et al., 2014). These 66 practices are also grouped into eight requirements management process areas: *Requirements Document, Eliciting Requirements, Requirements Analysis and Negotiation, Describing Requirements, System Modelling, Requirements Validation, Requirements Management,* and *Critical System Requirements* (Sommerville & Sawyer, 1997). In the description of each practice, cost of introduction and cost of implementation is provided to support organisations to make a cost-benefit analysis (Sommerville & Sawyer, 1997).

During assessment, a checklist of the 66 REGPG practices should be scored according to the ways they are implemented in the organisation. There are four scenarios of implementation (Sommerville & Sawyer, 1997):

1) Standardised. The practice has a documented standard in the organisation and is used throughout the organisation in a standardised way. Score = 3.
2) Normal use. The practice is widely followed in the organisation but is not mandatory. Score = 2.
3) Used at discretion of project manager. Some project managers may have introduced the practice, but it is not universally used. Score = 1.
4) Never. The practice is never or very rarely applied. Score = 0.

The maturity level is calculated by summing the weighted scores for all implemented practices in Basic, Intermediate and Advanced categories as summarised in Table 2.4.

Table 2.4 REGPG process maturity levels (Sommerville & Ransom, 2005)

Maturity level	Scores of practices
Initial	Score of above 54 in Basic Practices
Repeatable	Score of above 54 in Basic Practices and below 40 in (Intermediate + Advanced) Practices
Defined	Score of above 54 in Basic Practices and above 39 in (Intermediate + Advanced) Practices

A difference from CMM is that the REGPG uses a continuous representation of maturity level instead of a staged one (Solemon et al., 2014). That is to say, the process activities are not associated with a single maturity level. Organisations are supposed to achieve improvement by implementing practices across multiple process deliverables or activities (Solemon et al., 2014). Thus, this model is able to reflect particular areas of weaknesses and allow organisations to select practical options for further improvement (Solemon et al., 2014). This model is well-suited for organisations initiating a requirements management process improvement program (Solemon et al., 2014).

Nevertheless, it is important to note that the REGPG was initially designed for the safety-critical domain. Adapting it for use in other domains is currently lacking. Additionally, the classification of good practices within the model, incorporating eight levels of cost for introducing guidelines, has been perceived as overly intricate and complex (Solemon et al., 2014).

2.7.2.2 Overview of REPM

Based on the REGPG, CMM and other studies on requirements management process improvement, Gorschek and Tejle (2002) developed the Requirements Engineering Process Maturity (REPM) model. However, the REPM only focuses on evaluating requirements management processes maturity of a project instead of a whole organisation (Solemon et al., 2014). Five maturity levels were developed in REPM based on the CMM framework:

REPM 1 – Initial (Wood). At this level, the requirements management process is very poor with no planning procedures or validation of requirements.

REPM 2 – Basic (Bronze). At this level, the requirements management process is more structured and complete. In order to establish repeatability, organisations at this level implement standardised requirements specification and documentation procedures, with stakeholders being identified (Gorschek & Tejle, 2002). While these organisations might allocate dedicated resources for the requirements management process, they might overlook aspects of the system environment, such as the application domain or business processes (Gorschek & Tejle, 2002).

REPM 3 – Formulated (Silver). At this level, thorough attention is given to studying the application domain and business processes, with a deliberate effort to involve all stakeholders. Requirements are systematically prioritised and re-prioritised to accommodate new additions. The interdependencies, interactions and conflicts among requirements are also carefully addressed. A comprehensive risk assessment is also carried out on selected requirements (Gorschek & Tejle, 2002).

REPM 4 – Developed (Gold). At this level, both the human domain and business domain are thoroughly taken into consideration. Furthermore, there is a focus on advanced risk assessment and traceability. Although a meticulously examined and standardised requirements management process is in place, there is an absence of a planned and systematic approach to requirements, as well as a structured framework for requirements reuse (Gorschek & Tejle, 2002).

REPM 5 – Advanced (Platinum). At this level, a deliberate effort is made to reuse requirements whenever feasible, and any declined requirements are duly documented. Furthermore, the creation of software architectural models takes place, alongside the utilisation of system model paraphrasing to validate requirements. Additionally, an advanced process of re-prioritising requirements is performed (Gorschek & Tejle, 2002).

When it comes to the assessment area, a logical and expandable tree-structure is presented in REPM. At the top are three Main Process Areas (MPAs) including Requirements Elicitation, Requirements Analysis and Negotiation, and Requirements Management (Gorschek & Tejle, 2002). Several Sub Process Areas (SPAs) are developed under each MPA, and at the bottom are

60 Actions (similar to practices in REGPG). Actions encompass both activities and elements that should be present within the project. These actions have a general character and are aligned with the five maturity levels of the REPM model. The design of the model was intentionally organised to allow its content to be structured in a manner that facilitates ongoing model development (Gorschek & Tejle, 2002). Curiously, while these levels can signify the requirements management process maturity of a project, organisations are not obligated or advised to elevate all their projects to the highest maturity level (Solemon et al., 2014).

Similar to REGPG, a checklist consisting of the 60 actions is used to assess the requirements management process maturity of projects (Gorschek & Tejle, 2002). Each action can be assessed in one of three states: completed, not completed, and satisfied-explained (Gorschek & Tejle, 2002). An action is marked as satisfied-explained, which holds equivalent weight as the completed state, if it is either incomplete or partially fulfilled, but not applicable to the requirements management process of the organisation evaluating the project (Gorschek & Tejle, 2002). After completion of the REPM assessment checklist, the outcomes are added up based on the corresponding REPM level. To achieve a specific maturity level, a project must have successfully completed or satisfied-explained all the actions associated with that particular REPM level (Gorschek & Tejle, 2002).

In general, REPM has potential as an assessment tool of small and medium enterprises (SMEs) (Solemon et al., 2014). However, it is worth noting that this model concentrates on evaluating projects rather than the entire organisation scope (Solemon et al., 2014). Additionally, its emphasis lies solely on process assessment and does not encompass process improvement (Solemon et al., 2014). Essentially, REPM serves as a checklist delineating the recommended requirements management practices to be implemented within a project context (Solemon et al., 2014).

2.7.2.3 Overview of R-CMM

The Requirements Capability Maturity Model (R-CMM) (Beecham et al., 2003; Beecham, Hall & Rainer, 2005) is recognised as the University of Hertfordshire Model (Solemon et al., 2014). This model gives practitioners guidelines to understand their own requirements management process and navigate through the various stages inherent in requirements management process enhancement (Solemon et al., 2014). The R-CMM is a direct adaptation of the CMM, specifically the Software Capability Maturity Model (SW_CMM) (Beecham et al., 2003; Beecham, Hall & Rainer, 2005). It leverages the five maturity levels from SW_CMM to categorise requirements management processes. This model adopts a Goal Question Process Metric (GQM) approach, aiding organisations in evaluating their existing practices and establishing achievable objectives when embarking on requirements management process improvement (Solemon et al., 2014). There are five R-CMM levels:

R-CMM Level 1: The goal of this level is to cultivate awareness about the requirements process. Organisations at this level exhibit ad-hoc requirements procedures, and challenges with requirements are frequent. At this level, organisations are striving to cultivate a structured and disciplined process (Beecham et al., 2003).

R-CMM Level 2: The goal of this level is to establish a repeatable requirements process. At this level, companies possess repeatable requirements processes, with an emphasis on establishing project-level standards. Standard requirements processes are documented and implemented across similar projects. At this level, organisations are focused on establishing a standardised and coherent process (Beecham et al., 2003).

R-CMM Level 3: The goal of this level is to initiate a defined requirements process. Organisations at this level achieve companywide communication and standardisation of requirements processes that extend to all projects. Organisations at this level are aiming to achieve a process that is predictable and reliable (Beecham et al., 2003).

R-CMM Level 4: The goal of this level is to implement a managed requirements process. Organisations at this level employ measurements to monitor processes and identify areas for enhancement. At this stage, organisations are dedicated to enhancing the process in a continuous manner (Beecham et al., 2003).

R-CMM Level 5: The goal of this level is to establish an optimising requirements process. Organisations here employ enhanced requirements methods and tools in a stable and foreseeable environment. At this level, organisations are dedicated to achieving continuous improvement in their processes (Beecham et al., 2003).

The objective of each level is then broken down into five questions related to requirements, which serve to identify requirements process phases (Beecham et al., 2003). These phases encompass *requirements management*, *elicitation*, *analysis and negotiation*, *documentation*, and *verification and validation* (Beecham et al., 2003). Similar to REPM MPAs, within the R-CMM, each phase outlines a set of processes at each maturity level. This model recognised a total of 68 processes drawn from three primary sources: SW_CMM, empirical research, and existing literature (Beecham et al., 2003). For the sake of clarity and precise execution, an in-depth guideline was devised for each process. These detailed guidelines retain the Goal Question Process Metric framework, and each process guideline prescribes sub-processes required to attain improvement objectives (Beecham et al., 2003). However, only the detailed guidelines for level 2 have been finalised and tested, while the guidelines for levels 3 to 5 remain unpublished.

During process assessment of R-CMM, a score ranging from 0 to 10 (outstanding=10, qualified=8, marginally qualified=6, fair=4, weak=2, poor=0) is assigned to each process based on three evaluation criteria (i.e., approach, deployment, and results) ((Beecham et al., 2003; Beecham, Hall & Rainer, 2005). These evaluation criteria are adapted from the assessment method used at Motorola as elucidated in Daskalantonakis (1994). The average score for each process is computed by considering the scores for approach, deployment and results. Subsequently, the scores for all processes in a particular phase are totalled, and this summation is carried out across all five phases to generate an overall capability score. This score serves to pinpoint weaknesses in the organisation's requirements process. The overall capability score aligns with the following framework: Level 1: 0–2, Level 2: 3–4, Level 3: 5–6, Level 4: 7–8 and Level 5: 9–10.

The strength of the model is that it provides detailed guidelines for processes at Level 2. However, weaknesses of the R-CMM include that the model cannot relate to all types of requirements management processes, nor does it reflect the iterative and cyclical nature inherent to the ongoing requirements management processes (Solemon et al., 2014). Moreover, the model may remain partially completed until subsequent efforts are undertaken to finalise levels 3 to 5 (Solemon et al., 2014).

2.7.2.4 Overview of REPAIM

Following the CMMI for Development (CMMI-DEV) standard version 1.3, the Requirements Engineering Process Assessment and Improvement Model (REPAIM) provides detailed and explicit guidance on requirements management practices (Rana et al., 2015; Solemon et al., 2012). Two main stages in developing the REPAIM include building the requirements management process maturity model (PMM-requirements management) and building the requirements management process assessment method which is known as the Flexible Lightweight Assessment method for requirements management (FLA-requirements management) (Solemon et al., 2012). Each stage comprises several activities in building corresponding components in REPAIM. Guided by success criteria such as completeness, consistency, practicality, usefulness and verifiability, activities in PMM-requirements management development include 1) creating the maturity model framework, 2) identifying the structure and components of the maturity model, and 3) defining the components with detailed information (Solemon et al., 2012). Then, the steps in developing FLA-requirements management are identification of requirements management assessment stages and steps, definition of the assessment method components with detailed information, and preparation for supporting tools (Solemon et al., 2012).

There are four levels of maturity in this model, providing a way to measure the current state of the requirements management process in an organisation as well as the evolutionary path for improvement (Solemon et al., 2012). The following paragraphs describe each requirements management maturity level in further detail.

Level 0 of requirements management maturity is described as an incomplete requirements management process which is similar to level 0 of CMMI-DEV. At this level, requirements management activities are either not performed at all or partially performed (Rana et al., 2015).

Level 1 of requirements management maturity can be described as a performed requirements management process. At this level, requirements are elicited, analysed, prioritised, documented, verified and validated, requirements changes are managed, and requirements traceability is maintained (Rana et al., 2015). However, a performed requirements management process usually does not have the supporting infrastructure in place.

Level 2 of requirements management maturity is described as a managed requirements management process with decreasing weaknesses compared with level 1. At this level, requirements management processes are properly planned; relevant stakeholders are involved; adequate resources are allocated; staff are trained; the requirements management process is supervised and reviewed; requirements management process outputs are validated; the requirements management process is verified; and requirements management status is monitored by management (Rana et al., 2015; Solemon et al., 2012).

Level 3 of requirements management maturity can be described as a defined requirements management process with more detailed description and more rigorous execution compared with level 2. This level clearly states process objectives, assumptions, related standards, policy, performed activities, inputs and outputs to/from activities, assigned resources, person responsible for each activity, and supporting tools for requirements management processes (Rana et al., 2015; Solemon et al., 2012). This level also includes gathering improvement related information such as work products, processes and product measures and improvement suggestions for requirements management processes (Rana et al., 2015).

The REPAIM shows its capability to assess requirements management processes and prioritise their improvement, adapt and complement existing maturity standards and assessment approaches, and adapt to the demands of different organisations (Solemon et al., 2012). However, there are two identified drawbacks of REPAIM.

One of the main drawbacks of the model is that training is still required by the practitioner to understand the model regardless of the details provided within the model (Solemon et al., 2012). Another drawback of this model is that it appears to need further examples, templates and instructions to inform an effective implementation by potential users (Solemon et al., 2012).

2.7.2.5 Overview of RPMM

The Requirements Process Maturity Model (RPMM) was proposed by Louie (2015) in the SysEne Blog as a general framework. This model was developed based on CMMI, Six Sigma, MBSE, PLM and the author's expertise in the industry. It covers not only the requirements management process, but also consider the techniques, tools, integration, organisation structure, training and culture (Louie, 2015). There are five maturity levels (i.e., initial, managed, defined, quantitatively managed, and optimising) defined in this model which is similar to the CMMI style. The structure of RPMM and a brief description of each level is shown in Table 2.5.

The structure of RPMM is applicable to many domains including construction and rail. However, the content of the model is conceptual and difficult for an organisation to directly implement. Further development and validation are necessary before implementation.

Table 2.5 Requirements process maturity model (Louie, 2015)

Maturity Levels / Main Themes	1 Initial (ad hoc)	2 Managed (organised)	3 Defined (structured)	4 Quantitatively Managed (traced)	5 Optimising (integrated)
Process	Processes unpredictable, poorly controlled, and reactive	Process characterised for projects and often reactive	Process characterised for the organisation and is proactive	Process measured and controlled	Focus on process improvement and integration
Practices and Techniques	▪ Person dependent ▪ Informally and inconsistently ▪ Written (partial)	▪ Written, formatted ▪ Accessible, security, version control	▪ Specific types ▪ Attributes defined (importance, stability, release differences)	▪ Applied, integrated and measured ▪ Fully traceable	▪ Continuously improved
Tools	▪ Separated documents, separated packages (i.e., Word and Excel)	▪ Consistent templates in Excel or Word ▪ May use RM tool	▪ Consistent templates in Excel or Word ▪ May use RM tool	▪Typically uses a RM tool	▪ Automated and integrated tools
Integration	▪ None	▪ Key projects use, others may not ▪ Some linkage to other processes	▪ All projects and functions use ▪ May be integrated with PLM	▪ Integrated with PLM	▪ Integrated with design models and DFMEA (design failure modes and effects analysis)
Organisation	▪ Limited support ▪ Partly defined roles ▪ Little training	▪ Informal structure ▪ External training	▪ Formal structure and organisation ▪ External, custom training	▪ Fully operational, managed and measured ▪ Internal training	▪ Integrated ▪ Internal, specialty training
People	▪ Driven by few	▪ More believers	▪ Across company ▪ May have internal experts ▪ Some cultural norms	▪ Internal experts ▪ High quality requirements culture	▪ Advanced level of proficiency ▪ Culture: DNA of Organisation

2.7.3 Developing Capability Assessment and Improvement Models in the Context of Complex Rail Transport Projects

As introduced in Section 2.1, a complex rail transport system is a safety-critical system. Requirements in rail transport projects implementing DE not only include the technical systems requirements that were decomposed during the planning and design phases, but also the information requirements (AIRs, PIRs and EIRs) about the digital twin modelling of the rail transport system. Requirements management in complex rail transport projects should not only consider the development and management of these two different types of requirements, but more importantly, the interface management of technical system requirements and information requirements. Thus, the development of a requirements management capability assessment and improvement model in complex rail transport projects should consider both types of requirements as well as the interaction between them.

In terms of the maturity levels, considering the immaturity of requirements management practices in complex rail transport projects, REGPG and REPAIM styles are considered as the main references in this research. The main challenge is to identify assessment areas for the model. Since systems engineering has a level of implementation in rail transport projects, maturity models REGPG, REPAIM and RPMM, which are also based on system engineering, are selected as the reference for requirements management process areas (REGPG, REPAIM), techniques and organisation areas (RPMM). In this thesis research, the revision of technical system requirements management and development of information requirements management activities is conducted based on the findings from literature, industry interviews, surveys and feedback sessions.

The assessment process of this model adopts a hybrid style combining project and organisation level assessment. The REGPG style is adopted for assessing organisational maturity level by generating assessment checklists of the activities, and then scoring each activity based on the level of standardised implementation (standardised = 3, normal use = 2, discretionary = 1, never = 0). When the model is adopted at the project level, it could be regarded as a checklist of activities required for effective requirements management.

2.8 Research Gaps

The primary gap identified from reviews of the literature and standards and industry investigation is that there is currently a lack of a whole-of-system and whole-of-life approach to support effective information requirements management in the context of digital engineering enabled complex rail transport projects. The traditional systems engineering V-model is outdated with regards to information requirements management capabilities as it neglects the design and simulation of the virtual model (Hatakeyama et al., 2018). In complex rail transport projects, the implementation of digital approaches to requirements management is immature in comparison to manufacturing sectors (Chen & Jupp, 2018; Johnson et al., 2021). Thus, requirements management in complex rail transport projects should not only consider the development and management of different types of requirements, but more importantly, the interface management of technical system requirements and information requirements. The alignment between system engineering requirements verification processes during each phase of the project with those reflected in the digital engineering of asset data deliverables is currently neglected. Although the central role that configuration management plays in support of systems engineering process and digital engineering capabilities has been recognised in transport infrastructure projects, the process of configuration management remains primarily manual. Moreover, although there are some maturity models for requirements management improvement in the literature, and there are guidelines for systems engineering process and digital engineering management process guidelines in the industry, there is a lack of an implementation ready and activity-based model or framework to assess the maturity level of information requirements management practices and provide potential improvement pathways in the transport infrastructure sector.

To address the research gaps, the aim of this research is to develop a Capability Improvement Framework for information requirements management on complex rail infrastructure to support an effective management of technical systems requirements (for physical deliverables) and information requirements (for digital deliverables). This research focuses on the following three research questions:

Q1: In the context of complex project delivery, what is the current status of information requirements management and what capabilities are essential to the efficient and effective management of information requirements?

Q2: In the specific context of complex rail transport projects implementing digital engineering approaches, what capabilities are essential to information requirements management and what is the current status of information requirements management practices in industry?

Q3: In the context of complex rail transport projects, what levels of capability can be identified to assess the relative maturity of information requirements management practices, and what activities are required to support the improvement of information requirements management?

2.9 Summary

This chapter concentrated on establishing the groundwork for the research study, with the objective of identifying relevant boundaries and existing gaps within the research domain. Figure 2.13 presents the structure of this chapter.

First, features of complex rail transport systems were presented. This was followed by a further discussion about whether the complex rail transport system is a cyber-physical system. Various concepts of the digital twin and its implementation in complex rail transport systems were also investigated. The role of AIRs specification defined by clients in support of the creation of digital twins was explored. The current "state-of-the-art" in systems requirements management was examined. This involved describing and contrasting various requirements management process models, followed by the identification of fundamental activity domains within requirements management. The study then explored suitable requirements management methods applicable in the rail transport sector.

The chapter then presented a conceptual framework defining the main characteristics of lifecycle information requirements management in the context of the infrastructure construction industry as a starting point for research development. Additionally, the chapter explored and analysed various maturity models that aid in capability assessment and enhancement. Common components shared by these maturity models were identified. The research focused on maturity models tailored specifically for requirements management by reviewing their capabilities and identifying their limitations within the context of the overarching research.

Based on findings from the background literature review, the research gap was identified. The research aim and research questions are presented with the intention of addressing the research gap. The following chapter introduces the methodology and the implementation of a design science research framework to address the research questions with a three-step process.

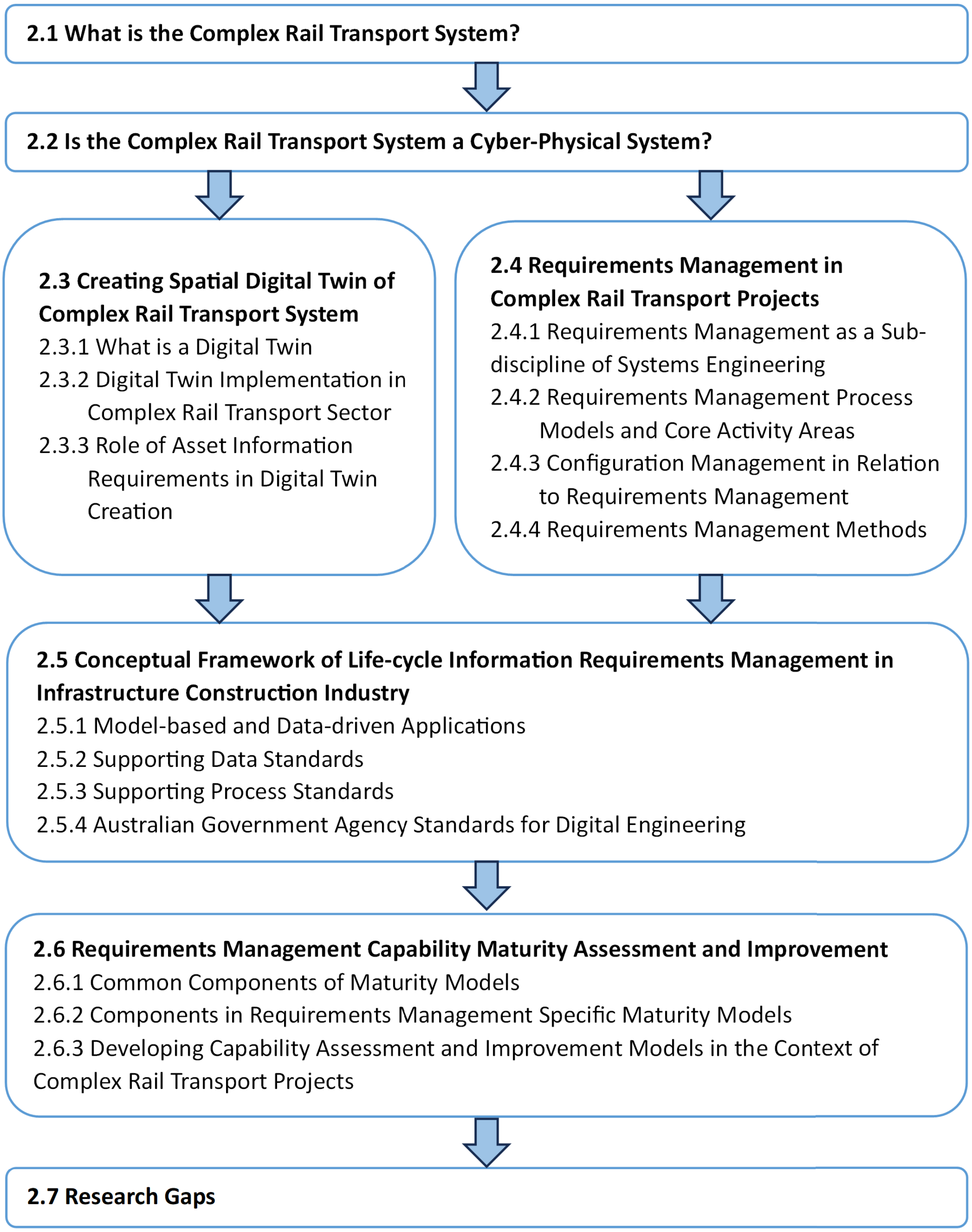


Figure 2.13 Structure of Chapter 2 content

Chapter 3 Research Methodology and Design

This chapter introduces the research methodology and research design to achieve the goals and objectives of this study. The research methodology and design are documented in the following sub-sections: overall strategy of inquiry; desktop-based research (using second-hand data); multiple-case study and online survey; development of the Capability Improvement Framework; and research management strategies.

3.1 Overall Strategy of Inquiry

This research seeks to address the main question of *how are information requirements managed on complex rail transport projects, especially in terms of the implementation of digital engineering, and how can information requirements management practices be improved?* In responding to this research question, the epistemological assumption of this study is constructivism, which falls under the qualitative research paradigm. Thus, an inductive research approach is commensurate with this type of research for three principal reasons. First, the area under investigation is relatively unexplored and it is difficult to conduct a quantitative study, which requires a large number of samples. Second, the aim of the research is not to test the effectiveness of a theory but to explore the improvement of information requirements management capability in supporting data and model integrity throughout planning, delivery and operation stages in complex rail transport projects. Third, in the broader field defining project management, the ontological assumption is subjective, and the impact of participants should therefore not be neglected. A constructivist approach understands the world as rich and complex, favouring the view that there may not be a single truth as the researchers' background shapes their interpretation (Creswell & Poth, 216).

Accordingly, the research methods applicable to this research project include design science research, action research, case study research, surveys, grounded theory, archival research, histories and ethnography (Saunders et al., 2009; Yin, 2013). The design science paradigm fits well with the objective of this research as it aims to push the limits of humans and capabilities of organisations by developing novel and innovative artefacts. Figure 3.1 adapts the design science research framework of Information Systems proposed by Hevner et al. (2004) and overlays three inherent research cycles – relevance cycle, rigour cycle and design cycle (Hevner, 2007).

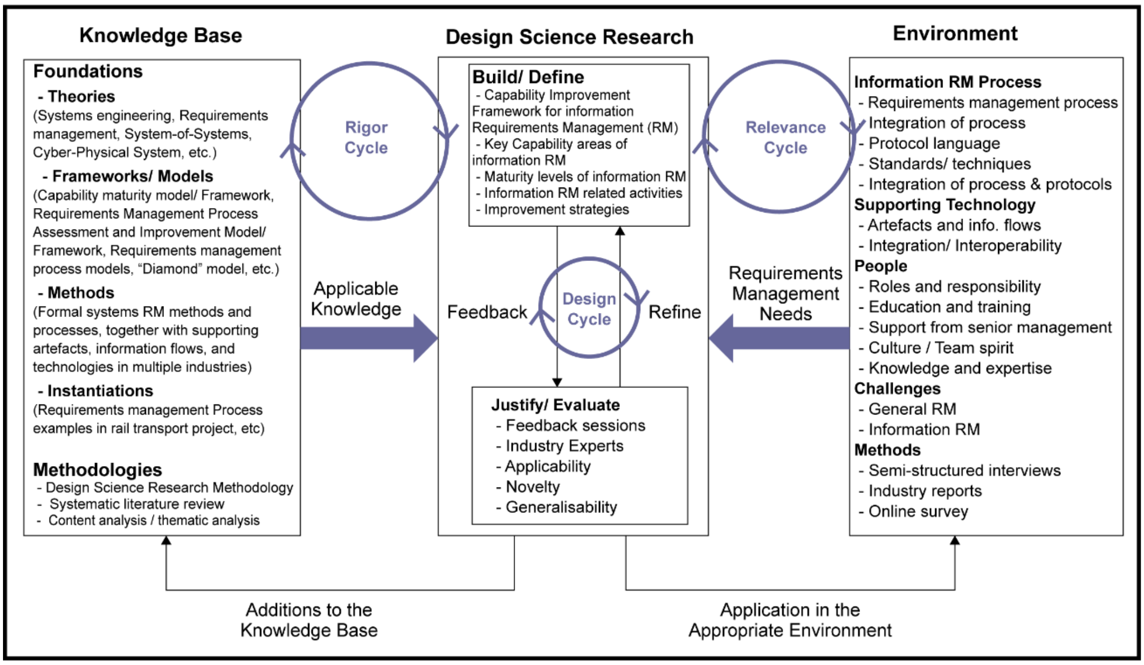


Figure 3.1 Design science research conceptual framework (adapted from Hevner et al., 2004)

Figure 3.1 reflects three main areas of this research study including the general knowledge base of the research area, the environment of the research problem, and the core design science research activity. The content in each area has been adapted based on the research scope, nature of the research problem, industry context, and the availability of resources. The following sections provide details of these three main areas and their interrelationships.

3.1.1 Knowledge Base and Rigour Cycle

The knowledge base provides the foundations and methodologies from and through which this research is accomplished (Hevner et al., 2004). Prior research and results from reference disciplines provide foundational theories, frameworks, instrument, models, methods and instantiations adopted in the build phase of a research study (Hevner et al., 2004). Methodologies provide guidelines used in the justify/evaluate phase. The rigour cycle connects the design science activities with the knowledge base of theoretical foundations, existing models and frameworks, experience and expertise that informs the research project (Hevner, 2007). The rigour of the research is achieved via the application of existing foundations and methodologies. Desktop-based research provides a robust and rigorous way of comprehensively describing the landscape of current applicable and recognised approaches to information requirements management as well as challenges to information requirements management.

The approach aims to provide a review of not only the practices as they relate to the rail transport sector, but also best practices drawn from across other sectors that use requirements management approaches as well as challenges to requirements management. The findings identified in the desktop-based research are therefore crucial to forming the foundations and framework for the design cycle of the research. The research's theoretical foundations in systems engineering and requirements management theory together with a "whole-of-system" and "whole-of-life" viewpoints are adopted for the purpose of research analysis, resulting in a preliminary analysis framework.

3.1.2 Environment and Relevance Cycle

The environment defines the problem context (Simon, 1996) in which resides the phenomena of interest. For this research, it consists of process, technology, organisation and people. In it are the goals, tasks, problems and opportunities that define requirements management needs in a traditional and digital engineering context. Requirements management needs are shaped by the senior management, culture and team spirit and knowledge and expertise of people within the organisation (Hevner et al., 2004). They are then assessed and evaluated within the context of roles and responsibility, education and training (Hevner et al., 2004). They are positioned relative to existing requirements management process and supporting technology (Hevner et al., 2004). Together these define the requirements management need or 'problem' as perceived by the researcher.

According to Yin (2013), the case study method is appropriate when the research covers both the phenomenon and the contextual conditions, when the research questions are posed in terms of "how" or "why", and when the investigator cannot control the behavioural events relevant to the study. It helps conduct an in-depth investigation into the evolution of organisational activities in its natural setting (Benbasat et al., 1987; Flyvbjerg, 2006; Yin, 2013). Moreover, case study research methods provide an iterative approach closely linked to data for theory development that is evidence based, testable and empirically valid (Eisenhardt, 1989). Multiple case studies allow findings to be compared between the different cases, which allows the study to be more robust than if a single case study was to be used (Yin, 2013). This study focuses on the implementation of requirements management approaches, with a particular focus on the management of requirements relative to the processes, digital and document-based artefacts, workflows and technologies and the role of these features and functions of requirements management in the creation of both the technical system requirements and information requirements of complex rail transport projects. This is an area of industry practice and research where theory has not been well developed, and thus a multiple-case study approach is appropriate to and commensurate with the aims and objectives of the relevance cycle in this research study. In addition, an online survey is adopted following the multiple-case study to 1) verify the findings from the case study, 2) further investigate the requirements management practices situation, and 3) identify the significance of challenges to requirements management practices.

3.1.3 Design Science Research and Design Cycle

The central design cycle iterated between core activities of developing the Capability Improvement Framework, its evaluation, and subsequent feedback to refine the framework (Hevner, 2007). As shown above in Figure 3.1, findings from desktop-based research about theories and methods were drawn from the rigour cycle, while findings drawn from the case study and online survey were input from the relevance cycle. Once a preliminary Capability Improvement Framework was developed, feedback sessions with industry experts were used to justify and evaluate the rigour of the framework.

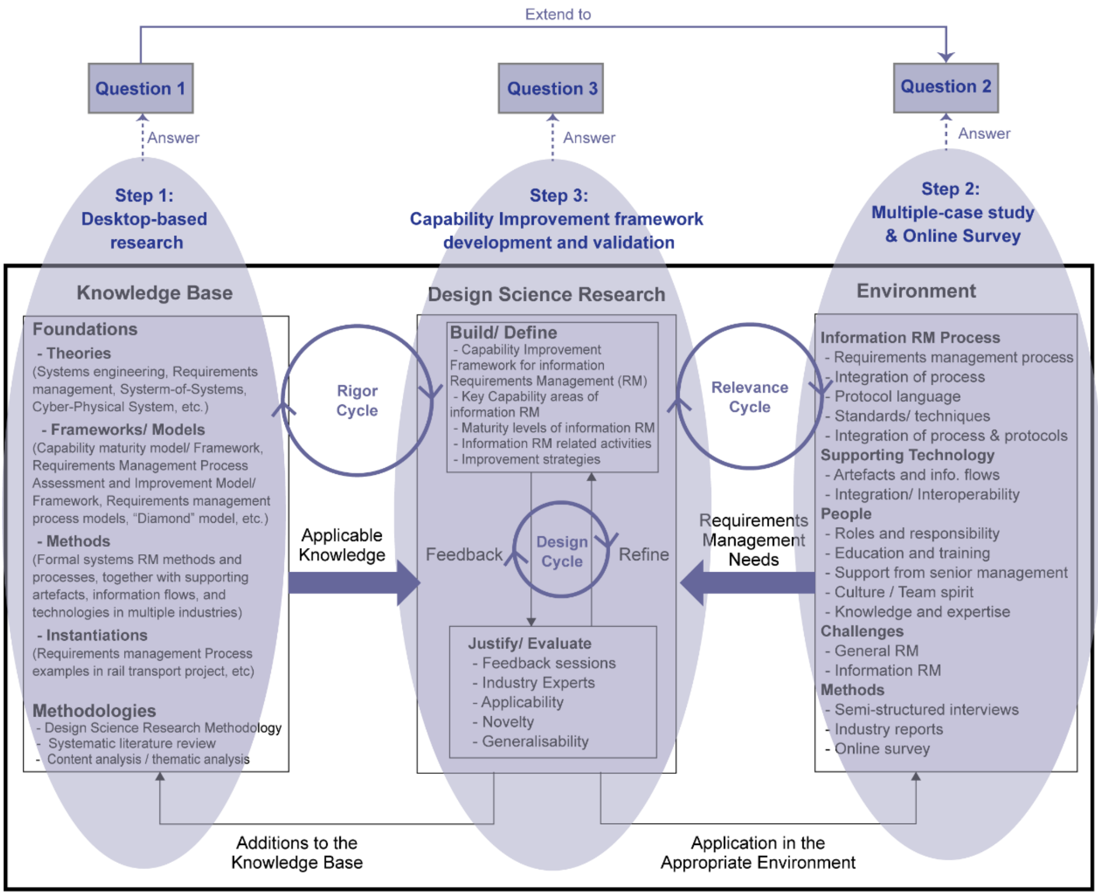


Figure 3.2 Mixed methods research steps

In summary, this research adopted a design science research framework and mixed-methods strategy. This research first used a desktop-based research approach to investigate requirements management approaches in literature. Subsequently, a multiple-case study approach was adopted to further investigate requirements management practices in the complex rail transport sector. Then an online survey was adopted to verify findings from the previous research steps. The relationships between these methods and their mapping to the design science conceptual framework are presented in Figure 3.2. As illustrated in Figure 3.2, the research process was described in three steps encompassing desktop-based research, multiple-case study and online survey, and Capability Improvement Framework development and validation. Each step aimed to answer one research question. Details are provided in the following sections.

3.2 Step 1: Desktop-Based Research

The Step 1 desktop-based research, using secondary data, encompassed the iterative process of framing and reframing the research questions, refining the research scope and detailing the research design. The desktop-based research encompassed three main research areas:

(i) *Theoretical foundations*: Formal systems requirements management methods and processes, together with supporting artefacts, information flows and technologies

(ii) *Contemporary practice*: Industry-led implementations documented in case studies that describe the application of information requirements management methods and processes throughout planning, and/or delivery of digital engineering enabled projects

(iii) *Emerging approaches*: New practices and frameworks documented in the research literature that describe requirements management in the context of planning and delivering systems with both technical system requirements and information requirements.

The Step 1 desktop-based research was designed to answer the first research question as stated in Chapter 1:

Q1: In the context of complex project delivery, what is the current status of information requirements management and what capabilities are essential to the efficient and effective management of information requirements?

Question 1 was then broken down into a set of specific sub-questions:

Q1-1: What capabilities of information requirements management have been identified to support the delivery of digital engineering enabled projects?

Q1-2: What initiatives have been proposed to support information requirements management in digital engineering enabled projects?

Q1-3: What are the challenges to requirements management, especially information requirements management in digital engineering enabled projects?

During this stage, the first research question was investigated using the critical review and analysis of research articles, industry reports and project reports shared on websites. First, an overview of what capability areas the articles cover was presented together with the domains they focused on (see Table 3.1 as an example). Moreover, a summary of requirements management capabilities identified in the literature review were presented from the perspectives of process, technology and people (see Table 3.2 as an example).

Table 3.1 Example of desktop-based research analysis structure

No.	Articles	Domain	Process	Technology	People
1	Article 1	AECO			
2	Article 2	Infrastructure			
3	Article 3	Manufacturing			
4	…				
5	…				

Table 3.2 Structure of requirements management capabilities identified from desktop-based research

Dimensions	Requirements Management Capabilities
A. Process related capability	1. Requirements Elicitation
	Requirements management capability A2
	Requirements management capability A3
	…
B. Technology related capability	1. Requirements modelling software
	Requirements management capability B2
	Requirements management capability B3
	…
C. People related capability	1. Definition of roles and responsibility to support requirements management
	Requirements management capability C2
	Requirements management capability C3
	…

Furthermore, initiatives proposed in the literature across multiple domains to support information requirements management in digital engineering enabled projects were investigated. These initiatives were then linked with the capabilities by identifying their relationships. The relationship could be either the initiative which supports the capability, or the initiative that uses the capability. As a result, a relationship matrix was developed. Finally, challenges to requirements management practices in digital engineering enabled projects were analysed, coded and summarised, to identify the gaps in requirements management practices across domains.

The critical evaluation of previous research provides this project with an understanding of large-scale, multidisciplinary requirements management methods and processes, together with the artefacts, information flows and tool ecologies that support them. The details and findings of desktop-based research are presented in Chapter 4.

3.3 Step 2: Multiple-Case Study and Online Survey

The focus of the multiple-case study and online survey was on developing a comprehensive understanding of contemporary approaches to requirements management in the complex rail transport sector from the perspective of multiple stakeholders. For example, demand-side stakeholders include large public agencies with divisions established to manage various stages and levels of rail assets, and consultants who help clients to develop requirements lists in planning phases. Functionalities of divisions within public agencies include but are not limited to strategy developer, client representative, project developer, project deliverer, operator and maintainer, and supporting divisions. Some divisions have multiple responsibilities. Supply-side stakeholders include the design team, general contractors, sub-contractors, suppliers, engineers, and consultants who participate in public rail projects in multiple phases.

The implementation of formal requirements management on complex rail transport projects is defined by:

(i) recent updating of standards of digital engineering to adapt to digital transformation in transport

(ii) recent changing of standards around systems engineering in rail transport projects

(iii) looking at requirements management from a rail system network level.

As stated in Section 1.3, this thesis explored the improvement of information requirements management in rail transport projects from the perspective of the client. This makes the information requirements management practices within public agencies the target of investigation. Thus, the execution of information requirements management methods and processes on public rail infrastructure projects can be defined by:

(i) evolving requirements (Aaramaa et al., 2015)

(ii) continuous interaction between the development process and the requirement elicitation process (Aaramaa et al., 2015)

(iii) consistent, traceable elicitation and management of requirements (Fontan et al., 2014).

The multiple-case study was designed to enable an in-depth investigation of the methods (e.g., processes, tools, etc.) of managing technical system requirements and information requirements during the early project phases of a complex rail transport project.

The Step 2 multiple-case study and online survey was designed to answer the second research question as stated in Chapter 1:

Q2: In the specific context of complex rail transport projects implementing digital engineering approaches, what capabilities are essential to information requirements management and what is the current status of information requirements management practices in industry?

Question 2 was then broken down into a set of specific sub-questions:

Q2-1: What capabilities have been identified as key to information requirements management by project teams in complex rail transport projects? [Chapter 5]

Q2-2: What initiatives have been implemented in practice to support information requirements management by project teams in complex rail transport projects? [Chapter 5]

Q2-3: What are the challenges to requirements management, especially information requirements management encountered by project teams in complex rail transport projects? [Chapter 5]

Q2-4: What is the prevalence of use of digital engineering process standards and data standards in Australia? [Chapter 6]

Q2-5: What are the current maturity levels of requirements management practices in a complex infrastructure industry (process, technology, people)? [Chapter 6]

Q2-6: Of the challenges identified in the management of technical system requirements and asset information requirements, how significant are they and how should they be prioritised? [Chapter 6]

Section 3.3.1 presents the data collection methods that underpin the case study investigations. Then, Section 3.3.2 presents a reflection of asset lifecycle and targeted phases of investigation, followed by cases identification and the participant sampling strategy in Section 3.3.3. The approach to case study data analysis is presented in Section 3.3.4 and the online survey is introduced in Section 3.3.5. The details and findings of the case study are presented in Chapter 5, while the findings from the online survey are elaborated on in Chapter 6.

3.3.1 Data Collection Methods

Using multiple sources of evidence, as emphasised by Yin (2013), is an important principle of data collection in case study, as multiple evidence sources help to triangulate the data (Eisenhardt, 1989; Tellis, 1997; Yin, 1981). Specifically, each of these approaches provides a different filter to view the facts and provides different insights into factors that contribute to project and management practices and performance. The proposed data collection methods adopted in this study include documentation and semi-structured interviews (Yin, 2013). In this way, the investigators are able to get not only the objective information, but also the subjective interpretation of the participants (Benbasat et al., 1987).

3.3.1.1 Documentation

Documentation at the organisational level included requirements management related protocols, reports, standards, and guidelines published by participant organisations. These documents can be obtained either online or from the participants. Moreover, project documentation on the delivery of digital deliverables is reviewed to form a basic understanding of the current adopted requirements management process, protocols and tools. More information includes but is not limited to if stakeholders developed their project quality assurance management plans (both project and data related) in response to the requirements from the clients, how project monitoring was reflected in the Digital Engineering Execution Plan for design and the Digital Engineering Execution Plan for construction, and the project management team structure, the roles and responsibilities to manage requirements etc.

3.3.1.2 Semi-Structured Interviews

Semi-structured interviews were the main approach of data collection during the case study phase. Identified key themes based on findings from desktop-based research were discussed. More themes were added according to the feedback from interviewees. Data collected from previous interviews and project documentation was validated through the following interviews. Semi-structured interviews helped to understand the drivers and barriers and challenges when implementing information requirements management approaches in supporting digital deliverables of the projects from different stakeholders' perspectives. As there were different interview participants involved in one or multiple stages of the project, questions were carefully designed according to their participation. The interviews were audio-recorded and then transcribed in Otter Mobile Application. As the interview data collection was during the COVID-19 pandemic in Australia, interviews were conducted face to face with a safe distance or online to minimise the health concerns of both interviewees and interviewers.

To strengthen the validity of semi-structured interview questions, an interview guide that contains questions drawn from literature on the topics was developed. Based on this, an interview protocol was developed. A thorough check by a panel of experts (e.g., supervisors, industry experts) was then adopted to determine whether the content of the interview guide and protocol was appropriate. Pilot interviews with potential participants were conducted after refining the interview protocol. Further adjustments were made based on their reactions to the questions.

Interview questions were experience oriented with concrete examples or situations to minimise interviewee bias. The details of interview questions are presented in **Appendix D**.

3.3.2 Asset Lifecycle and Targeted Investigation Phases in Multiple-Case Study

The scope of the multiple-case study focuses on the early demand and need phase, the planning phase, the project delivery phase (design, build and integrate) and the handover or commissioning phase. The operational phase is not included in the scope. The decision to restrict the case study to these project planning and design phases was partly a time-based constraint, and partly due to the focus on information requirements management in the context of dynamic project-based systems.

This research looks at asset information requirements management issues from a closed loop perspective including the phases of demand/need (customer strategy), plan (rail network), acquire (rail infrastructure) and operate/maintain (rail system). However, the client-side decision of adopting requirements management approaches is normally set up during the early planning stages. Approaches of asset information requirements management of the contractor side were normally documented in the early stages, and the interface management of technical system requirements and information requirements happened during design phases. It was therefore envisaged that data collection should focus on the demand/need, plan and acquire phases (as reflected in Figure 3.3).

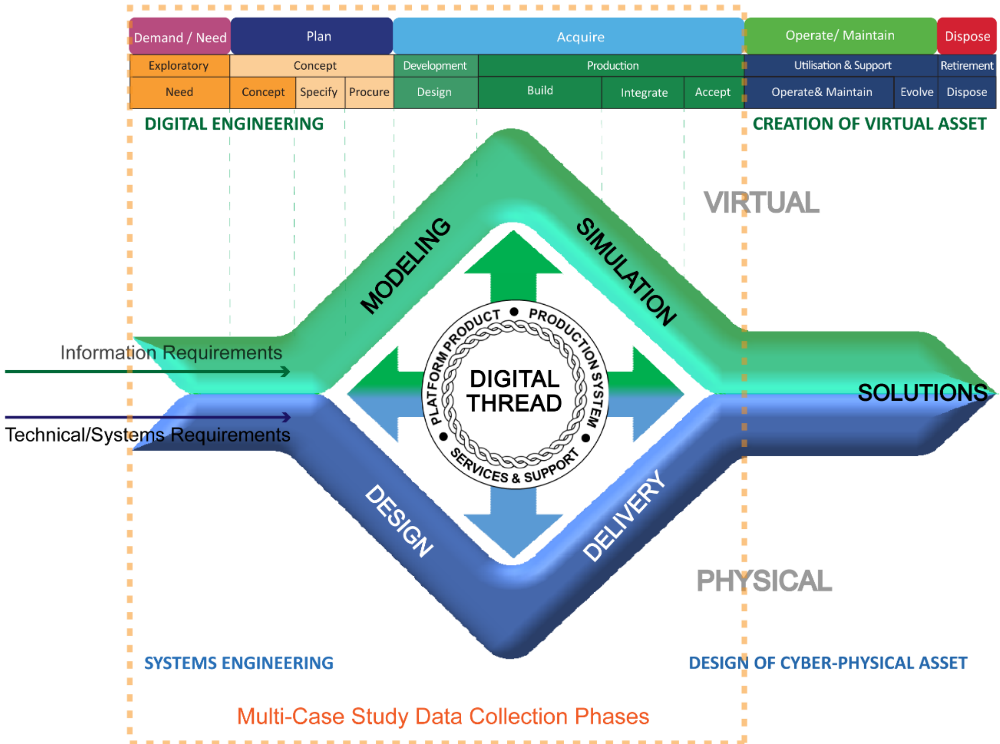


Figure 3.3 Lifecycle and multiple-case study data collection phases

3.3.3 Cases Identification and Participant Sampling Strategy

The chosen public agencies play different roles in different stages of rail transport projects and programs. Potential interviewees were either systems engineering consultants or digital engineering guideline developers, or strategic level managers in transport government agencies in Australia. Initial contact was made with people in the existing networks of the researcher and supervisor. A formal project participant recruitment email was sent to the potential participants with an introduction to the research project.

In New South Wales and Victoria, we chose two government agencies that have adopted digital engineering approaches to project delivery and developed organisational digital engineering standards for rail infrastructure, which are highly recommended to be implemented by project teams. The first agency, Transport for NSW, is responsible for the development of most linear infrastructure (rail projects, light rail projects, etc.) and has developed its own digital engineering strategy since 2016 and formed a digital engineering team responsible for development of its Digital Engineering Framework Program. There have been four releases of the digital engineering framework since 2018.

The second agency, Victoria's Department of Transport (VDT), is responsible for ongoing operation and coordination of the state's transport networks, as well as the delivery of new and upgraded transport infrastructure. Similarly, VDT has developed the Victorian Digital Asset Strategy (VDAS) guidance for government stakeholders who plan, create and operate Victoria's assets. It provides detailed guidance on planning, implementing, managing and maintaining an effective digital asset strategy throughout the lifecycle of the organisation's asset base. Based on VDAS, the Digital Asset Policy describes three levels of capabilities of 14 requirements in organisational and project levels throughout the asset lifecycle.

Other than these two government agencies, three consulting organisations were also selected as relevant participants due to their roles in managing and verifying requirements across the lifecycle of rail infrastructure projects.

A key targeted outcome of the multiple-case study interviews was the identification of suitable rail transport projects that had adopted initiatives to support more effective and efficient information requirements management. A list of potential projects was created, with the selection criteria introduced in later sections. Some initiatives have been identified by the researcher to secure the Transport for NSW and VDT case studies:

- As the gatekeeper of each case, senior management support is essential. During the connection with them, it is important to understand their issues and expectation.
- The researcher's involvement will also benefit the community as feedback from the field

will be valuable for continuous improvement of information requirements management processes, the definition of guidelines and manuals, or standards for future projects.

- Interview protocols will be made available to participants based on the agreement from the client enabling support from case study participants.

During interviews, one question asked was if there is any rail transport project that has implemented initiatives to support information requirements management. Project selection criteria focused on criteria related to new and ongoing rail transport projects. A “snowball strategy” was adopted in the case projects selection. With the list of potential projects obtained from the interviews, initial contacts with the project clients were essential to gain approval from them. After that, we were able to make contact with key actors involved in the management practices of technical system requirements or asset information requirements in the case projects. Other than interviews, published reports of best practice projects, and presentations by key actors of targeted projects are also vital sources of data.

Considering the time intensive nature of the research, two projects were initially selected. One project was the first rail transport project that implemented digital engineering to support requirements verification during design reviews. The second project was a digital system program for rail transport, where a model-based systems engineering approach was adopted before the commencement of requirements development to reduce the risk of rework and to facilitate a more efficient requirements development and management process. These two projects were identified as recommendations in the rail transport sector that implemented initiatives to support more effective requirements management (Roodt et al., 2020b).

3.3.4 Approach to Multiple-case Study Data Analysis

Data collection and data analysis were not sequential processes but interrelated and interactive with each other (Saunders et al., 2009). Analysis of data occurred during the data collection process (Kvale, 1996). Key points raised by interviewees were verified throughout this stage of interviews and follow-up surveys to minimise the bias of both interviewees and interviewers, before commencing data analysis.

Multiple analysis methods such as content analysis and thematic analysis approaches were adopted to look at the qualitative data in different ways. First, key capabilities and challenges identified during literature review (Chapter 4) were used as the existing codes when analysing interview data. Interview transcripts were colour coded according to the existing codes in terms of key capabilities and challenges. During this process, new codes emerged and were added in the analysis framework. Initial data analysis was refined according to discussion with and feedback from supervisors and industry experts.

The rigour of data analysis should be ensured in terms of reliability and validity. To ensure the reliability of the analysis, during the coding process a codebook presenting the coding analysis guide was developed and updated regularly; the consistency of coding was checked after finishing coding. To meet the validity requirements, it was necessary to revisit data collection questions, revisit the literature review and recode codes.

Validity criteria adopted in this research include contingent validity, multiple perceptions about a single reality, and construct validity (Healy & Perry, 2000). Contingent validity was addressed by analysing data from various sources and multiple stakeholders such as public agency departments, client-side consultant, contractors, sub-contractors, and the design team (Healy & Perry, 2000). Corroborating evidence from multiple sources helped to shed light on a theme or perspective (Creswell & Poth, 2016). The data was analysed from multiple perspectives (systems engineering perspective versus digital engineering perspective) to address the validity criteria using multiple perceptions about a single reality. As the majority of studies in this research were of explorative nature due to the relative immaturity of the requirements management approaches in support of digital twin creation, the construct validity was evaluated by designing suitable interview and survey questions (Mont, 2004). Data analysis results were compared with similar cases reported in the literature to triangulate the findings.

3.3.5 Online Survey – a Deeper Investigation of Requirements Management Practices in Industry

The choice of data collection method plays a pivotal role in shaping the subsequent data analysis process within a research study (Baddoo, 2001). Given the exploratory nature of this research, which seeks to develop an improvement framework, it was imperative to gain a comprehensive understanding of the current state of requirements management practices in the sector. Therefore, an online survey (questionnaire) was selected as the primary data collection method. This choice aligned with the nature and type of data that needs to be analysed. The survey results served a dual purpose: they corroborate some of the findings from the semi-structured interviews and assessed the significance of challenges identified during previous stages of research.

Prior to the commencement of the survey, an introduction was provided that outlines the background and objectives of the survey. The purpose of this introduction was to offer participants a clear understanding of the research context and objectives, thus minimising potential biases in their responses. The survey was structured into three main parts:

(1) **Background information**: This section collected essential background information from participants. It included details such as the sector they are involved in, their roles (whether in systems engineering or digital engineering positions) within the projects, their experience in

requirements management, and their familiarity with relevant standards. Figure 3.4 has an example question.

What is your **level of experience** in the use of digital model-based methods and tools to support a strategic approach to asset information lifecycle management?

For example, implementing building information modelling for facilities management, COBie, digital twin technologies.

- ◯ **No Experience**
- ◯ **Beginner** (1-2 years experience)
- ◯ **Intermediate User** (3-5 years experience)
- ◯ **Advanced User** (6-10 years experience)
- ◯ **Expert** (Over 10 years experience)

Figure 3.4 Example question in part 1 of the online survey

(2) **Current maturity status:** The second part of the survey was designed to gauge the current maturity status of technical system requirements (within the survey, the phrase physical system requirements was used, referring to the same meaning) and asset information requirements (AIRs) management processes and tools in a general sense. It also explored the importance of resources and the involvement of different stakeholders in requirements management processes. Figure 3.5 has example questions.

Please choose the description that best represents the **nature of the process and protocols*** supporting the handling of **asset information requirements** on your most recent project/s.

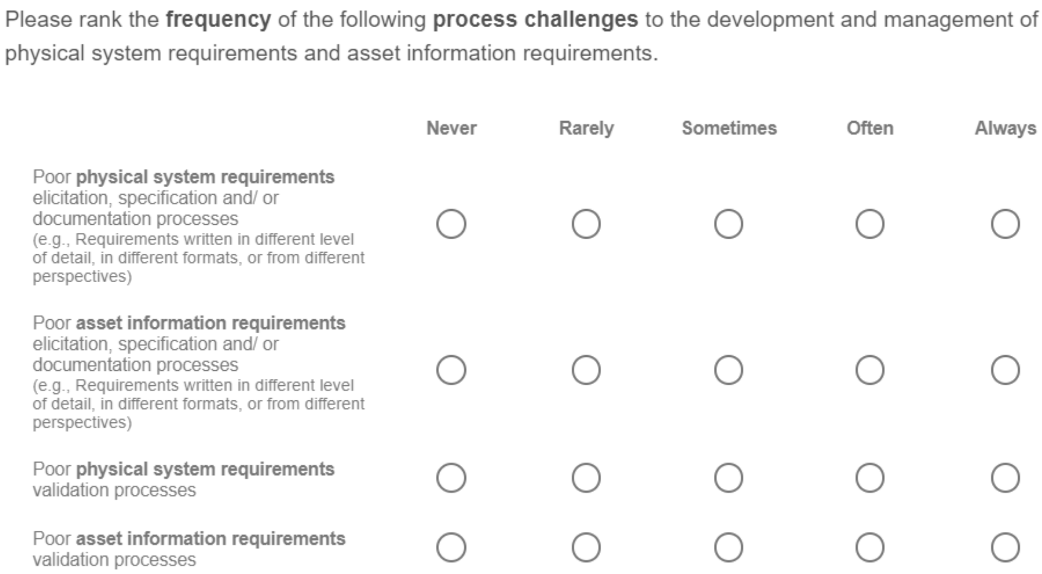
* As specified either by the Appointing Party or developed by your own or collaborating party.

	LEVEL 1: Very poor/ no process or protocol (There is no formal process or protocol defined or implemented)	**LEVEL 2: Poor formal process and protocol** (An ad hoc process and protocol is implemented during project delivery)	**LEVEL 3: Fair processes and protocols** (An organisational standard exists that describes a generic process)	**LEVEL 4: Well-defined processes and protocols** (Level 3 + Process is monitored, and performance is assessed)	**LEVEL 5: Very well-defined processes and protocols** (Level 4 + Continuous process improvement enabled by performance feedback loop)
Asset Information Requirements (AIR)					
Requirements elicitation process	◯	◯	◯	◯	◯
Requirements analysis and prioritisation process	◯	◯	◯	◯	◯
Requirements allocation and verification process	◯	◯	◯	◯	◯
Negotiation of conflicting requirements amongst stakeholders	◯	◯	◯	◯	◯
Requirements change management process	◯	◯	◯	◯	◯
Requirements validation process	◯	◯	◯	◯	◯

Figure 3.5 Example questions in part 2 of the online survey

(3) **Challenges occurrence frequency**: The third section of the survey aimed to identify the occurrence frequency of challenges that were previously identified in Step 1 and Step 2. The objective is to pinpoint critical challenges and key gaps within requirements management practices. Figure 3.6 has example questions.

To enhance the validity and effectiveness of the survey, a rigorous process was followed. First, the questions and grouping of questions were comprehensively evaluated by a panel of experts. These experts include supervisors and industry professionals who have substantial knowledge and experience in the field of the research. A pilot survey was conducted with potential participants. During this phase, the survey was refined based on the feedback received from these individuals. The feedback covered various aspects including the participants' comprehension of the question, their level of knowledge, the difficulty they faced in responding to the questions, and the relevance of questions to the research. The pilot study also evaluated the amount of time participants needed to complete the survey. More detailed information about the online survey is in **Appendix E**.



Please rank the **frequency** of the following **process challenges** to the development and management of physical system requirements and asset information requirements.

	Never	Rarely	Sometimes	Often	Always
Poor **physical system requirements** elicitation, specification and/ or documentation processes (e.g., Requirements written in different level of detail, in different formats, or from different perspectives)	○	○	○	○	○
Poor **asset information requirements** elicitation, specification and/ or documentation processes (e.g., Requirements written in different level of detail, in different formats, or from different perspectives)	○	○	○	○	○
Poor **physical system requirements** validation processes	○	○	○	○	○
Poor **asset information requirements** validation processes	○	○	○	○	○

Figure 3.6 Example questions in part 3 of the online survey

The survey was created and administered using the online platform Qualtrics, which facilitated both the development of the survey and the collection of responses. Given the specialised nature of both systems engineering and digital engineering disciplines, and their relatively recent application in complex infrastructure projects, the pool of professionals with expertise in these areas is limited. Nevertheless, a total of 36 valid responses were obtained with a 50% response rate. While this is a small sample size, it is important to note that the respondents have a high level of expertise and domain knowledge, making the sample quite robust in terms of expertise. All survey responses were collected between February and July 2022. The data gathered through the survey was extracted from Qualtrics and comprehensively analysed. Chapter 6 presents the detailed outcomes of this survey analysis.

3.4 Step 3: Capability Improvement Framework Development and Validation

While Step 1 provides past knowledge and existing frameworks, theories and tools to form the structure of the framework, findings from Step 2 provide the input and content of the Capability Improvement Framework. To create a framework that is replicable and verifiable, a formal development approach is adopted in Step 3.

Development of the framework encompasses building the Capability Improvement Framework structure, defining maturity levels, and defining the activities required for information requirements management. More details are presented in Section 3.4.1. Feedback sessions with industry experts were implemented to validate the Capability Improvement Framework. See Section 3.4.2 for details.

Step 3 is designed to answer the third research question as stated in Chapter 1:

Q3: In the context of complex rail transport projects, what levels of capability can be identified to assess the relative maturity of information requirements management practices, and what activities are required to support the improvement of information requirements management?

Question 3 can then be broken down into a set of specific sub-questions, including:

Q3-1: What are the key components of a capability improvement framework for information requirements management in complex rail transport projects?

Q3-2: How to assess and improve the capability of information requirements management in complex rail transport projects at the organisational level and at the project level?

Section 3.4.1 presents the approach used to develop the Capability Improvement Framework. Following this, Section 3.4.2 introduces the process of validating this Capability Improvement Framework. The details and components of the Capability Improvement Framework are presented in Chapter 7.

3.4.1 Development of Capability Improvement Framework

As detailed in Section 2.6, this research adheres to a capability-based process improvement approach. Following a thorough review of various maturity models, this research opts for a continuous representation of maturity level, akin to the Requirements Engineering Good Practice

Guide (REGPG) and Requirements Engineering Process Assessment and Improvement Model (REPAIM) styles, as opposed to a staged approach. In this approach, the information requirements management activities within the framework accumulate and are not restricted to a specific maturity level. This enables a more flexible and adaptable approach to process improvement.

Similar to the REGPG and REPAIM maturity models, the capability maturity levels are first established in the framework. After comprehensive consideration, four levels of maturity have been defined: 1) Incomplete, 2) Performed, 3) Managed and 4) Integrated. For each of these maturity levels, a detailed description is developed to provide a clear understanding of what each level entails within the context of the research.

The primary content of the Capability Improvement Framework centres around the assessment area. This area encompasses information requirements management related activities, often referred to as “practices” in the REGPG model. These activities span across the demand, plan and acquire phases of rail transport projects and play a crucial role in addressing gaps within the current project delivery process. These information requirements management activities have been meticulously developed based on insights gleaned from the research conducted in Step 1 and Step 2. Additionally, they draw from existing standards and guidance related to SE and DE processes that are applicable to the rail transport sector.

The information requirements management activities are presented in the order according to the project development phase in which they should be executed. Importantly, these requirements management activities encompass not only process related aspects but also consider the technology and people related aspects. For instance, activities like “establish the client-side common data environment” pertain to the technology related aspect, while activities like “identify asset/facilities managers as primary stakeholders and support the delivery team in understanding the operational service needs” address the people related aspect. This holistic approach ensures that the Capability Improvement Framework comprehensively covers all relevant dimensions of information requirements management.

Building on the nature of each maturity level, the information requirements management activities are categorised into two tiers: Basic activity and Advanced activity. This categorisation mirrors the structure found in the REGPG model. The assessment process and approach are subsequently defined, aligning with the REGPG model. This consistency in approach ensures that the assessment process is robust and reliable. Finally, a definition of scores at each maturity level is proposed. This final step helps quantify the maturity level achieved in information requirements management capabilities, providing a clear indicator of progress and improvement.

3.4.2 Validation of Capability Improvement Framework

Validation is defined as the process of ensuring that the developed framework is sufficiently accurate and suitable for its intended purpose (Carson, 1986) or whether the right framework has been built (Robinson, 1997). In this research, the validation process serves to establish that the components in this framework have a satisfactory level of accuracy that aligns with the intended application of the framework (Beecham, Hall, Britton, et al., 2005). It is important to note that due to resource and time constraints, the framework's quality, usability and utility have not been directly evaluated in this research (Beecham, Hall, Britton, et al., 2005; Gass, 1983). Therefore, to verify whether the framework directly meets the needs of specific users is proposed as future work.

Workshops with industry experts were organised to obtain valuable feedback on the Capability Improvement Framework. The aim of these workshops was to assess several key aspects:

(1) **Clarity of maturity levels**: Ensuring that the setup of maturity levels is clear and accurately reflects the proper level of maturity of an organisation in information requirements management.

(2) **Comprehensiveness of information requirements management activities**: Confirming whether the information requirements management activities within the assessment area are comprehensive and cover all relevant aspects exhaustively.

(3) **Appropriateness of activity categorisation**: Evaluating whether the categorisation of information requirements management activities into basic, intermediate and advanced activities is appropriate.

According to Hakim (1987), the use of small expert panels to gain feedback is a recognised practice, particularly in the early stages of the research. Previous studies have successfully used small samples to gain expert feedback to evaluate and support model development. For example, Dyba (2000) used 11 experts to conduct his review process, El Emam and Madhavji (1996) interviewed 30 experts to elicit criteria for their instrument to evaluate requirements management success, and Beecham et al. (2005) used 23 experts to validate their requirements process improvement model.

For the expert panel in this research, individuals were selected from a population of experienced practitioners and researchers with expertise in rail transport projects, systems engineering and digital engineering. The definition of an "expert" in the context is someone who meets one of the following criteria: (a) has a wide publication record in recognised journals in the field of requirements management and/or systems engineering; or (b) has substantial practical experience in requirements management and digital engineering within large transport infrastructure projects, with several years of experience and holding positions of responsibility (Beecham, Hall, Britton, et al., 2005).

3.5 Research Management Strategies

3.5.1 Ethical Considerations

Ethical issues considered as pertinent to this research design include (i) the privacy of possible and actual participants, (ii) the voluntary nature of participation and the right to withdraw partially or completely from the process, (iii) maintenance of confidentiality of data provided by individuals or identifiable participants and (iv) participants' right to maintain their anonymity (Saunders et al., 2009). This has been comprehensively considered in the Ethics Approval (ETH18-2619) by the University of Technology Sydney.

Strategies for managing these ethical issues include the following:

(i) Confidentiality agreements were signed by the researcher and the case study organisations to ensure the confidentiality of any commercial information. A formal approval of access from the case organisations was then issued. The researcher developed a protocol, known as the **Informed Interview Consent Form**, to interview project participants in consultation with supervisors and the project partners.

(ii) The interview protocol outlined in the **Informed Interview Consent Form** specifies that: I understand the following interview protocols will be followed: (1) as an interview participant, I was contacted prior to interview and that I have previously agreed to participate, (2) researchers may contact me again to undertake follow-up interviews, where partner organisations have agreed to 2~3 interviews for approx.1 hour each, (3) at any point I have the opportunity to express any discomfort with the interview process, (4) audio from the interview will be recorded on an audio recording device and transcribed, and (5) any confidential information discussed during the interview can be identified by me and will not be recorded or transcribed by the researcher.

(iii) Interview participants were provided with copies of the **Interviewee Contact Letter** and **Informed Interview Consent Form** prior to any research discussion and recording. These consent forms were signed by all participants prior to each interview.

(iv) During the online surveys, to pose a minimal risk to participants, a simple consent paragraph was included in place of a separate consent form. Participants were given the same type of information (e.g., voluntary participation, risks, confidentiality/anonymity, and right to withdraw). While participants did not sign a separate consent form, consent was obtained by virtue of completion. The researchers implemented agreed procedures to maintain the confidentiality of participant data.

(v) The information collected is kept in de-identified form and stored securely.

(vi) Research data management strictly followed and adhered to the University of Technology Sydney's policies.

(vii) The research design ensured that there is an appropriate application and documentation of Australian university ethical policies and guideline lodged with the University of Technology Sydney and a full ethics approval process undertaken.

3.5.2 Risk Management Strategy

3.5.2.1 Materials and Data

Transport for NSW and VDT provided access to staff to be able to undertake interviews with their personnel as well as share related documentation surrounding their methodologies and use of technologies for the design, delivery, operations and use of the case project.

3.5.2.2 Assumptions

It was assumed that the project partners make relevant documents and data available prior to commencement of the project and during the project should information be requested in relation to this project.

It was assumed that researchers have access to the staff, project details and data, and relevant documents and professional development staff (to conduct interviews and surveys) for the purposes of this project.

3.5.2.3 Risk and Risk Mitigation Strategies

The main risk surrounding the thesis research project's delivery identified was the availability of resources to be provided by the project partners. Another risk identified during the research is the outbreak of COVID-19. As a result, interviews were conducted face to face or online flexibly according to the availability of project partners. The risks predominantly surround the assumptions outlined above.

- It was assumed that project partners make the documents and data specified above available before project commencement.
- It was assumed that researchers have access to the relevant documents and professional development staff (for interview and surveys) for the purposes of this project.

- It was assumed that potential interviewees have access to the internet and availability for online interviews.
- It was assumed that potential interviewees' health is not threatened by COVID-19.

To mitigate against these risks, the researcher used best practices and methods in research management. More time was taken to keep potential participants connected.

3.6 Summary

This chapter presents the research methodology and research design to achieve the goals and objectives of this research. Figure 3.7 illustrates the structure of this chapter.

First, the overall strategy of inquiry of this research was described. The primary research methodology is the design science research approach which has three main steps: the general knowledge base of the research area, the environment of the research problem, and the core design science research activity. Each step addresses one research question.

Step 1 on desktop-based research is designed to answer research question 1. A systematic literature review approach in Chapter 4 (following the background literature review in Chapter 2) was adopted to investigate key capabilities supporting information requirements management, the initiatives proposed in literature supporting information requirements management, and challenges to information requirements management across multiple domains.

Step 2 includes multiple-case study and a follow-up online survey to address research question 2. Data collection methods (documentation and semi-structured interview) in the multiple-case study were described and asset lifecycle and targeted phases (demand/need, plan and acquire) of investigation were introduced. Cases identification and participant sampling strategy were presented, followed by a description of the case study data analysis approach. The online survey structure and procedures were described.

Step 3 for the Capability Improvement Framework development and validation process was presented. The main reference maturity models of the improvement framework were first introduced. The development of the Capability Improvement Framework encompasses the development of maturity levels, information requirements management related activities, and the assessment instructions. Feedback sessions with industry experts were proposed as the approach to validate the framework.

Last, research management strategies including ethical considerations and risk management strategy were discussed. The ethical considerations were presented, outlining the fundamental principles guiding the ethical application for this research. The risk management strategy to mitigate potential risks that could impact the progress of the research was presented.

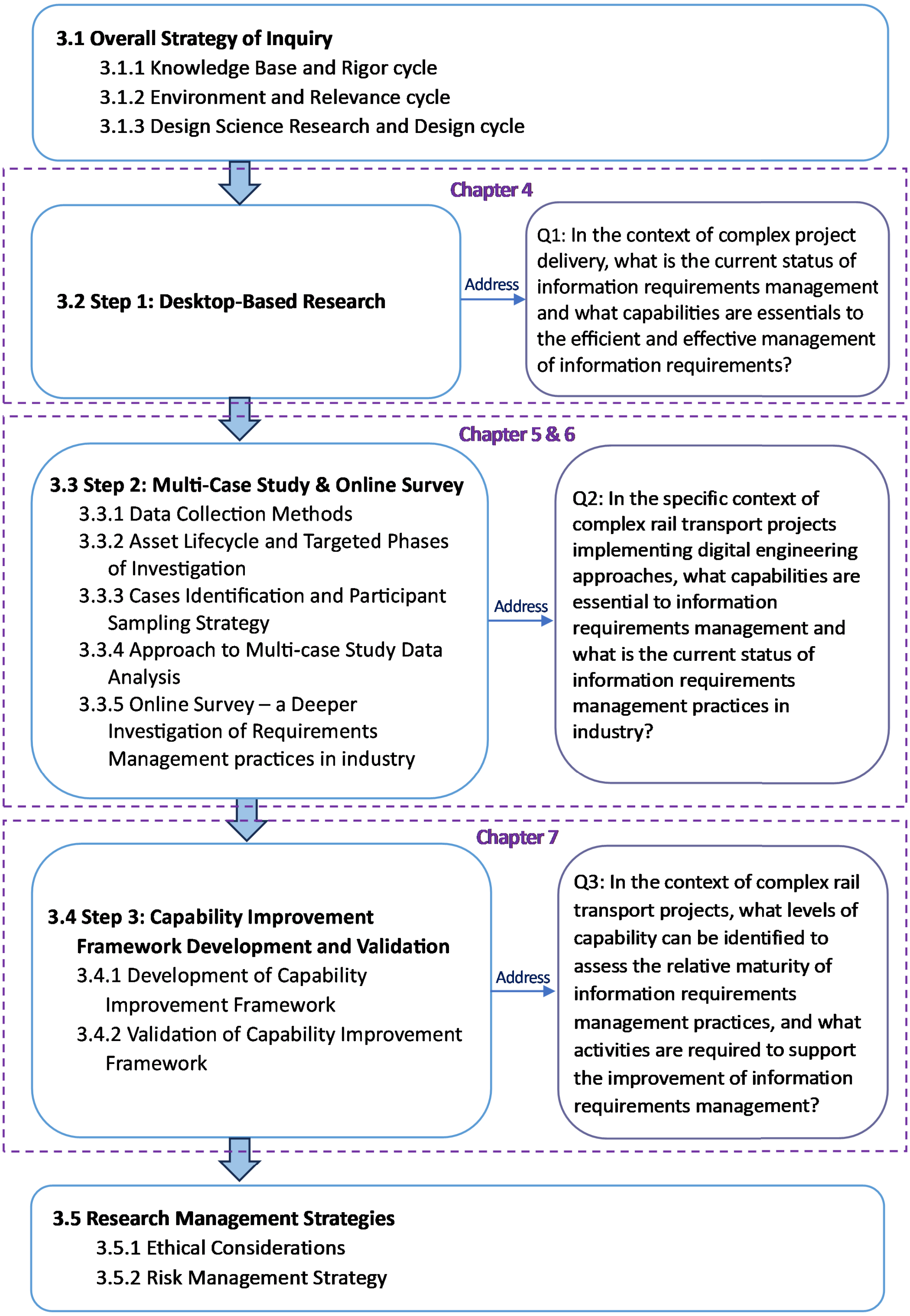


Figure 3.7 Structure of Chapter 3 content

Chapter 4 Requirements Management across Multiple Domains: Capabilities, Initiatives and Challenges

This chapter addresses research question 1 in a desktop-based research approach to better understand requirements management capabilities, initiatives and challenges in digital engineering enabled projects across three domains. First, the systematic literature review process and general survey statistics of the literature sourced are presented. This is followed by a thematic analysis commencing with the literature on the key capabilities of requirements management methods that support the management of technical system requirements and information requirements, which are then grouped into three categories including process, technology and people. Initiatives proposed in several project-based industry domains that have the potential to support lifecycle information requirements management are investigated in a comparative analysis with the complex rail transport domain. The main challenges to general requirements management and information requirements management across multiple domains are identified and analysed.

4.1 Systematic and Multi-Domain Literature Review Process

To effectively identify the existing approaches and methods supporting the management of both technical system requirements and information requirements, as well as the main challenges to the management of different requirement types, a structured, transparent and repeatable approach to the literature review was adopted (Bandara et al., 2011; Garza-Reyes, 2015). A systematic literature review (SLR) method with the following phases was implemented: (1) formulating questions, (2) locating studies, (2) selecting and evaluating studies, (4) analysing and synthesising, and (5) reporting and using the results (Garza-Reyes, 2015). The SLR method considers the multidisciplinary nature of the research questions. Figure 4.1 summarises the main phases, methods and tools used, and the order of the SRL phases presented in this chapter.

The result of the first phase, *question formulation*, is presented in Section 1.3. The second and third phases of the SLR method – *locating studies* and *study selection* and *evaluation* – are described in Section 4.1.1, while Section 4.1.2 presents phase 4 *analysis and synthesis* of the literature. Phase 5, *reporting and using the results*, is described in Sections 4.2 to 4.4.

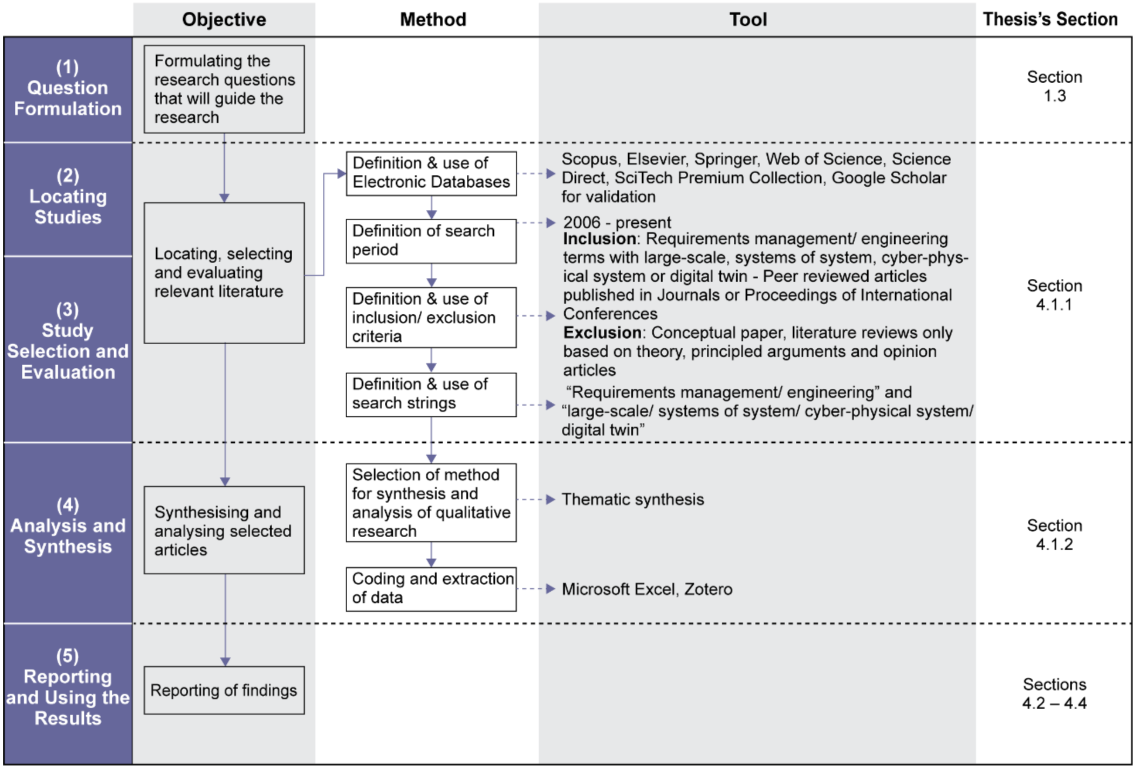


Figure 4.1 Systematic literature review phases, methods, tools and location in the chapter (adapted from Garza-Reyes, 2015)

4.1.1 Location and Selection of Studies

The targeted literature includes academic articles and conference proceedings located through electronic databases (e.g., Scopus, Elsevier, Springer, Web of Science, Science Direct, SciTech Premium Collection) and Google Scholar. Although the use of Google Scholar created an overlap with the electronic databases, this served as a validation for the searches to ensure that all relevant articles meeting the search criteria were included (Garza-Reyes, 2015).

This research is focused on understanding recent aspects of engineering practice rather than how engineering practice has evolved historically. Relevant concepts in this area of practice emerged after 2006. For example, the concept of cyber-physical system was first introduced in 2006; standardised DE and BIM technologies and processes supporting requirements management in construction and rail infrastructure projects did not appear until 2008; large-scale requirements management concepts were first proposed in 2008; and, while digital twin was first coined by Grieves (2014) in 2003, it was not until the application of digital twin technologies by the aerospace industry in 2010 that the concept and the creation of digital twins were developed. Thus, the period for this review was established to encompass from 2003 to present. Initially, the period of time was set as 2003 to 2021. During the progress of the review, new emerging literature has been added.

Key terms used to search and source literature in the databases were “requirements management/requirements engineering” and “large-scale/system of systems/cyber-physical system/digital twin” with the search string {(TS=(requirement* engineering OR requirement* management) AND TS=(large-scale system OR system of systems OR cyber-physical system* OR digital twin* OR BIM OR digital engineering))} used to source, identify and sort the literature. An additional “manual checks” process to refine the initial search was then implemented to determine research quality and validity. Table 4.1 shows the search and selection process and the number of articles after inclusion and exclusion criteria were applied.

Table 4.1 Literature searching and selection process

Selection Process	Criteria	Result
Primary Inclusion Criteria	• Search terms: “Requirements management/ requirements engineering” • Language: English • Year of Publication: 2003 – present (was 2021) • Publication type: Peer-reviewed Journal article or Conference proceedings	Identified: 197 articles
Secondary Inclusion Criteria (by reading the abstract)	• Requirements management/ engineering in supporting “large-scale/ system of systems/ cyber-physical system/ digital twin/ BIM/ digital engineering”	Retained: 76 articles
Exclusion Criteria (by broadly going through the article)	• Industry domain: Papers not from manufacturing, construction or transport infrastructure	Retained: 52 articles
Tertiary Inclusion Criteria (by reading the full article)	• Empirical study or technical studies, and summative reviews of empirical studies	Retained: 29 articles
Other: Reference review	• Relevant articles in references	Added: 5 articles

A vital criterion for selection was the nature of the research belonging to reported or published empirical or technical studies, and summative reviews of empirical studies. This criterion was chosen because the research is focused on practical applications of requirements management and digital twin creation methods. Empirical case studies and the nature of industry-based research findings are significant in understanding and grounding the theory of requirements management and in principled arguments. Hence, conceptual articles, principled arguments and opinion articles were excluded. Articles focused on engineering education or on academics or students’ perceptions of engineering practice were also excluded. Another important selection criterion is the domain of the research should focus on manufacturing, construction or transport infrastructure according to the scope and objective of this review.

Search results included peer-reviewed articles published in academic journals and proceedings of international conferences only to ensure a higher threshold of quality and peer-review rigour throughout, while keeping the scope of the review manageable. Since the research topic is relatively immature, inclusion of peer-reviewed conference papers helps maintain the quantity of potential literature for analysis. A final sample of 34 articles with reference to requirements management and digital twin creation was identified.

4.1.2 Analysis and Synthesis

The final corpus of articles therefore focused on issues related to requirements management for the development of physical and digital assets. The final corpus was read in full and coded based on the following themes:

1) Industry domain
2) Requirements management capabilities
3) Requirements management initiatives
4) Requirements management challenges.

Articles were initially coded using themes 1 and 2 and findings were used to respond to research question Q1-1 (Section 4.2.2). Theme 3 was then used to explore research question Q1-2 (Section 4.3). Section 4.2 provides an overview of the literature and general analysis of the articles.

4.2 Overview of the Literature and General Analysis

This section analyses general attributes of the literature identified, followed by an overview of the capability categories mentioned in identified literature.

4.2.1 General Attributes

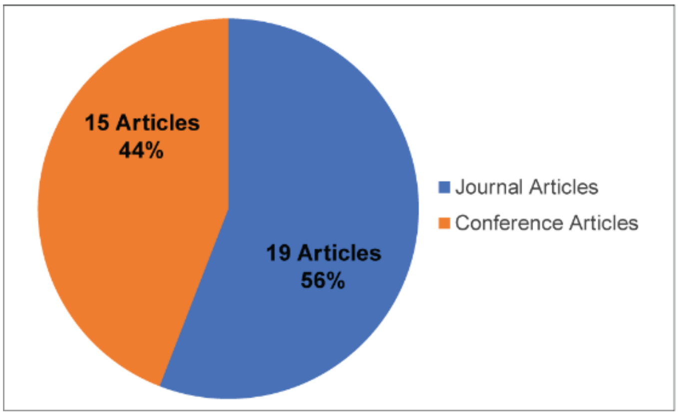
Considering the systematic literature review is multidisciplinary in nature, backward and forward searching was conducted based on the initial search results to capture more relevant articles (Bandara et al., 2011). As a result, a total of 34 articles were identified for further analysis (see **Appendix C** for details). Figures 4.2 and 4.3 present the following general attributes of the literature:

(a) Articles were published by journals or refereed conference proceedings

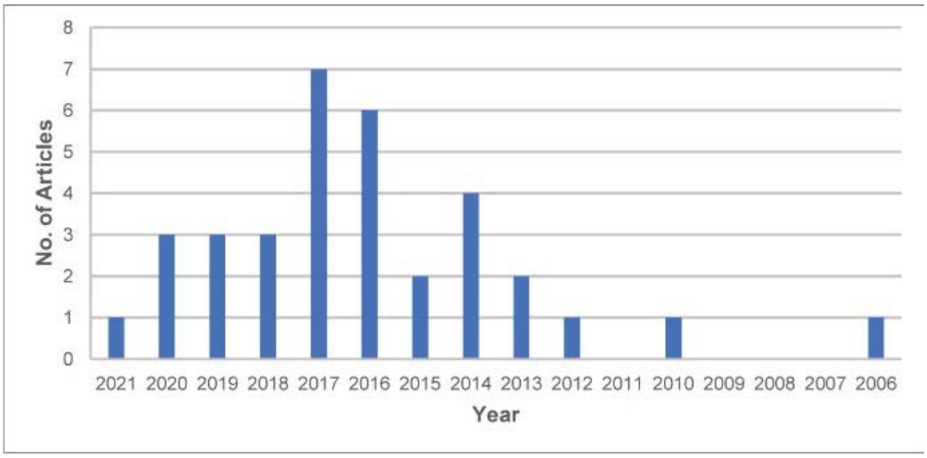
(b) Number of publications per year according to the research topic

(c) Number of publications per journal

(d) Number of publications per conference.



(a)

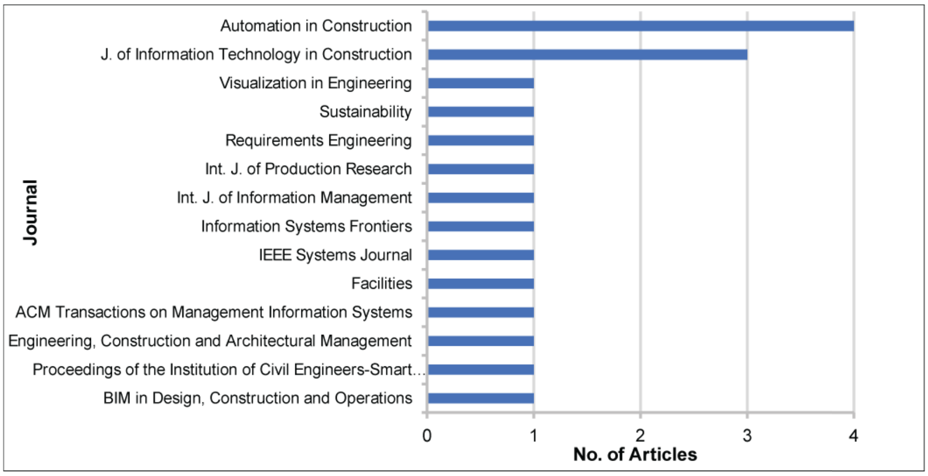


(b)

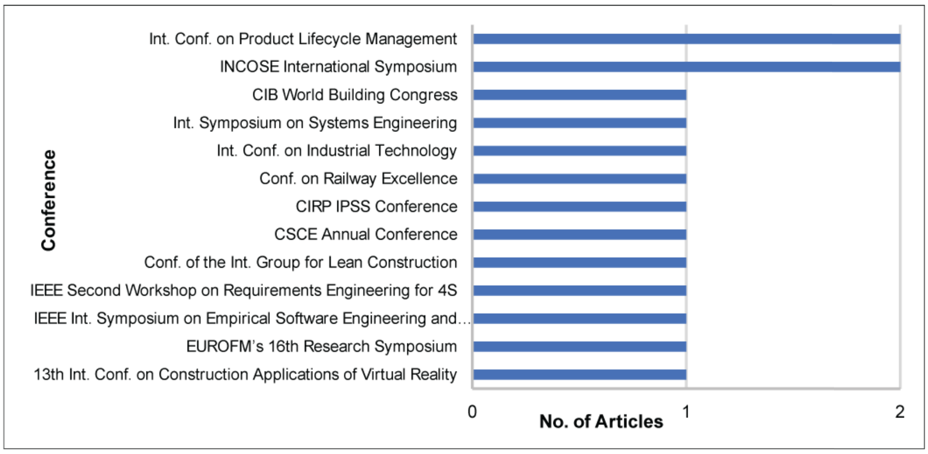
Figure 4.2 Descriptive search results for 34 articles:
(a) Proportion of journal and conference publications, and (b) Year of publication

The topic of requirements management has increased in interest and popularity in the academic community since 2014 as 85% (29 articles) of the 34 publications released in the period from 2006 to 2021 have been since 2014. This indicates that requirements management has increased as a research topic in relation to Industry 4.0 and the digital transformation of many industries, and is particularly relevant to digital twin and CPS development, both being relatively new and emerging research topics. Figure 4.2 (a) also indicates that conferences and journals have a similar proportion of publications and have been used equally by researchers to disseminate investigations into requirements management.

In terms of the number of publications per journal shown in Figure 4.3 (a), *Automation in Construction* and *Journal of Information Technology in Construction* have the most publications indicating that architecture, engineering and construction (AEC) domains have an increasing focus on the topic of requirements management in support of digital twin creation. The number of publications per conference reflects that articles focusing on this topic largely appear in manufacturing domain conference proceedings (see Figure 4.3 (b)).



(a)



(b)

Figure 4.3 (a) Number of publications per journal, and (b) Number of publications per conference

4.2.2 Capabilities of Information Requirements Management Supporting Digital Engineering Enabled Project Delivery

This section explores and responds to research sub-question Q1-1:

Q1-1: What capabilities of information requirements management have been identified to support the delivery of digital engineering enabled projects?

A variety of capabilities of information requirements management have been identified to support the delivery of digital engineering enabled projects. These projects have aspirations to deliver both physical and digital assets. To understand the scope of the capabilities discussed in the literature, they are listed relative to the domains using the "process, technology and people" taxonomy from knowledge management theory as capability dimensions (Pee & Kankanhalli, 2009). In tagging the capabilities relative to "people", we also account for "supply chain" and "organisation" capabilities as shown in Table 4.2.

Table 4.2 Capability dimensions of information requirements management across domains

Articles	Domain	Process	Technology	People
1. (Baldauf et al., 2020)	AECO	✓	✓	
2. (Succar & Poirier, 2020)	AECO	✓	✓	
3. (Gebru & Staub-French, 2019)	AECO		✓	
4. (Heaton et al., 2019)	AECO	✓	✓	✓
5. (Soliman-Junior et al., 2019)	AECO	✓	✓	
6. (Arayici et al., 2018)	AECO	✓	✓	
7. (Ashworth et al., 2017)	AECO	✓		✓
8. (Cavka et al., 2017)	AECO	✓		✓
9. (Jallow et al., 2017)	AECO	✓	✓	✓
10. (Jupp & Awad, 2017)	AECO			✓
11. (Kubler et al., 2016)	AECO	✓	✓	
12. (Parsanezhad et al., 2016)	AECO	✓	✓	
13. (Patacas, Dawood, Greenwood, et al., 2016)	AECO	✓	✓	
14. (Navendren et al., 2015)	AECO			✓
15. (Jallow et al., 2014)	AECO	✓	✓	
16. (Baldauf et al., 2013)	AECO		✓	
17. (Kelly et al., 2013)	AECO			✓
18. (Yu et al., 2010)	AECO	✓		✓
19. (Arayici et al., 2006)	AECO	✓	✓	
20. (Johnson et al., 2021)	INF	✓	✓	
21. (Shirvani et al., 2020)	INF	✓	✓	
22. (Ramos, 2018)	INF	✓	✓	✓
23. (Fucci et al., 2018)	INF		✓	
24. (Tolmer et al., 2017)	INF	✓		
25. (Arnaut et al., 2016)	INF	✓	✓	✓
26. (Scott et al., 2016)	INF	✓		
27. (Nekvi & Madhavji, 2014)	INF	✓	✓	
28. (Koltun et al., 2017)	MANF	✓	✓	
29. (Wiesner et al., 2017)	MANF	✓	✓	✓
30. (Pavalkis, 2016)	MANF	✓	✓	
31. (Holt et al., 2015)	MANF	✓		
32. (Berkovich et al., 2014)	MANF	✓		
33. (Papinniemi et al., 2014)	MANF	✓	✓	
34. (Penzenstadler & Eckhardt, 2012)	MANF	✓	✓	

Note: AECO – Architecture, Engineering, Construction and Operations, INF – Infrastructure; MANF – Manufacturing

Table 4.2 shows a high prevalence of articles addressing process and technology capabilities on information requirements management themes. Process capabilities are mentioned in 82% articles (28 out of 34) and technology capabilities are mentioned in over 70% of articles (24 out of 34).

An overview of the 22 individual requirements management capabilities identified in the 34 articles is presented and grouped in Table 4.3.

Table 4.3 Summary of information requirements management capabilities in process, technology and people perspectives

Dimensions	Requirements Management Capabilities
A. Process related capability	1. Development of Systems Architecture Framework supporting Requirements (Jallow et al., 2017; Scott et al., 2016; Shirvani et al., 2020) 2. Requirements Elicitation (Arayici et al., 2006; Arnaut et al., 2016; Berkovich et al., 2014; Cavka et al., 2017; Heaton et al., 2019; Holt et al., 2015; Johnson et al., 2021; Patacas, Dawood, Greenwood, et al., 2016; Tolmer et al., 2017; Yu et al., 2010) 3. Requirements Analysis and Prioritisation (Baldauf et al., 2020; Kubler et al., 2016; Nekvi & Madhavji, 2014) 4. Requirements Verification and Validation (Arnaut et al., 2016; Baldauf et al., 2020; Heaton et al., 2019; Parsanezhad et al., 2016; Patacas, Dawood, Greenwood, et al., 2016; Ramos, 2018) 5. Requirements Negotiation and Communication (Arnaut et al., 2016; Berkovich et al., 2014; Cavka et al., 2017; Heaton et al., 2019; Wiesner et al., 2017) 6. Requirements Change Management (Berkovich et al., 2014; Holt et al., 2015; Jallow et al., 2014, 2017; Koltun et al., 2017; Nekvi & Madhavji, 2014; Patacas, Dawood, Greenwood, et al., 2016; Ramos, 2018; Yu et al., 2010) 7. Requirements Traceability (Baldauf et al., 2020; Berkovich et al., 2014; Holt et al., 2015; Jallow et al., 2014, 2017; Pavalkis 2016; Penzenstadler & Eckhardt, 2012) 8. Integration of Requirements Processes (Arayici et al., 2018; Arnaut et al., 2016; Jallow et al., 2014, 2017; Papinniemi et al., 2014; Tolmer et al., 2017; Wiesner et al., 2017) 9. Requirements management protocols and languages (Ashworth et al., 2017; Patacas, Dawood, Greenwood, et al., 2016; Pavalkis, 2016) 10. Integration of requirements management protocols with product/project management protocols (Ashworth et al., 2017; Baldauf et al., 2020; Soliman-Junior et al., 2019) 11. Effective management of information requirements (Succar & Poirier, 2020).
B. Technology related capability	1. Requirements modelling software (Arayici et al., 2006; Arnaut et al., 2016; Baldauf et al., 2020, 2013; Koltun et al., 2017; Papinniemi et al., 2014; Penzenstadler & Eckhardt, 2012; Shirvani et al., 2020) 2. Requirements storage and workflow platforms (Baldauf et al., 2020; Fucci et al., 2018; Heaton et al., 2019; Jallow et al., 2014, 2017; Johnson et al., 2021; Parsanezhad et al., 2016; Patacas, Dawood, Greenwood, et al., 2016) 3. Requirements documentation and validation tools and tool chains (Baldauf et al., 2020; Gebru & Staub-French, 2019; Pavalkis, 2016; Soliman-Junior et al., 2019; Wiesner et al., 2017) 4. Digital and paper-based artefacts (Nekvi & Madhavji, 2014; Ramos, 2018) 5. Information flows (pertaining to information requirements management) across project phases (Jallow et al., 2017; Succar & Poirier, 2020) 6. Integration/interoperability of tools (Arayici et al., 2018; Fucci et al., 2018; Jallow et al., 2014, 2017; Kubler et al., 2016; Pavalkis, 2016).
C. People related capability	1. Definition of roles and responsibility to support requirements management (Arnaut et al., 2016; Jallow et al., 2017; Yu et al., 2010) 2. Early involvement of stakeholders (Arnaut et al., 2016; Jupp & Awad, 2017; Kelly et al., 2013; Navendren et al., 2015; Wiesner et al., 2017) 3. Specialist expertise in relevant industry standards (Cavka et al., 2017) 4. Experience in the application of protocols or guidelines supporting information requirements processes (Ashworth et al., 2017; Heaton et al., 2019; Jupp & Awad, 2017) 5. Ongoing investment in training of requirements management software (Ramos, 2018).

As mentioned in Chapter 1, requirements management in complex rail transport projects should not only consider the development and management of technical system requirements and information requirements, but more importantly, the governance structure and governance interface these two types of requirements were overlaid onto and driven by the different DE and SE management frameworks. However, there is still a lack of effective governance structure and governance interfaces to support the collaborative management of these interfaces. The capabilities identified in the SLR (as shown in Table 4.3) not only cover the management of information requirements, but also cover the collaborative management of the interfaces between technical system requirements and information requirements.

4.3 Initiatives Supporting Information Requirements Management in Digital Engineering Enabled Projects

This section answers the following research sub-question Q1-2:

> *Q1-2: What initiatives have been proposed to support information requirements management in digital engineering enabled projects?*

A couple of initiatives have been proposed in the literature identified in the review (see Table 4.2) across multiple domains to support the information requirements management in digital engineering enabled projects. Industry domains under investigation include AECO, infrastructure and complex discrete manufacturing.

4.3.1 Initiatives in AECO Domain

In the AECO domain, three types of methods are proposed to support requirements management in the context of DE: (1) BIM models, (2) requirements and information management frameworks, and (3) open data standards and technologies.

Several research works have explored the use of BIM models to support requirements management in recent years (Baldauf et al., 2020). Two types of support for client requirements management have been provided by BIM-based tools (Parsanezhad et al., 2016). One type of support is achieved by using a hierarchical tree structure to store and display technical and functional requirements for designers who use BIM models (Baldauf et al., 2020). Another type of support is achieved by translating requirements information into rules for automated checking of design solutions, especially with regulatory and qualitative requirements (Jallow et al., 2014; Parsanezhad et al., 2016).

A variety of frameworks have been proposed to support the co-management of technical system requirements and information requirements. Kubler et al. (2016) addressed the lack of a closed-loop system in the AECO domain by proposing an open and interoperable web-based building lifecycle management system based on BIM and its similarity with Product Lifecycle Management (PLM). Cavka et al. (2017) proposed a BIM requirements framework describing the relationship between the digital (model) and physical (design solution) products with the types of owner requirements and organisational constructs to bridge design requirements and facilities management requirement with regards to information being generated and consumed by various stakeholders in different stages. Jallow et al. (2017) presented an information-centric enterprise architecture framework for managing client requirements information across all phases of a construction project and through-life of a built asset. This framework is process-oriented in exchanging information between multiple systems, has a mechanism specified for impact analysis through dependency checking and enables automatic change management process (Jallow et al., 2017). Succar and Poirier (2020) proposed a Lifecycle Information Transformation and Exchange framework as an extendable conceptual skeleton for defining, managing and integrating project and asset information. Integrating multiple components including information statuses, states, milestones, flows, gates, routes, loops, actions, sets and tiers, this framework aims to predict information flow across an asset's lifecycle.

Open data standards and technologies are adopted in the AECO domain to support effective data exchange across multiple stages and artefacts. Patacas, Dawood, Greenwood, et al. (2016) developed a framework combining the use of Information Delivery Model (IDM), Industry Foundation Classes (IFCs), Construction Operations Buildings Information Exchange (COBie) and Content Management Interoperability Services (CMIS) in the development of Asset Information Models (AIM) to fulfil the client's requirements (asset information requirements) throughout the lifecycle of a building. Another case study adopts IDM and Model View Definition (MVD) in a collaborative way to support the development and execution of an interoperability specification for the Integrated BIM practice from a performance-based design perspective (Arayici et al., 2018). In the case study, IDM proposes a systematic method to capture and progressively integrate business processes and provide details of defined specifications of information that need to be exchanged during different stages of a project. Then, a MVD sets the interoperability at software level by translating IDM outputs in a readable language schema such as IFC Open Standard (Arayici et al., 2018).

4.3.2 Initiatives in Infrastructure Domain

In infrastructure domains, three main initiatives that have been proposed and developed to support information requirements management in the context of digital engineering are (1) integrated requirements management processes, (2) model-based systems engineering (MBSE) architecture framework, and (3) integration of requirements management with digital engineering.

Arnaut et al. (2016) developed a systematic requirement process that considers both technical and managerial activities for the concept phase, integrating a set of methods and techniques of requirements management and project management. This comprehensive process involves activities, input and output protocols, supporting tools and artefacts, as well as requirements management work parties who are responsible for requirements management activities.

Scott et al. (2016) developed a MBSE architecture framework that structures the available data and provides guidance and traceability between the datasets. Similarly, Shirvani et al. (2020) examined how MBSE can be employed to enhance the procurement processes and any required evolution of the available languages to develop architecture frameworks to support them. Both frameworks adopt “The Rail Architecture frameworK” (TRAK) approach to support modelling of all procurement requirements in a standardised knowledge structure for information sharing in case studies.

Notably, Tolmer et al. (2017) have used systematic requirements management to adapt and redefine the “Level of Detail” concept, to provide more complete definitions of BIM model use in complex infrastructure projects. Level of Detail (or LOD) and Level of Information (or LOI) are widely used data definition standards that describe geometric (LOD) and non-geometric (LOI) information. To extend these concepts, Tolmer et al. introduced “Level of Abstraction” (LOA) to describe relevant objects for different types of DE model use based on object modelling. The application of systematic requirements management was successfully implemented to support specific areas of digital engineering enabled infrastructure projects focused on the specification of exchange information requirements (Hellmuth, 2020). A drawback of the LOA method proposed by Tolmer et al. (2017) concerns the need for clear classifications for the LOA, in terms of which LOA level is more (or less) “abstract” than the other across different model uses. Furthermore, the LOA definitions themselves do not include all disciplines, including structural engineering (Hellmuth, 2020). More detailed testing on larger project work packages is also required. Moreover, the focus of Tolmer et al. was on the EIRs and neglected the AIRs processes that are linked to the DE and DT use domain. The applicable phase of this approach starts after the DE preparation and brief phase which is too late in the asset lifecycle.

4.3.3 Initiatives in Manufacturing Domain

In the manufacturing industry, especially complex discrete manufacturing which focuses on vehicles, aircraft and aerospace, methods adopted to support information requirements management in CPS or digital twin systems focus on three areas: (1) use of systems modelling language (SysML) and natural language processing (NLP) to support better coordination among stakeholders; (2) requirements data model for structuring requirements; and (3) integration of requirements management and MBSE with PLM to achieve lifecycle management.

To facilitate better understanding and effective collaboration across multiple stakeholders, SysML (the visual modelling language for system design based on UML) is used to define the items of the content model (Penzenstadler & Eckhardt, 2012). However, in the development of large and complex CPS, formal descriptions (e.g. SysML, UML) are required for communication among artefacts and machines to support the achievement of a high degree of automation (Wiesner et al., 2014). NLP techniques are used to support requirements exchanges between the system user and stakeholders by transforming the most basic format used by end users and stakeholders (the natural language) into system or machine-readable language. To support the requirements traceability, Holt et al. (2015) proposed an approach for context-based requirements management (at systems level) as a starting point for developing the future model-based requirements management approach (at systems of systems level), where SysML is chosen to support requirements modelling. Similarly, based on SysML, Koltun et al. (2017) proposed a model-document coupling approach aimed at automatically identifying and propagating manual changes to documents into a systems engineering model.

To address the problem around requirements rationale, multi-level requirements clarification and requirements concretisation, Berkovich et al. (2014) developed a requirements data model that describes different types of requirements and the relations between them. This model especially addresses the problems of structuring the requirement, enabling traceability, and recognising conflicts.

As MBSE is a natural choice for CPS and DT systems to deal with numerous heterogeneous requirements where solid verification and validation are required at multiple levels, integration into the product lifecycle management (PLM) tool chain is recognised as a solution for lifecycle management of MBSE data. Papinniemi et al. (2014) examined and categorised the challenges of requirements management related to PLM, and then identified core points of where and how the concepts of PLM and requirements management should be developed. Pavalkis (2016) explored the challenges and potential solutions for the integration of MBSE and requirements management with the PLM tool chain.

In summary, initiatives proposed to support information requirements management in digital engineering enabled projects include:

(1) BIM models

(2) Requirements and information management frameworks

(3) Open data standards and technologies

(4) Integrated requirements management processes

(5) Model-based systems engineering (MBSE) architecture framework

(6) Integration of requirements management with DE

(7) Use of systems modelling language (SysML) and natural language processing (NLP) to support better coordination among stakeholders

(8) Requirements data model for structuring requirements

(9) Integration of requirements management/MBSE with PLM to achieve lifecycle management.

4.3.4 Relationships between Initiatives and Capabilities

Further analysis is conducted by mapping the relationships between initiatives identified in Sections 4.3.1–4.3.3 with information requirements management capabilities identified in Section 4.2.2. In Table 4.4, different types of relationships are presented as "S", indicating that the specific initiative has a potential to "support" the specific capability to information requirements management, or "U", representing to "utilise" the specific capability to achieve the goal of the proposed initiative. In other words, the capability is a pre-condition of the initiative.

As shown in Table 4.4, information requirements management capacities supported by most initiatives include:

- A2 – requirements elicitation (8/16)
- A7 – requirements traceability (7/16)
- B1 – requirements modelling software (7/16).
- A4 – requirements verification and validation (6/16)
- A6 – requirements change management (6/16)
- A8– integration of requirements processes (6/16)
- B5 – information flow across project phases (6/16)
- B6 – integration and interoperability of tools (6/16).

There are some capabilities with no supporting initiatives, including one technology related capability B3 – requirements documentation and validation tools, and three people related capabilities C3 – specialist expertise in relevant industry standards, C4 – experience in the application of requirements management guidelines and C5 – ongoing investment in training of requirements management software. It is obvious that these initiatives focus more on supporting process and technology related capabilities than people related capabilities, as these initiatives are process based or technology based methods or frameworks. For people related capabilities, efforts taken to make improvement are more from organisation management or human resource management perspectives such as training, support from senior management, or education.

Another insight gained from Table 4.4 is that A9 – requirements management protocols and languages is recognised as an important capability to support the achievement of many initiatives. One common solution to the complexity of requirements management practices is using a common data language to achieve alignment between requirements across different disciplines and different product development phases.

The next section focuses on the main challenges to general requirements management and information requirements management across multiple domains identified in the literature.

Table 4.4 Relationships between initiatives and information requirements management capabilities

Domain	Initiatives Supporting information Requirements Management / **Requirements Management Capabilities** (RM – requirements management PM – project management)	A1 Systems Architecture Framework development	A2 Requirements elicitation	A3 Requirements analysis and prioritisation	A4 Requirements verification and validation	A5 Requirements negotiation and communication	A6 Requirements change management	A7 Requirements traceability	A8 Integration of requirements processes	A9 RM protocols and languages	A10 Integration of RM protocols with PM protocols	A11 Effective information RM	B1 Requirements modelling software	B2 Requirements storage and workflow platform	B3 Requirements documentation and validation tools	B4 Digital and paper-based artefacts	B5 Information flow across project phases	B6 Integration/ Interoperability of tools	C1 RM roles and responsibilities	C2 Early involvement of stakeholders	C3 Specialist expertise in relevant industry standards	C4 Experience in the application of RM guidelines	C5 Ongoing investment in training of RM software
AECO	**DE/ BIM Model** (Baldauf et al., 2020; Parsanezhad et al., 2016)			S	S	S		S		S	S		S	S	U	S							
AECO	**Web-based building lifecycle management framework** (Kubler et al., 2016)		S	S	S													S					
AECO	**DE/ BIM requirements framework** (Cavka et al., 2017)		S			S															U		
AECO	**Enterprise architecture framework for electronic Req. Info. Mgmt.** (Jallow et al., 2014, 2017)	S					S	S	S			S		U			S	S	U				
AECO	**Lifecycle Information Transformation and Exchange framework** (Succar & Poirier, 2020)									S	S	S					S	S					
AECO	**MVD, IDM** (Arayici et al., 2018)								S									S					
AECO	**Combine the use of IDM, IFC, COBie, CMIS in AIM development** (Patacas, Dawood, Greenwood, et al., 2016)		S		S					S		S		U			S	S					
INF	**RM process for concept phase** (Arnaut et al., 2016)		S		S	S	S		S		S		S						S	S			
INF	**MBSE Architecture Framework approach** (Scott et al., 2016; Shirvani et al., 2020)	S	S					S		U			S										
INF	**Integration of RM with BIM/ DE** (Tolmer et al., 2017)		S						S	U		S				S	S						
MANF	**Model-document coupling approach based on SysML** (Koltun et al., 2017)						S			U			S			S	S						
MANF	**Context-based RM based on SysML** (Holt et al., 2015)		S		S		S	S		U													
MANF	**Requirements Content Model based on SysML** (Penzenstadler & Eckhardt, 2012)							S		U			S			S							
MANF	**Requirements Data Model** (Berkovich et al., 2014)		S		S	S	S	S	S							S							
MANF	**Integrating MBSE with PLM** (Pavalkis, 2016)							S		S		S	S		U		S	S					
MANF	**Integrating RM with PLM** (Papinniemi et al., 2014)						S		S				S										
	Total Number of "S"	**2**	**8**	**2**	**6**	**4**	**6**	**7**	**6**	**4**	**3**	**5**	**7**	**1**	**0**	**5**	**6**	**6**	**1**	**1**	**0**	**0**	**0**

4.4 Challenges to Requirements Management Practices in Digital Engineering Enabled Projects

This section investigates challenges to general requirements management and specifically information requirements management. By reviewing the relevant literature identified, the intention is to identify challenges to requirements management and challenges specifically related to information requirements management to understand their potential impact on the creation of digital twins throughout project delivery. Accordingly, this section responds to research sub-question Q1-3:

> *Q1-3: What are the challenges to requirements management, especially information requirements management in digital engineering enabled projects?*

Based on the corpus of literature, 12 general challenges to requirements management practices and 6 challenges specifically related to information requirements management were identified. Using the same process, technology and people taxonomy as used in Section 4.2, the variety challenges were categorised according to process, technology and people influences, as shown in Tables 4.5 and 4.6.

4.4.1 General Challenges to Requirements Management Identified in the Literature

Three main types of requirements management challenges were identified: process related, technology related, and people related. The nature of the challenges is presented in Table 4.5, and is labelled according to a unique identifier, type and author.

Process related challenges were amongst the most commonly investigated issues facing modern requirements management practices. One of the most significant issues concerns the early involvement of stakeholders, which is considered essential in supporting the requirements elicitation, prioritisation, negotiation and communication processes defining most requirements management methods. The absence of key stakeholders during the planning phase and early design stage of the acquisition phase of the asset lifecycle brings challenges to all activities in the requirements development process due to the knock-on effects to downstream requirements-dependent tasks (RM-PRC-01) (Heaton et al., 2019; Jupp & Awad, 2017; Navendren et al., 2015). The continuous changes to AECO requirements and lack of adequate change management processes are some of the most well-documented challenges reported by researchers over the last decade (RM-PRC-03) (Koltun et al., 2017; Nekvi & Madhavji, 2014; Papinniemi et al., 2014; Patacas, Dawood, Greenwood, et al., 2016; Soliman-Junior et al., 2019; Yu et al., 2010). Other process-related challenges include disconnects in requirements traceability workflows linking requirement types and levels (RM-PRC-02) (Berkovich et al., 2014) and disconnects in distributed requirements processes across organisational units and project disciplines with different levels of abstraction (RM-PRC-04) (Penzenstadler & Eckhardt, 2012).

Table 4.5 Challenges to requirements management practices identified in the literature

Code	Challenge	Source	Area
RM-PRC-01	Lack of collaborative requirements management processes across project team members in development stage	(Heaton et al., 2019; Jupp & Awad, 2017; Navendren et al., 2015)	Process based Challenges
RM-PRC-02	Disconnects in requirements traceability workflows linking requirement types and levels	(Berkovich et al., 2014)	
RM-PRC-03	Disconnects between requirements traceability and design change management (change propagation)	(Yu et al., 2010; Nekvi & Madhavji, 2014; Patacas, Dawood, Greenwood, et al., 2016; Koltun et al., 2017; Soliman-Junior et al., 2019)	
RM-PRC-04	Disconnects in distributed requirements processes across organisational units and project disciplines with different levels of abstraction	(Penzenstadler & Eckhardt, 2012)	
RM-TEC-01	Disconnected between SE-DE* tool chains due to lack of interoperability between requirements management and modelling software *SE: Systems engineering, DE: Digital engineering	(Arayici et al., 2018; Heaton et al., 2019; Kelly et al., 2013; Patacas et al., 2015)	Technology based Challenges
RM-TEC-02	Heterogeneous data inputs and outputs (e.g., different levels of detail, formats, units, etc.)	(Berkovich et al., 2014; Cavka et al., 2017; Jupp & Awad, 2017; Papinniemi et al., 2014)	
RM-TEC-03	Limitations of software supporting the management of conflicting requirements during development stage	(Cavka et al., 2017; Soliman-Junior et al., 2019; Scott et al., 2016)	
RM-TEC-04	Lack of application of available configuration management software during development stage	(Ramos, 2018)	
RM-TEC-05	Lack of investment in requirements management software throughout asset lifecycle	(Ramos, 2018)	
RM-PPL-01	Low levels of stakeholder expertise across diverse and distributed requirements development and management processes	(Emes et al., 2012; Lynghaug et al., 2021; Penzenstadler & Eckhardt, 2012)	People based Challenges
RM-PPL-02	Lack of investment in training in requirements management and related software skills	(Ramos, 2018)	

From both system engineering scholars and industry practitioners, requirements traceability is receiving increasing attention due to the need for more tightly integrated tool ecologies capable of managing the complexity of verifying requirements of cyber-physical systems

(Vogel-Heuser et al., 2020). According to the Object Management Group (2015), a trace "records a link between a group of objects in the output models". There is a wide range of tools and methods to visualise, present and manage these requirements traces. Vogel-Heuser et al. (2020) identified three groups or classes of technology: (1) traceability matrices, (2) cross-references and (3) graph-based visualisation. Different technologies are used across the acquisition for a variety of purposes and systems. The technology-related challenges relating to these tools are vast and include errors or failures related to software interoperability (RM-TEC-01) (Arayici et al., 2018; Heaton et al., 2019; Kelly et al., 2013; Patacas, Dawood, Vukovic, et al., 2015), deficiencies in common data input and output requirements (RM-TEC-02) (Berkovich et al., 2014; Cavka et al., 2017; Jupp & Awad, 2017; Papinniemi et al., 2014), limited software support for and access to appropriate software (server-based) licenses for managing conflicting requirements (RM-TEC-03) (Cavka et al., 2017; Scott et al., 2016; Soliman-Junior et al., 2019), the lack of system-level requirements management tool integrations (RM-TEC-04) (Jupp & Awad, 2017; Ramos, 2018) and ongoing investment on requirements management software (RM-TEC-05) (Ramos, 2018).

People related challenges were most often associated with a lack of training and education or grounded in the temporary nature of AECO supply chains. Other issues are related to the high level of diversity of stakeholders using different representations of the design and at different levels of abstraction used by different stakeholders (RM-PPL-01) (Penzenstadler & Eckhardt, 2012). In addition to these diversity issues is a lack of understanding and educational support in systems engineering methods and software in the construction industry. AECO practitioners are therefore not familiar with the processes and technologies used to support requirements management activities during project delivery (Emes et al., 2012; Lynghaug et al., 2021). The ongoing investment in requirements management software training is also regarded as a critical challenge across the AECO supply chain (RM-PPL-02) (Ramos, 2018). Compounding this lack of expertise and training in requirements management is the distributed nature of AECO projects, where the spatial and organisational separation of AECO stakeholders creates a number of challenges to collaboration and communication (Penzenstadler & Eckhardt, 2012).

4.4.2 Challenges to Information Requirements Management Identified in the Literature

Information requirements specification, development and management is a relatively recent task that has evolved together with increasing levels of DE maturity and has been formalised by the increasing application of related standards, including ISO 19650 and ISO 55000. While there are a number of similarities and challenges shared between general requirements management and information requirements management practices, there are also those that are specific to the specification, development and management of information requirements. The nature of the challenges is presented in Table 4.6, and is labelled according to a unique identifier, type and author (source).

The specification and allocation of organisation information requirements (OIRs) combined with the consistent management of asset information requirements (AIRs) and exchange information requirements (EIRs) throughout the project amplify traditional requirements change challenges. The focus of this thesis is on the asset information requirements (AIRs), which is related to other types of information requirements (OIRs, EIRs and PIRs). The relationship between them was explained in Section 2.5.3. Other issues surround deficiencies in the requirements specification process resulting in unclear, incomplete (iRM-PRC-01) (Aaramaa et al., 2015) or conflicting requirements (Scott et al., 2016; Soliman-Junior et al., 2019), the lack of process standards (iRM-PRC-04) (Cavka et al., 2017; Jupp & Awad, 2017; Patacas, Dawood, Vukovic, et al., 2015), unstructured and late delivery of data and information to facilities management phases (iRM-PRC-03) (Patacas, Dawood, Vukovic, et al., 2015), and absence of a common language for AECO requirements (iRM-PRC-02) (Jallow et al., 2014).

Table 4.6 Challenges to information requirements management identified in the literature

Code	Challenge	Source	Area
iRM-PRC-01	Delays in information requirements specification and development processes / incomplete information requirements	(Aaramaa et al., 2015; Johnson et al., 2021; Kelly et al., 2013; Scott et al., 2016; Soliman-Junior et al., 2019)	Process based Challenges
iRM-PRC-02	Lack of agreed and consistent requirements language describing information requirements	(Jallow et al., 2014)	
iRM-PRC-03	Delays in timely handover process supporting structured transfer of digital deliverables from acquisition phase to operational phase	(Patacas, Dawood, Vukovic, et al., 2015)	
iRM-PRC-04	Lack of process standards supporting information requirements specification, development and management	(Cavka et al., 2017; Jupp & Awad, 2017; Patacas, Dawood, Vukovic, et al., 2015)	
iRM-TEC-01	Multiple disconnects in the flow of information due to technology-based deficiencies	(Jupp & Awad, 2017; Succar & Poirier, 2020)	Technology based Challenges
iRM-PPL-01	Low levels of stakeholder expertise in information requirements management (esp. supporting digital twin creation)	(Cavka et al., 2017; Heaton et al., 2019; Jupp & Awad, 2017)	People based Challenges
iRM-PPL-02	Lack of a clear description of roles and responsibilities supporting information requirements management	(Kelly et al., 2013; Patacas, Dawood, Vukovic, et al., 2015)	

Breaks in information flow due to either a lack of interoperability between requirements and 3D modelling technologies, a lack of integrated requirements modelling and 3D object-based modelling technologies, or a lack of platform-enabled technologies were identified as the main technology related challenges to information requirements specification, development and management (iRM-TEC-01) (Jupp & Awad, 2017; Succar & Poirier, 2020).

In terms of knowledge and expertise, there is a lack of awareness and expertise of standards and guidelines supporting information requirements processes (iRM-PPL-01) (Cavka et al., 2017; Jupp & Awad, 2017; Patacas, Dawood, Vukovic, et al., 2015). There is also a lack of clear roles and responsibilities, and contract and liability framework for information requirements management (iRM-PPL-02) (Kelly et al., 2013; Patacas, Dawood, Vukovic, et al., 2015).

4.5 Summary

This chapter focused on investigating the current requirements management research in the context of digital engineering enabled projects across project-based domains including AECO, infrastructure, and complex discrete manufacturing to answer the first research question based on desktop-based research adopting a systematic literature review approach. Figure 4.4 presents the structure of this chapter.

First, an overview of the search results was presented in terms of the proportion of the publication sources in relation to whether the articles were published by journals or conference proceedings, number of publications per year, and the specific journal or conference where the articles were published. This indicates that the requirements management implementation in digital engineering enabled projects is a relatively new and emerging research field. Targeting research sub-question Q1-1, key capabilities supporting the governance management of technical systems requirements and information requirements were then investigated, with 22 capabilities relative to process, technology and people dimensions identified.

Initiatives proposed and developed in different domains that support information requirements management in digital engineering enabled projects were investigated and analysed to answer research sub-question Q1-2. AECO, infrastructure and manufacturing were the three industry domains investigated. In each domain, three main types of methods or frameworks were summarised. MBSE and BIM/PLM relevant approaches were identified as the most popular ones adopted across industry domains. The relationship between initiative and requirements management capabilities is further explored.

Challenges and open issues of general requirements management and information requirements management in support of the delivery of digital engineering enabled projects were investigated to answer research sub-question Q1-3. In total, 11 general requirements management challenges and 7 information requirements management challenges were identified and categorised into process, technology and people related areas. These findings formed the knowledge foundation for the interview questions in the next chapter. Challenges related to requirements management identified in real transport projects were further explored and compared with challenges identified in the literature.

In summary, this chapter forms the knowledge foundation according to the design science research framework employed by this study. To investigate the environment requirements of the research, the next chapter presents findings from case studies in terms of contemporary requirements management practices used in complex rail transport projects.

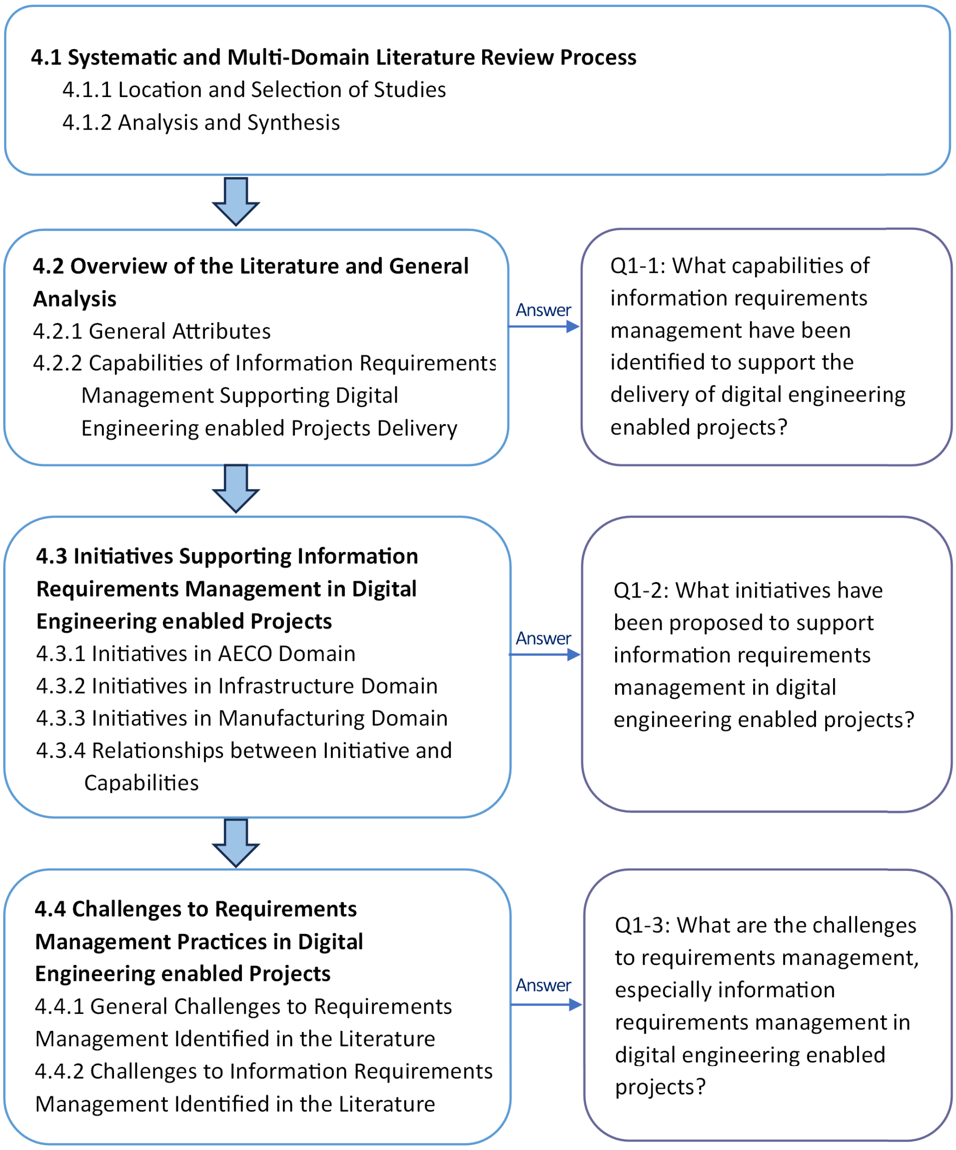


Figure 4.4 Structure of Chapter 4 content

Chapter 5 Information Requirements Management Practices in Complex Rail Transport Projects: Capabilities, Initiatives and Challenges – Case Studies

This chapter addresses research question 2 and adopts a case study approach to investigate key requirements management capabilities, existing initiatives, and challenges encountered by project teams when developing and managing information requirements in complex rail transport projects. First, the multiple-case study scope and process are presented, followed by an overview of some capabilities identified that are key to effective and efficient information requirements management in complex rail transport projects. Initiatives implemented in case projects supporting requirements management and information requirements management are introduced and analysed. The main challenges to general requirements management and information requirements management in complex rail transport projects are identified and mapped in the requirements management process throughout the lifecycle of the asset.

In the previous chapter, requirements management capabilities, initiatives and challenges in three domains were investigated: architecture, engineering, construction and operational (AECO), infrastructure and manufacturing. As the second stage of the design science research methodology, this chapter forms the "environment" which defines the problem context. It is essential to understand the key capabilities identified by the project team, best practices and initiatives implemented to support information requirements management, as well as challenges encountered by project teams in the specific context of complex rail transport projects. In alignment with the sub-questions proposed in Chapter 4, Chapter 5 explores the following sub-questions that support research question 2:

Q2-1: What capabilities have been identified as key to information requirements management by project teams in complex rail transport projects?

Q2-2: What initiatives have been implemented in practice to support information requirements management by project teams in complex rail transport projects?

Q2-3: What are the challenges to requirements management, especially information requirements management, encountered by project teams in complex rail transport projects?

5.1 Multiple-Case Study Scope and Process

Following the literature review, the research collected primary data to investigate challenges encountered by organisations and project teams when developing and managing information requirements. A multiple-case study (Hox & Boeije, 2005) approach was adopted, and data collection involved semi-structured interviews with experts from Australian firms engaged in the delivery of complex rail transport projects. Additional data collection methods included attending lectures and presentations by industry experts that introduced best practices in implementing digital engineering in rail transport projects, and symposiums and summits organised by industry organisations (e.g., SydBIM events, future infrastructure summit).

The semi-structured interviews ensured that multiple topics surrounding the research problem could be covered. First round interview themes included the following areas:

- experience in developing and managing requirements of physical assets and digital deliverables (e.g., best practices, initiatives)
- experience in adopting digital engineering in complex rail transport projects (e.g., best practices, initiatives)
- current challenges to developing and managing different requirement types.

Based on their experience in the topics and availability, we conducted second and third rounds of interviews with some participants to further discuss and explore practice cases and initiatives.

Thirteen participants across six companies were interviewed between February 2020 to July 2022 (see Table 5.1). Each interview took one to two hours, and recordings were subsequently transcribed and verified.

Table 5.1 Number of organisations and interviewees

Organisation	Role	# Interviewees
Client-side (Public Agency Project Office)	Digital Engineering Director	1
	Digital Engineering Manager	1
	Senior Project Manager	1
	Engineering Lead	1
	Systems Architecture Principal Engineer	1
	Senior Systems Engineering Manager	1
Supply-side (Project Delivery)	Systems Engineer	2
	Rail Systems Engineer	3
	Digital Engineering Lead	2
Total Interviews With Transport Authorities and Authorised Engineering Organisation (AEO) firms		13

5.2 Support for Requirements Management Capabilities in Digital Engineering Enabled Projects

This section investigates five key capabilities supporting the requirements management in digital engineering enabled complex rail transport projects that were mentioned in the research interviews and industry presentations: process standards supporting information requirements management, the integration of DE within SE processes, requirements verification process, the implementation of a common data environment (CDE), and development of a common data structure and coding standard.

5.2.1 Process Standards Supporting Information Requirements Management

In complex rail transport projects, the development and management of different requirement types adhere to the formal methods and processes of systems engineering methodologies (Chen & Jupp, 2023a). In Australia, the release of landmark ISO standards in the past decade – together with other business-related and industry drivers – has accelerated recent efforts in government agencies to release new project standards to enable integrated digital approaches to the planning, acquisition and operation and maintenance (O&M) of transport assets (Chen & Jupp, 2023a). In the planning and acquisition phases of complex rail transport projects, and particularly those implementing a strategic approach to through-life asset information management, a network of authorised engineering organisations, or AEOs, develop and manage tens of thousands of requirements about the cyber and physical systems as well as their virtual replicas, and the complex of interfaces between them.

The identification and importance of asset information requirements (AIRs) have been developed in response to opportunities to use new technologies to support integrated digital environments to support asset management, which have increased in popularity and capability over the past five years (Chen & Jupp, 2023a). Globally, a growing number of government transport agencies have adopted asset management standards (e.g., ISO, 2014a), systems engineering standards (e.g., ISO/IEC/IEEE 15288:2015) and new standards supporting information management across the asset lifecycle (e.g., ISO, 2020).

New DE standards have been developed and implemented by a growing number of state infrastructure agencies, including Transport for NSW (2022a, 2022b), the Office of Projects Victoria (2020), Queensland's Department of State Development, Infrastructure, Local Government and Planning (Queensland Government, 2020), and South Australian Department for Infrastructure and Transport (2019). Australian state transport infrastructure agencies are therefore implementing a complex set of international and organisational standards to achieve a more strategic approach to asset information lifecycle management (Chen & Jupp, 2023a).

However, the Australian experience is not unique. For the past two decades, there has been a growing maturity in the application of process and information management standards supporting model-based approaches to asset planning and acquisition. This has resulted in new service-oriented offerings linking, for example, Building Information Modelling (BIM) to facilities management (Matarneh et al., 2019), and more recently to the development of spatial digital twins (DTs) to support the O&M of transport assets (Johnson et al., 2021; Tchana et al., 2019; Zhao et al., 2022). As mentioned in Chapter 2, to support requirements management in complex infrastructure projects, the International Standard ISO 55000 (2014a) and ISO 19650 Parts 1 and 2 (2018a, 2018b) provide procedural methods and much needed consistency in the terminology, concepts and principles underpinning the development of asset management strategy and identification of supporting requirements. ISO 55000 and ISO 19650 procedural methods together play a central role in the development and management of AIRs, as well as the ongoing management of digital information and digital deliverables supporting asset management.

5.2.2 Integrating Digital Engineering within Systems Engineering Process

For Transport for NSW projects, management over the asset or system lifecycle is supported by the systems engineering (SE) methodology (Transport for NSW, 2017). The Transport for NSW system "V" lifecycle model (Figure 5.1) shows the relationship between asset lifecycle stages and critical configuration management gates, adapted from the International Council on Systems Engineering (INCOSE, 2007, 2021) systems "V" lifecycle model. The asset or system lifecycle stages as defined by INCOSE (2007, 2021) and ISO/IEC/IEEE 15288:2015 (ISO, 2015) are as follows: a) concept, b) development, c) production, d) utilisation and support, and e) retirement.

The configuration management gates in Transport for NSW projects include initiation, requirements complete, initial design, for construction, ready to test, accept assets and asset review (Transport for NSW, 2017). Each configuration management gate is associated with a specific baseline that outlines the criteria for deliverables at the review gate. This ensures that each stage of the project is properly reviewed and approved before progressing to the next phase. The need for effective configuration management in transport infrastructure projects is critical to ensure efficient and error-free progress throughout the project lifecycle. Without proper configuration management, there is a higher risk of delivering incomplete or faulty products that do not meet the required standards. Therefore, it is important for transport infrastructure projects to implement automated configuration management tools and processes to streamline and enhance the efficiency of their operations. The establishment of a common data environment solution and workflow has the potential to facilitate the automation in configuration management. See detailed discussion in Section 5.2.4.

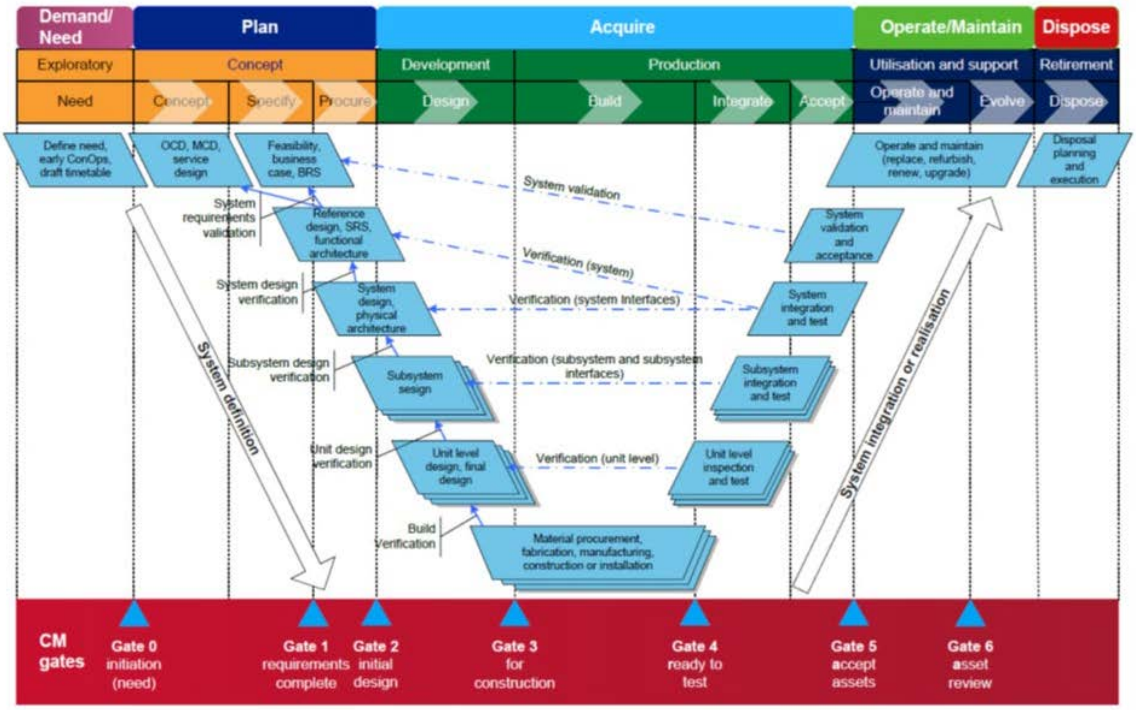


Figure 5.1 Transport for NSW (2017) system V lifecycle model, showing key activities related to requirements management and configuration management gates

To support more strategic and integrated approaches to digital asset management, during the acquisition phase, AIRs describing physical systems, their virtual replicas, and real-time behaviours must also be developed and managed. AIR is the precise description of the information required to operate and maintain a specific built asset through its lifecycle. The information required in AIRs focuses on the as-built state. It defines not only what information is required (content) but also how it should be delivered (form and accepted formats of deliverables). The AIR is a subset of the overall project brief. The processes of delivering the assets and the associated data and information are parallel and connected (see Figure 5.2 below).

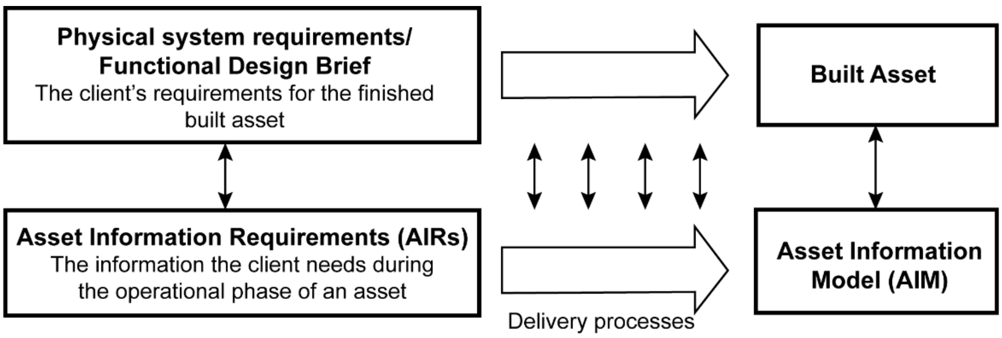


Figure: Parallel delivery of built asset and asset data

Figure 5.2 Parallel delivery of built asset and asset data (Australasian BIM Advisory Board, 2018)

To visualise the interface management of physical system requirements together with information requirements, and particularly those supporting the development of the asset information model (AIM), defined by the AIR, a reflected V-model, or "Diamond" model

(Hatakeyama et al., 2018; Seal, 2018) can be used. This follows work undertaken at Boeing. Figure 5.3 presents an adaption of Boeing's Diamond model (Seal, 2018) according to the V-model used by the Transport for NSW SE Standard (Transport for NSW, 2017), and DE practices in complex rail transport projects. The lower V reflects the classic SE process embedded with design activities supporting the development of the physical system of transport. Key review gates including system functional review, preliminary design review, critical design review, test readiness review, and system verification review have also been mapped in the SE processes (the lower V). The mirror reflection of the V above represents the development of different types of information requirements, virtual asset modelling, simulation and integration (Hatakeyama et al., 2018). The inverted V represents the design and realisation of behavioural simulations (Hatakeyama et al., 2018). Integration of development of asset, construction and assembly systems, and operations and maintenance systems are vital to the development of the digital thread.

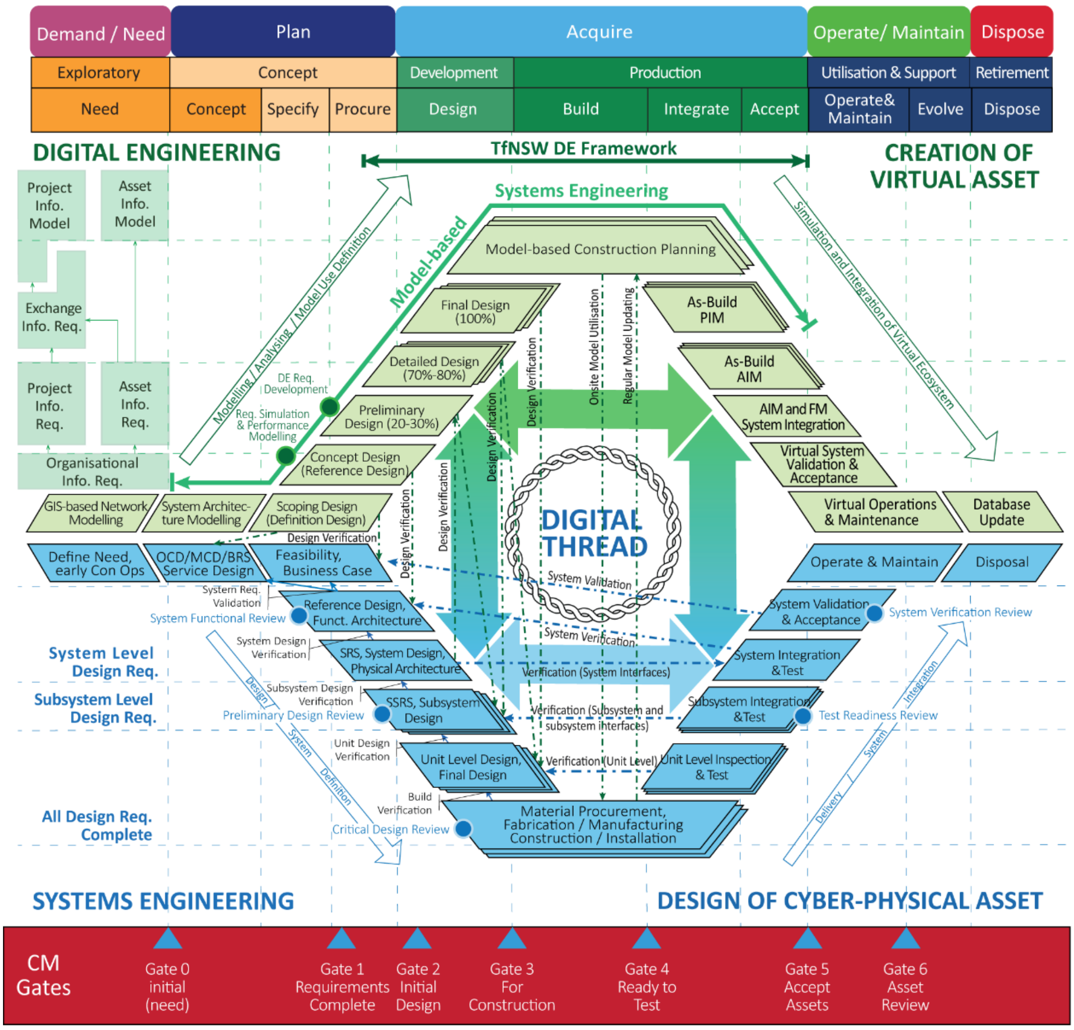


Figure 5.3 Diamond lifecycle model (adapted from Boeing, 2020 and Transport for NSW, 2017)

During the interviews with industry experts who had experience in rail infrastructure projects implementing DE, the adapted "Diamond" model was presented for their feedback.

Revisions were undertaken based on their responses and suggestions in terms of the design phases in the upper part of the model, and verification links between DE activities and SE activities.

5.2.3 Requirements Verification Process in Complex Rail Transport Projects

During the design phase of complex rail transport projects, the verification of requirements follows a structured sequence of activities encompassing systems, sub-systems and detailed design review (Pallipattu, 2022). Typically, these processes involve the manual checking of the proposed design solution, either through consultations with subject matter experts or by comparing it against a relevant technical standard such as AS61000 (Pallipattu, 2022). In addition to manual checks, requirements verification may also entail system configuration testing and the identification of anomalies through simulations using computational and analytical models. These simulations are typically performed at the systems design review level. To facilitate the manual checking process and maintain configuration tracking for specific systems, sub-systems or test series, technical requirements captured in spreadsheets are combined with the design documentation (2D drawings). However, it is important to note that these processes are labour-intensive. Coordinating these activities and manually updating requirements data for numerous entries fall under the responsibility of a systems engineer. Each level of review requires significant time investment for manual post-processing of requirements data using the current verification process, which spans multiple design stages.

With the growing adoption of Transport for NSW's new SE and DE Standards, there is an increasing potential to leverage the digital environment and structured data. This opens up new possibilities for enhancing integration between SE and DE activities, particularly during the planning and acquisition phases of the asset lifecycle. These opportunities primarily revolve around improving process efficiencies and the quality of requirements management processes. In the realm of SE, the introduction of system modelling language (SysML) requirements modelling at Transport for NSW has been identified as a best practice. This approach enables the systematic and structured representation of requirements. On the other hand, DE implementation has embraced best practices that facilitate the reliable production and coordination of structured 3D spatial information and associated metadata. This ensures a robust quality control process. Together, these model-based approaches offer exciting prospects for streamlining, automating and optimising requirements verification activities. By using the digital environment and structured data, the verification process can become more efficient and effective. This opens doors to enhance coordination, reduce manual efforts, and improve the overall quality of requirements verification.

The use of model-based verification during the design review phase offers significant benefits in terms of error tracing and impact analysis during later integration and testing phases (Schamai et al., 2011). It enables a seamless traceability from the initial requirements to test cases and test results, facilitating a comprehensive understanding of the system under development phases (Schamai et al., 2011). Currently, there are several rule-based verification schemas integrated within model checking software platforms such as Revizto, Solibri and Navisworks. These platforms help overcome semantic interoperability challenges that often arise when dealing with different technical information provider (TIP) tool ecologies (Pallipattu, 2022). Furthermore, existing model-based checking tools and requirements verification software have primarily been applied in the buildings sector, focusing on addressing spatial requirements verification. This approach improves the efficiency and accuracy of requirements verification, particularly in complex projects involving spatial requirements.

Nevertheless, there exist a variety of challenges when facilitating the verification of system requirements (Pallipattu, 2022). These challenges primarily stem from disconnected data flow and lack of data integration between the specification and modelling of system requirements using MBSE methods, and the system design and modelling of product and process solutions using DE methods (Pryke, 2020).

The flow of data throughout the infrastructure asset lifecycle can be divided into three parts: (1) system definition to system design, (2) system design to construction, and (3) construction to operations and maintenance (Yuan et al., 2017). Each stage of this data flow is critical for ensuring the successful implementation and operation of the asset. For instance, the asset information captured during the system definition to design phase, using tools like SysML models, holds significant value in downstream processes such as the verification of 3D spatial models during the design review and construction phase (Pallipattu, 2022). This integration allows for the identification of any potential re-works or design changes early on, reducing the need for costly modification (Pallipattu, 2022). To ensure the effectiveness of the 3D system design captured in DE/BIM tools, it is crucial to assess whether they fulfill or violate the requirements developed in the planning and early design stages (Pallipattu, 2022). This requires seamless integration and data flow between different teams and departments involved in the project.

However, there are obstacles to achieving smooth data flow and integration, particularly in the context of systems requirements verification. These obstacles primarily stem from the disconnections between siloed teams and departments, as well as the lack of software and semantic interoperability (Pallipattu, 2022). With semantic interoperability, the data is not only exchanged between two or more systems but also understood by each system (PAHO, 2021).

These barriers hinder the integration of diverse types of data and information models that describe requirements and their corresponding solutions (Pallipattu, 2022). Addressing these challenges is essential for improving data flow and achieving effective integration between different stages of the asset lifecycle (Pallipattu, 2022). By fostering collaboration, implementing compatible software tools, and promoting semantic interoperability, organisations can overcome these barriers and achieve a more integrated and streamlined approach to requirements verification processes (Pallipattu, 2022).

5.2.4 Common Data Environment in Complex Rail Transport Projects

In a complex rail transport project, a common data environment (CDE), often described as an "ecosystem of technology platforms" (Jupp, 2024), is a centralised digital platform or system where project stakeholders can securely store, manage and exchange project-related information and data (ISO, 2018a). This includes documents, drawings, 2D and 3D models, specifications, schedules, and other critical project information and asset information. The CDE serves as a collaborative hub for all project participants, ensuring that everyone has access to the most up-to-date and accurate data, which is essential for the successful execution of large and complex projects like rail transport infrastructure development. Moreover, the CDE must combine workflow and storage solutions to aid in the management of asset information (ISO, 2020). Information models such as PIM and AIM are key outcomes of CDE that contain federated information deliverables produced by the CDE workflow to address all stakeholders' perspectives (ISO, 2018a). A CDE has three major components: electronic document management systems (EDMS), workflow management, and 2D and 3D coordination (CIC, 2022).

The function of a CDE is to supply the right information to the right people at the right time (Jupp, 2024). Key features and benefits of a CDE in a complex rail transport project may include:

- **Centralised data storage**: All project-related data and documents are stored in one central location, making it easy to locate and access information.
- **Version control**: The CDE typically includes version control capabilities, ensuring that everyone is working with the latest versions of documents and designs.
- **Access control**: Access to the CDE is controlled through permissions, ensuring that only authorised individuals can view or edit specific data.
- **Collaboration**: Project teams can collaborate more effectively by sharing and reviewing documents within the CDE, reducing the risk of miscommunication and errors.

- **Traceability**: Changes and updates to project data are tracked, providing a clear audit trail of who made changes and when.
- **Security**: Data in the CDE is typically stored securely, with measures in place to protect against unauthorised access or data breaches.
- **Compliance**: A CDE can help project teams meet regulatory and compliance requirements by ensuring data integrity and accountability.
- **Efficiency**: By streamlining data management and collaboration, a CDE can lead to improved project efficiency and reduced delays.

In the context of a complex rail transport project, the use of a CDE is essential to keep all stakeholders "on the same page", manage the vast amount of data involved, and ensure that the project progresses smoothly and according to plan. It plays a crucial role in modern project management practices, particularly in large infrastructure projects where coordination and information sharing are critical. There are several types of classifications for CDE (or sub-components of CDEs) with unique characteristics (Jupp, 2024). The components of CDEs include (Jupp, 2024):

(1) Enterprise content management systems (ECM): A full ECM system is now recognised as an essential sub-component of a contemporary CDE. Different from an Enterprise Document Management System (EDMS) which generally only includes the documents and file management functionalities, an ECM system not only offers features for storing and managing documents and files, but it also contains version control, access rights management, and basic collaboration tools. These systems are particularly useful for handling reports, drawings and other standard project documents. ECM systems also include correspondence modules such as transmittals, emails and RFIs for managing communication between client and suppliers in a controlled and traceable way.

Although the ECM system is a foundation component within a CDE, it was often mistaken or mislabelled as a CDE. ECM systems provide a centralised repository for document storage, version control, and metadata tagging, enhancing retrieval and organisation. They also offer workflow automation, collaboration and correspondence tools, and compliance features, ensuring efficient document-centric processes and adherence to industry regulations. For instance, Bentley ProjectWise can be illustrated as an ECM within the CDE of Transport for NSW.

(2) Collaborative BIM platforms: These advanced CDE modules are specifically designed for managing BIM data, supporting 3D models to enable stakeholder collaboration on a shared platform. BIM platforms offer sophisticated tools for visualisation, clash detection and seamless

integration with other project management tools. These capabilities allow for enhanced coordination and efficiency in managing complex project data, facilitating real-time collaboration and decision-making among project teams.

(3) Spatial data platforms: Focused on collecting and managing data from the field, these specialised CDEs are vital for projects requiring real-time data collection from construction sites or operational environments. They typically include mobile applications and sensors for data gathering, which are integrated with the central CDE for comprehensive data analysis, validation and management. This integration ensures that field data is accurately captured, validated and processed, supporting timely and informed decision-making throughout the project's lifecycle.

(4) Project management platforms: These CDEs focus on the overall project management aspects, including scheduling, resource allocation and budget management. While they handle documents and data, their primary focus is on facilitating project planning and execution.

(5) Integrated data environments: These are comprehensive platforms that combine features of document management, BIM and project management. Integrated data environments aim to provide a complete solution for all aspects of project data management, including model-based data, documents and project management functionalities.

(6) Asset management systems: These CDEs are tailored for managing data related to the operation and maintenance of built assets and are particularly useful post-construction for facility management, asset tracking and maintenance scheduling.

Figure 5.4 shows relationships between these data management systems in project management.

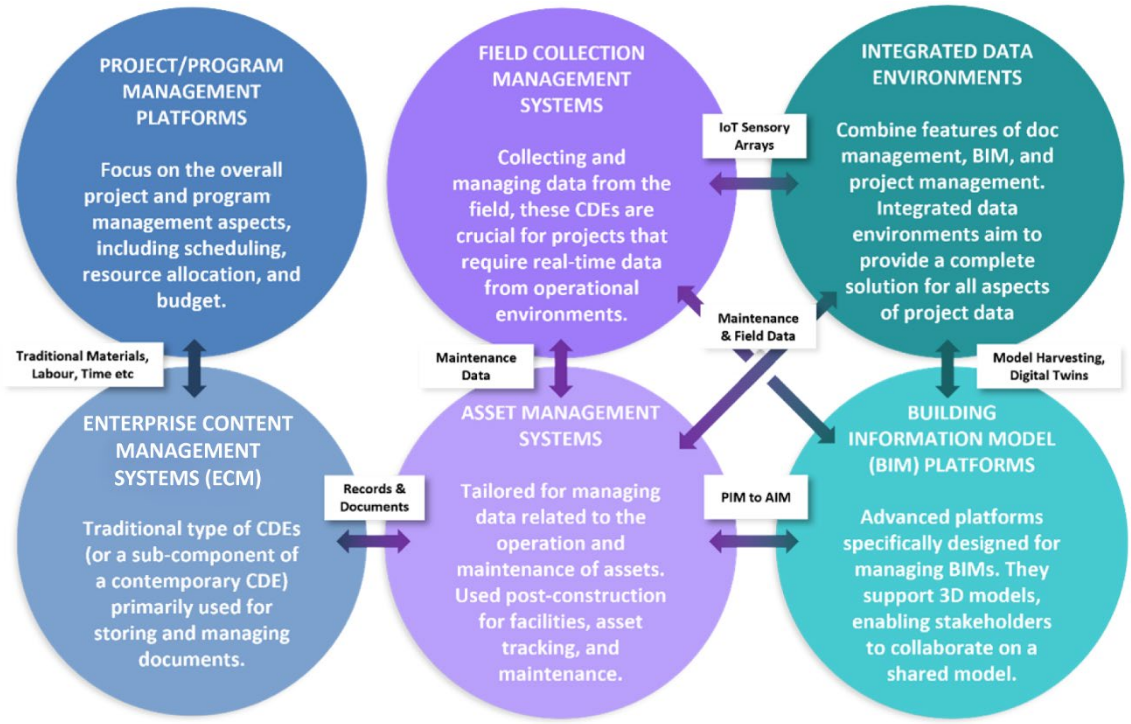


Figure 5.4 Relationships between data management systems in project management (Jupp, 2024)

The architecture of a CDE can vary based on project scale, industry standards and organisational requirements (Jupp, 2024). Larger projects often require more advanced features for model coordination and version control, while smaller projects may need simpler configurations (Jupp, 2024). A CDE can serve as a long-term infrastructure for managing information across the organisation, or as a short-term project-specific platform (CIC, 2022). There are three main levels of CDE for an enterprise to adopt: enterprise CDE, department CDE, and project CDE (CIC, 2022). An enterprise CDE is "an organisational-wide CDE that is completely integrated with the business, workflows, and existing systems (e.g., IT, procurement, asset management, etc) of the enterprise" (CIC, 2022, p. 17). A project CDE is "a CDE being used in a specific project or built asset. Compared with enterprise and departmental CDE, it has a lower entry level, and is simpler and more flexible, in terms of the CDE setup and adoption. Typically, a PIM CDE or AIM CDE is often regarded as a project CDE" (CIC, 2022, p. 17).

5.2.5 Developing a Common Data Structure and Coding Standard

Effective through life information management requires a comprehensive approach with written requirements on the information, people, processes and technology throughout the lifecycle of the infrastructure project (Jupp, 2024). In general, information requirements should structure and standardise all data that comprises the information model (Jupp, 2024). The data and information that is to be provided throughout the asset lifecycle (information requirements) are determined by the client's/asset owner's objectives at each stage (Jupp, 2024). The data and information are used to assess performance against the client's/asset owner's objectives, facilitate verification of requirements and assist in lifecycle decision-making (Jupp, 2024).

Project data building blocks (PDBB) are the standardised pieces of data and tools needed to plan, execute and manage a project's data effectively, from start to finish (Transport for NSW, 2022a). When working in DE with Transport for NSW, the PDBB is a collective name for the centralised structured data being used by the project team, which includes both standard building blocks and project-specific building blocks (Transport for NSW, 2022a).

The *Digital Engineering Standard Part 1: Concepts and Principles* (Transport for NSW, 2022a) provides requirements and guidance on project data building blocks (PDBB) and project data schemas (PDS) as tools to build a common language and structure for all project information and data, aligning the PIM and the AIM (Transport for NSW, 2022a). The PDBB categorise the collection of different essential types of project data necessary for efficient project management and delivery (see Figure 5.5), including (Transport for NSW, 2022b):

(1) Project details: Contains contracts and design packages.

(2) Location list: Uses Uniclass location references to identify project locations.

(3) Asset list: Uses Uniclass asset references to catalogue assets involved in the project.

(4) Disciplines: Divides data into technical and business disciplines.

(5) Transport for NSW data: Includes project stages and milestones specific to Transport for NSW.

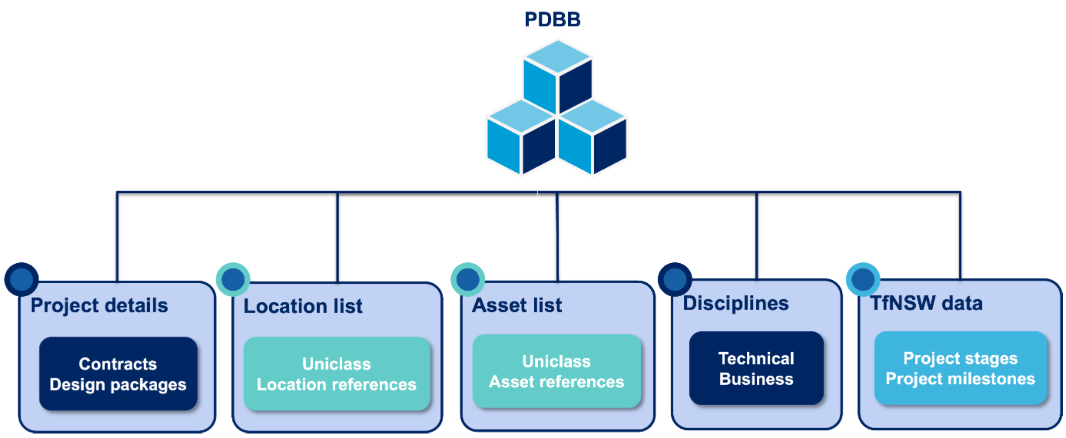


Figure 5.5 The content and structure of project data building blocks (PDBB) (Transport for NSW, 2022b)

The alignment of the Work Breakdown Structure (WBS) defining tasks, Cost Breakdown Structure (CBS) estimating costs and Asset Breakdown Structure (ABS) identifying assets in the AIM is crucial for effective data management in Transport for NSW DE-enabled projects

(Jupp, 2024), forming the backbone of project planning and control. Their alignment ensures consistency and transparency, facilitating data governance among stakeholders (Jupp, 2024). It allows the integration of cost, schedule and asset data, enabling comprehensive project monitoring and control, and importantly a seamless asset handover (Jupp, 2024).

PDBBs have integrated this approach with alignment across all three key breakdown structures to enhance decision-making, as they provide a holistic view of project performance, and allow the identification of issues and risks at an early stage. Furthermore, PDBBs support the traceability of information throughout the project lifecycle, from inception to operation, and even demolition. Therefore, the alignment of WBS, CBS and ABS is a key factor in achieving efficiency, effectiveness and sustainability for digital engineering and is core to the PDBB objectives.

The PDSs (project data schemas) are generated from the PDBB and define the structure of data required for information exchange between project participants and across various phases with the level of detail clearly outlined (Transport for NSW, 2022b). Each PDS is specific to each type of project deliverable (i.e.: survey, GIS, 3D models, cost, etc). The primary purpose of a PDS is to ensure that all data produced and shared within a project adheres to a common structure and coding standard, aligned with the master data standards (WBS, CBS and ABS) in the PDBB (Transport for NSW, 2022b). Each PDS includes a configuration specification, which defines the required information layers and attributions including their business descriptions, data format, level of the detail required at each project phase and information exchange property set (Transport for NSW, 2022b).

Figure 5.6 highlights how the same attributes from the PDBB appear in many of the deliverable PDSs.

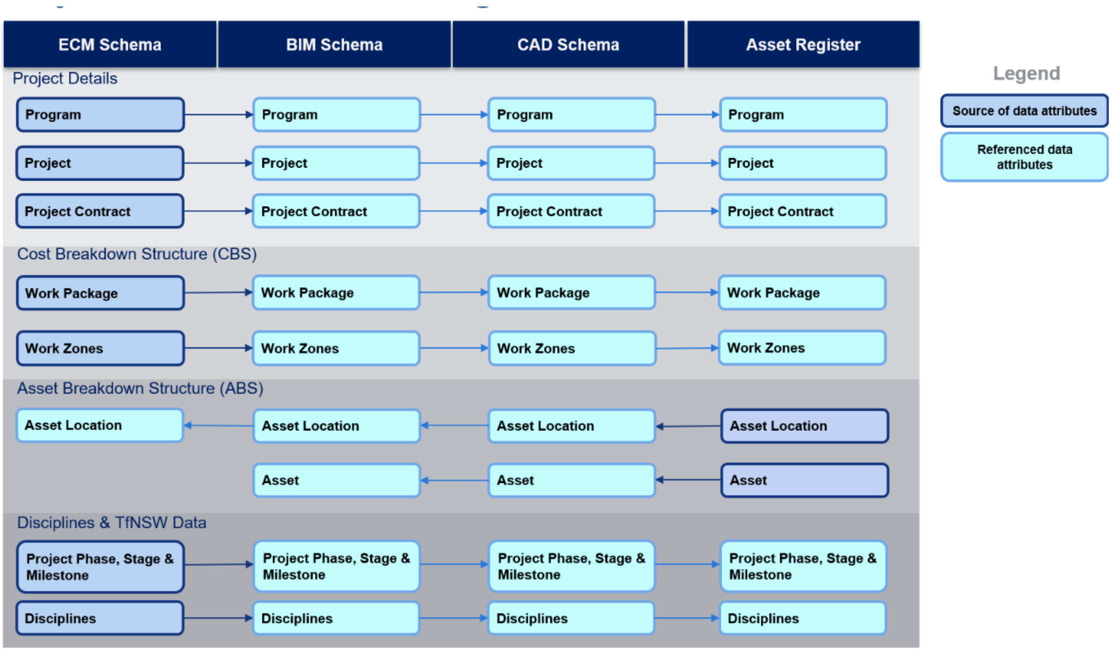


Figure 5.6 The content and structure of project data schemas (PDSs) (Transport for NSW, 2022b)

The diagram emphasises the flow of data (indicated by arrows) and the consistent referencing of data attributes (indicated by coloured boxes) across different schemas, ensuring efficient and seamless data integration throughout the project lifecycle. Attributes in the PDS are interdependent, meaning changes in one attribute can impact others, therefore they must be managed as master data in the PDBB. This ensures they remain integrated across the different schemas and therefore project information deliverables.

At the start of a project, initial data from the PDBB is seeded into the PDS with predefined project details and breakdown structure (WBS, CBS, ABS, etc) for each discipline (Jupp, 2024). As shown above, each attribute has a primary PDS as the source to ensure alignment (Jupp, 2024). These primary attributes are then referenced by the other PDSs that also need that attribute for their related data deliverable (Jupp, 2024). By governing the master data centrally in the PDBB, the project team can maintain the consistency of attribution and coding of the data across different deliverables (Jupp, 2024).

5.3 Initiatives Supporting Information Requirements Management in Complex Rail Transport Projects

The case studies of this chapter were based on 1) requirements management capabilities enabled within BIM-enabled projects at Transport for NSW (based on the DE Standards prior to Version 3), or 2) integrated requirements management capabilities enabled within DE-enabled projects at Transport for NSW (based on the DE Standards post Version 3 – projects executed using the DE Standards Version 4 and 4.1).

This section presents two major initiatives that have been implemented in complex rail transport projects that were mentioned by interviewees. The first case study is the implementation of BIM in a light rail project. The second case study is adopting the MBSE approach in a digital system program.

5.3.1 Adopting Digital Engineering Process in Light Rail Project

The light rail project was a major infrastructure in Sydney by Transport for NSW (NSW Government, 2024). It contains four major systems: the light rail vehicle, the infrastructure (i.e., the track work and the utilities below ground), the operation system from track work up to the stations, and the vehicle system. There were two main contractors delivering this project, one for the infrastructure and another for operation and maintenance (for a limited period of time of 7 years). Digital engineering was implemented with the following five objectives according to the DE manager of this project:

(1) To develop coordinated project information among the multiple disciplines with the objective of increasing efficiency and reducing issues by integrating multiple sub-systems and disciplines into a coordinated model.

(2) To improve the consistency and reliability of the information created throughout the various project phases.

(3) To produce coordinated information with sufficient definitions for relevant project phases.

(4) To maintain traceability and consistency between BIM model and drawing plans.

(5) To facilitate the optimal transition information from project information model (PIM) to the asset information model (AIM).

In terms of information requirements management, during the early planning phase, the client side defined the objectives and needs first (also known as asset information requirements and project information requirements). Then, the main contractor developed the DE execution plan (including the exchange information requirements or contractual requirements) based on client objectives and needs. The DE execution plan was then reviewed and signed off by the client before implementation. The implementation of DE support information requirements management had three aspects: i) using a unified classification schema for asset information; ii) verifying the design against information requirements using a BIM model; and iii) using a CDE for interface management of information between client and contractors.

During early planning and design phases, the DE team took the time to survey and check the utilities under the ground with Geographic Information Systems (GIS) data which was then transferred to the BIM model. A common asset classification language or unified classification schema was adopted so that the asset data received from the utility surveyors could be stored, checked and combined in a consistent manner. The classification schema contains three high-level areas: location classification, asset classification, and management processes and organisation arrangements. The development of an accurate underground utility model prevents "out of scope" changes which is a main cause of cost overrun in many rail projects. This unified classification schema was then adopted amongst main contractors and sub-contractors throughout the development phases of the project. During handover, the asset information could be extracted and directly used in the maintenance and/or operation systems as it is in the right format.

There are three design stages in this rail project: concept design, preliminary design, and detailed design. During the design review process, information requirements have been embedded in contract requirements and classified into technical requirements which were received by the contractors. Based on this, the contractors developed the BIM model with required asset information embedded and updated the model every fortnight. The utilisation of a BIM model makes it more efficient for the client during design reviews. Another implementation of the BIM model is the clash detection. Workshops were frequently set up to identify, rectify and solve clashes among designs of different disciplines. Once there were no clashes identified and the detailed design had been verified against the information requirement, the BIM model and relevant data still needed to be updated every fortnight during the build phase.

To support the interface management of information between contractors and the client, a sub-component of CDE – an ECM system – was introduced. A cloud-based platform called ProjectWise was used for the contractors to share the information with the client. Once the information was approved, it was published in another software called TeamBinder. There are three types of definitions of the models: authorised model, federated model, and post-handover model. The authorised models refer to all the models and data created by the contracts. Whoever created the model is responsible for its accuracy and updates. The federated model was the combination of all the available data and models from all the contractors. The operation and maintenance contractor was responsible for collating the information together and producing the federated model. From a post-handover point of view, all the agreed models were going to be completed on the licence with the current owner, and the previous owners were no longer responsible for any more data integration or data accumulation.

From a lessons-learnt perspective, five potential improvements were identified by DE managers of the project:

(1) Improvement needed for the design review tool using the BIM model

(2) Implementing the DE protocols and rules earlier in the project phase

(3) Using a single source of data coding language or schema

(4) Improving the ability to auto verify and validate requirements

(5) Supporting the contractors to gain a better understanding of the data coding schema and establish a clear process earlier.

The creation of a digital twin was the ultimate goal of the digital engineering enabled project. Although the industry was in an immature situation, the combination of SE and DE in this light rail project played a pivotal role in mitigating risks in the procurement process. It offered greater assurance to contractors participating in transport projects. From the perspective of information requirements management, DE demonstrates significant potential in streamlining requirements verification during the design review processes. The introduction of a unified asset classification language and schema during the early planning phase amplified the coherence of data and information flow. This encompassed data originating from GIS survey data, all the way to the BIM model and asset information. In this project, information requirements were embedded within technical system requirements which were then developed into contractual requirements. This initiative marked a pioneering rail transport project that implemented DE, and it yielded positive feedback on the capability of DE in enhancing the effectiveness and efficiency of the information requirements management process.

5.3.2 Adopting MBSE Approach in Digital System Program

To meet the growing demand of transport, the digital system program (DSP) is proposed to upgrade the rail network in NSW to create high capacity turn-up-and-go services (Roodt et al., 2020b). The resources for this case study came from both the interviews mentioned in Section 5.1 and the papers written by Roodt et al. (2020a, 2020b) as Roodt was the leader in this project. The project comprises three core components (Roodt et al., 2020b):

(1) **Implementation of European Train Control Systems (ETCS) Level 2**: This involves replacing conventional trackside signalling equipment with state-of-the-art “in-cab” train control technology, ETCS Level 2.

(2) **Integration of Automatic Train Operation (ATO)**: ATO is introduced to support train drivers, who still maintain control, in achieving reduced and more consistent journey times.

(3) **Introduction of a Traffic Management System (TMS)**: TMS is deployed to facilitate rapid recovery from disruptions within the railway system and to optimise the overall network management.

In this project, information requirements were viewed as a part of the technical requirement. Thus, in the rest of this section, the term “requirements” is used to refer to both technical system requirements and information requirements. A model-based systems engineering (MBSE) approach has been implemented to effectively handle the complexity inherent in the DSP system solution. This approach is based on an established architecture framework and involves the creation of a digital systems model (DSM). In this approach, a concept design lifecycle is used, which encompasses conceptual scenario development, architectural analysis, requirements allocation, change impact analysis, related project analysis, configuration management, and artefact generation processes (Roodt et al., 2020b). This holistic approach serves as the foundation for managing and advancing the DSP system solution.

In this project, the MBSE approach was implemented before the commencement of requirements development to reduce the risk of rework and to facilitate a more efficient requirements development and management process (Roodt et al., 2020b). The developed framework (see Figure 5.7) played a critical role in capturing both the current state, often referred to as the “as-is”, and future state, known as the “to-be” operational and maintenance scenarios (Pallipattu, 2022). A DSM was produced based on this framework, and this DSM was created using the Vitech GENESYS MBSE software tool, and populated with DSP relevant data (Roodt et al., 2020a). These scenarios were then linked to the business, system and sub-system requirements, which were managed using a dedicated requirements management tool, IBM DOORS Next Generation (Pallipattu, 2022). The system interfaces were deduced from this model, leveraging the aforementioned scenarios as a foundational element in their development (Pallipattu, 2022).

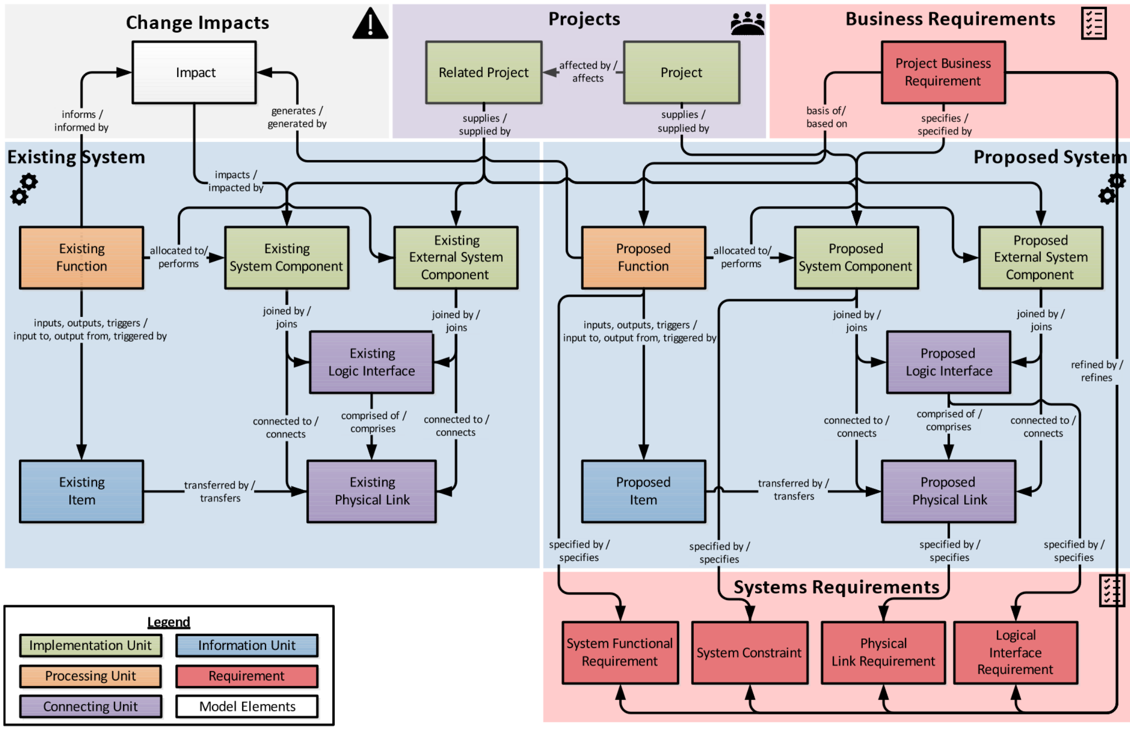


Figure 5.7 DSP project SysML metamodel (Roodt et al., 2020b)

During the establishment of system requirements and sub-system requirements, the operations and maintenance environment was fully considered. The Operations Concept Definition (OCD) and Maintenance Concept Definition (MCD) documents are critical references when eliciting system requirements and sub-system requirements. Through the application of MBSE, traceability from project business requirements through to system, sub-system and interface requirements are realised via the operational concept (Roodt et al., 2020a). Linking project business requirements to conceptual scenarios has guaranteed that all operational scenarios considered by the project align with the project requirements (Roodt et al., 2020a). As a result, the project scope boundary was refined, leading to the exclusion of the planning operations function from the project's scope (Roodt et al., 2020a).

Formal configuration management is applied across all artefacts used on the DSP to ensure any local changes are considered holistically (Roodt et al., 2020a). The DSM plays a pivotal role in tracing the impact of design changes (Roodt et al., 2020a). For instance, if there is a request for a change in a functional requirement, the impact assessment would require tracing from the requirement entity to its associated function, its allocated component, derived interfaces and potentially further up to the related project business requirement (Roodt et al., 2020a). This rigorous tracing process helps ensure that design changes are thoroughly evaluated and understood in their broader context.

In conclusion, the implementation of the MBSE approach within this project solved multiple issues. First, it effectively addresses certain vertical integration challenges in the early stages of the project by establishing a critical link between requirements management and conceptual scenarios (Pallipattu, 2022). Second, it adeptly manages horizontal integration issues by rigorously conducting change impact analysis and implementing robust configuration management practices across the entire project (Pallipattu, 2022). This comprehensive approach significantly elevates the efficiency and effectiveness of requirements management in the project, ultimately making a substantial contribution to its overall success. However, this approach has not been widely adopted in broader rail transport projects due to the absence of clear guidance on achieving interoperability between SysML models and BIM models, particularly in their continuous utilisation during the construction stage (Pallipattu, 2022).

The next section presents and analyses main barriers to the management of requirements during the lifecycle of complex infrastructure identified in interviews.

5.4 Challenges to Requirements Management Practices in Complex Rail Transport Projects

This section investigates challenges to requirements management practices, especially for information requirements management. Interviews were transcribed and analysed using the same taxonomy as identified in the literature review in Chapter 4. This section answers sub-question Q2-4:

Q2-4: What are the challenges to requirements management, especially information requirements management in complex rail transport projects?

After analysing the interview transcripts, a variety of challenges relating to process, technology and people (i.e., supply chain) maturity issues were identified. Analysis also revealed insights related to the adoption of more integrated and systems-based approaches to requirements engineering. The findings are presented as challenges to general requirements management practices (see Table 5.2) and challenges specific to information requirements management (see Table 5.3) in the following sub-sections.

5.4.1 General Challenges to Requirements Management Identified by Organisations

Five main challenges to traditional requirements management practices were identified by all interviewees in the six participating organisations. The five challenges included three process-related challenges and two technology-related challenges, which highlight a lack of maturity in these areas in the organisations represented by the interviewees (see Table 5.2).

There are three process-related challenges: (1) disconnect in requirements traceability workflows linking requirement types and levels, (2) disconnects between requirements traceability and design change management (change propagation), and (3) disconnects in process standards supporting physical, cyber and digital requirements verification and validation tasks.

Table 5.2 Challenges to requirements management practices identified by organisations

Code	Challenge	Phase	Area
RM-PRC-02	Disconnect in requirements traceability workflows linking requirement types and levels	Plan > Acquire	Process based Challenges
RM-PRC-03	Disconnects between requirements traceability and design change management (change propagation)	Acquire	
RM-PRC-05	Disconnects in process standards supporting physical, cyber and digital requirements verification and validation tasks	Acquire	
RM-TEC-01	Disconnected between SE-DE tool chains due to the lack of interoperability between requirements management and modelling software	Through-life	Technology based Challenges
RM-TEC-06	Disconnects in the digital workflows supporting requirements traceability and system definition review / preliminary design review/ critical design review	Plan > Acquire	

Disconnect in requirements traceability workflows linking requirement types and levels: In transport infrastructure, network level and system architecture requirements should guide the development of project level design requirements. However, a disconnect was reported by interviewees between the planning of the system architecture and the elicitation of project level requirements at the unit design level as reflected in the following response from the Systems Architecture Principal Engineer.

"There is disconnect between the planning of the system architecture and how requirements are not derived from a well-planned definition of the system network so as to inform and spill into a project level…" *Systems Architecture Principal Engineer*

Disconnects between requirements traceability and design change management (change propagation): It is common for changes to existing requirements or the emergence of new requirements to continuously occur during the development and delivery of complex infrastructure projects due to the unique, one-off nature of the project context. To minimise delivery risk, it is essential to ensure that proposed changes to requirements support the fundamental business goal by informing those project level changes to the network level. Moreover, it is also vital to ensure that the proposed changes are analysed to determine the nature and magnitude of requirements change and the cost implication – both in financial and schedule terms (Salo, 2013). However, it was reported that a robust process is often lacking. A common response from the systems engineers is reflected in the following comment. A *Systems Architecture Principal Engineer* noted:

> "…changes occur at the project level without informing the upper level – the network level – to evaluate the impact on the data of service that is expected at that given time in the future…"

Disconnects in process standards supporting physical, cyber and digital requirements verification and validation tasks: In complex discrete manufacturing sectors, such as aerospace and automotive industries, requirements validation – ensuring specified requirements meet the customer needs – is recognised as a critical activity in the requirements development process. A lack of robust requirements validation in built infrastructure was highlighted by all rail interviewees.

"The [requirements management] methods and behaviours that came from the Defence sector, where there is a lot of rigour in validating requirements and the mathematical information, is not being undertaken in transport infrastructure and the construction industry." *Systems Engineer*

Two key technology-related challenges are highlighted here: (1) disconnects between SE and DE tool chains due to the lack of interoperability between requirements management and modelling software, and (2) disconnects in the digital workflows supporting requirements traceability and system definition review, preliminary design review and critical design review milestones on complex rail transport projects.

Disconnects between SE and DE tool chains due to the lack of interoperability between requirements management and modelling software: Requirements management tools like IBM DOORS Next Generation were reported to be commonly used in transport infrastructure projects throughout some activities in the planning and acquisition phases. However, DOORS Next Generation was not widely used to support requirements elicitation during the planning phase, or requirements verification and configurations management during the delivery phase, with these software functionalities being underutilised. DOORS and Genesis were primarily used to model the requirements. Further, the automation of requirements verification or support for validation using a direct link with the 3D model or data derived from the model was also absent. Most participants noted an integrated tool ecology was therefore absent.

"They use DOORS to baseline the requirements on project. The problem is many people don't use DOORS to create requirements… they derive requirements from multiple sources, many requirements come out from the concepts of operations and the concepts of maintenance…” *Rail Systems Engineer*

Disconnects in the digital workflows supporting requirements traceability and system definition review, preliminary design review and critical design review: On major infrastructure projects, digital workflows are typically defined in the setup of the common data environment (CDE). A CDE provides a cloud-based platform for stakeholders to share geometric information as well as related asset information such as registers, schedules, contracts, reports and other document-based information. The CDE is defined as a common digital project space that provides distinct access areas for the different project stakeholders combined with clear status definitions and a robust workflow description for sharing and approval processes (Preidel et al., 2018). According to interviewees, the CDE is typically not configured to support a through-life approach to digital information management, and the scope of the CDE workflows focuses primarily on project delivery phases. The CDE therefore fails to adequately account for requirements management activities and methods required during construction, falling short in the management of information requirements during and beyond the handover and commission phase.

“The primary CDE was ProjectWise… However, ProjectWise does not support Revit well from the point of view of developing working progress models. So, they were using BIM 360 for the Revit models, and then also the 12D tool for the civil designs… so managing that sort of series of different CDEs, a connected data environment rather than a common one, meant that we have to fill in the gaps between each of those different systems…” *Digital Engineering Lead*

5.4.2 Challenges to Information Requirements Management Identified by Organisations

In addition to the challenges encountered by interviewees in traditional requirements management practices, new challenges specific to information requirements management were identified by all interviewees in the six participating organisations. Seven challenges were identified in total, including three process related, one technology related and three people related challenges (see Table 5.3).

Table 5.3 Challenges to information requirements management practices identified by organisations

Code	Challenge	Phase	Area
iRM-PRC-01	Delays in information requirements specification and development processes / incomplete information requirements	Plan > Acquire	Process based Challenges
iRM-PRC-02	Lack of agreed and consistent requirements language describing information requirements	Plan > Acquire	
iRM-PRC-04	Lack of process standards supporting information requirements specification, development and management	Through-life	
iRM-TEC-02	Lack of automated approaches to information requirements validation	Acquire	Technology based Challenges
iRM-PPL-01	Low levels of stakeholder expertise in information requirements development & management (esp. supporting DT creation)	Plan > Acquire	People based Challenges
iRM-PPL-02	Lack of a clear description of roles and responsibilities supporting information requirements development and management	Through-life	
iRM-PPL-03	Lack of support from senior management supporting information requirements development and management	Plan > Acquire	

The three new process related challenges are (1) delays in information requirements specification and development processes and incomplete information requirements, (2) lack of agreed and consistent language describing information requirements, and (3) lack of process standards supporting information requirements specification, development and management.

Delays in information requirements specification and development processes and incomplete information requirements: The information requirements should be recognised during the early planning phase and then fed into the design phase. However, the reality of many complex transport projects is that this occurs during the detailed design and even construction phases.

"The current rail industry is very, kind of, physically focused. The digital twin should be developed in parallel with physical rail. But it's very difficult to get the focus from the key stakeholders on the information requirements at the early stages of development… because the maturity of the industry is actually quite low with regards to the sort of requirements definition up front to feed into the design. It's very much geared around detailed design." *Digital Engineering Lead*

Lack of agreed and consistent language describing information requirements: Consistent requirement language (e.g., the structure and coding standard) supporting effective and efficient communication and collaboration among multiple stakeholders of a project was noted as lacking across the sector. The lack of a common or standard requirement language used across different rail transport projects was lamented by those engineers with systems backgrounds:

"…there is no common set of requirements that go down…" *Rail Systems Engineer*

Lack of process standards supporting information requirements specification, development and management: The use of industry standards typically indicates the maturity level of the industry. In the rail transport sector, there is a lack of industry-wide standards and guidance supporting structured processes and the management of information requirements throughout the lifecycle of the asset:

"People require information at different levels [of detail] in terms of how the systems wide requirements map with the project requirements and the functional requirements…" *Senior Project Manager*

The main technology related challenge identified across all organisations focuses on the lack of automated approaches to information requirements validation.

Lack of automated approaches to information requirements validation: As a physical-focused industry, the validation of physical deliverables and their functional requirements was seen as an important part of complex rail transport projects. However, the lack of formal validation tools (and processes) of the information requirements describing the digital deliverables (i.e., models and databases of physical assets and process behaviours) was noted:

"There is a lack of verification and validation for simulation, and certification of modelling" *Systems Engineer*

The three new people related challenges are (1) low levels of stakeholder expertise in information requirements management (especially supporting digital twin creation), (2) lack of a clear description of roles and responsibilities supporting information requirements management, and (3) lack of support from senior management supporting information requirements management.

Low levels of stakeholder expertise in information requirements management (especially supporting digital twin creation): Having relevant expertise and a minimum of common understanding in complex rail transport project teams was viewed as being critical to the successful implementation of information requirements processes, particularly those supporting the elicitation and documentation of AIRs that underpin the creation of the digital twin. The information requirements of a digital twin should be specified at the early stages of the project so that stakeholders are able to capture requirements in project contracts. However, the lack of knowledge and common understanding with regard to the requirement development, digital twin concept and related terms such as digital engineering was seen as a key barrier:

"…it (requirements document) says nothing about who is going to own what level of data, what level of specificity, what kind of schema…it (requirements) is not very performance-based, it is generally input-based…" *Engineering Lead*

Lack of a clear description of roles and responsibilities supporting information requirements management: It is essential to set up clear roles and responsibilities for efficient and effective requirements management. However, so far this role is not clearly set as captured by the following response:

"There is a whole bunch of reviews over the design but the information itself, nothing. Obviously, there is no professional accountability… We suggest that there should be a role of information manager who is accountable for systems process, workflows and data structures… The information is a skill set which is current lacking in the industry." *Digital Engineering Lead*

Lack of support from senior management supporting information requirements management: Support from senior management was viewed as the foundation for the successful implementation of new processes and technologies related to information requirements management. A common complaint was therefore the lack of support from the senior management on complex rail transport projects:

"…they are not budgeting for the asset information management… and how that feeds into what ultimately will become asset information management system in the operational environment…" *Systems Engineer*

5.4.3 Insights into Requirements Management Challenges

This section further analyses challenges identified from both literature (Section 4.4) and interview surveys (Sections 5.4.1~5.4.2) by grouping and colour coding according to their areas, types and phases affected. These challenges are then mapped to activities of requirements management using an adapted Diamond model (Section 5.2.2). The answers to the research questions are presented and discussed.

A total number of 22 challenges to requirements management were identified based on the literature survey and interview survey: 13 traditional and 9 new challenges. Figure 5.8 presents an overview of these challenges. Challenges are colour coded based on their areas (process, technology or people), types (traditional requirements management or new information requirements management), and phases affected (planning phase, acquire phase or through-life).

These challenges represent four main types of issues: i) process, technology or people gaps, ii) disconnect in information flow, iii) timing delays, and iv) resourcing requirement.

Gap refers to a lack of processes and methods to support the development and management of requirements. The most significant process related gaps lie in a lack of collaborative requirements management process across project team members, agreed and consistent information requirements language, and process standards supporting AIR management. The technology related gaps lie in a lack of software tools supporting the management of conflicting requirements, configuration management, and automated information requirements validation. People related gaps mainly focus on low levels of stakeholder expertise in requirements management and information requirements management, lack of clear definition of roles and responsibilities to manage information requirements, and lack of support from senior management.

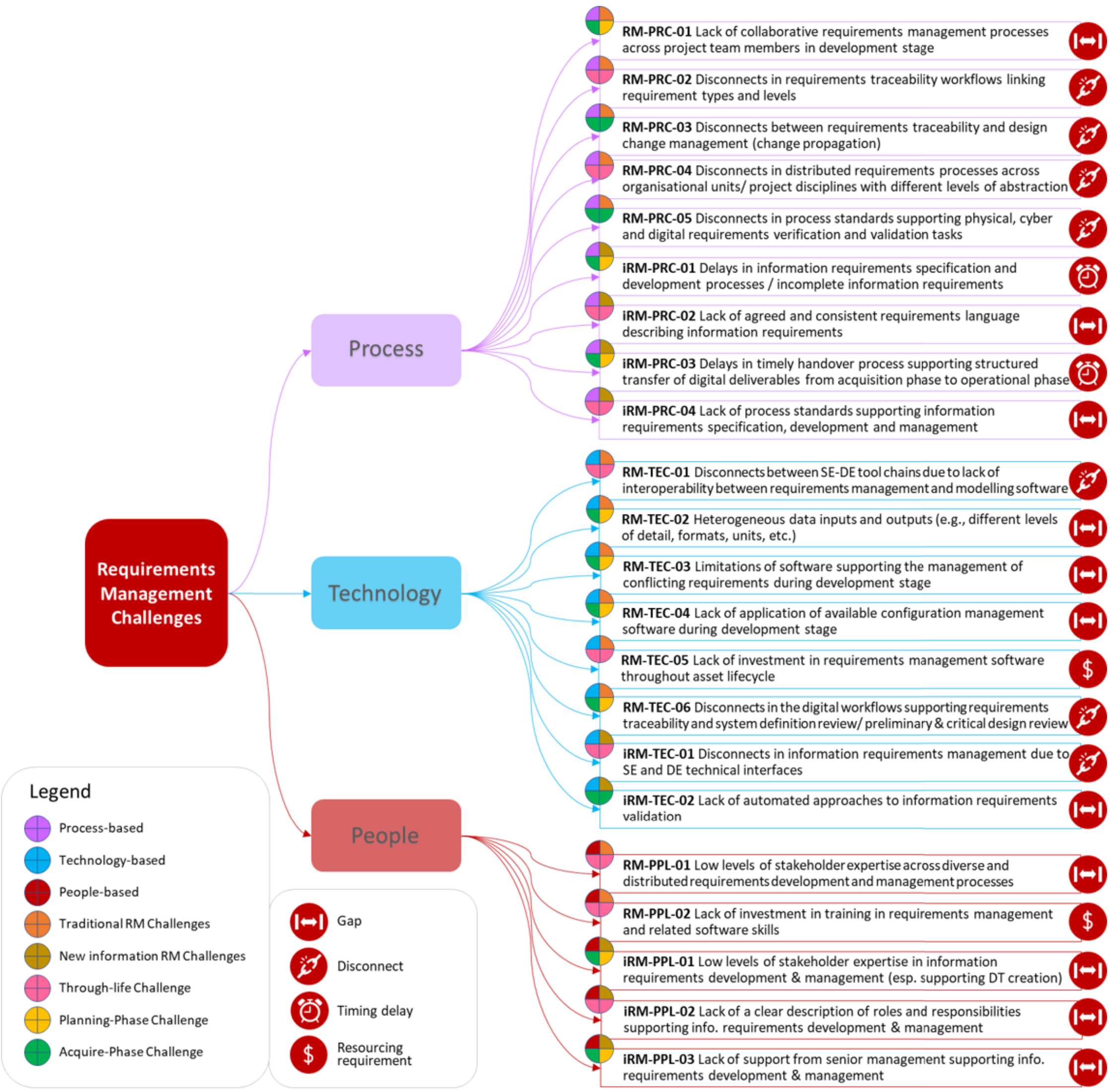


Figure 5.8 Overview of challenges to requirements management (Chen & Jupp, 2023a)

Disconnect refers to missing links from two important activities or workflows supporting an integrated approach to effective co-management of information requirements. Disconnects in information flow usually occur in requirements traceability workflows linking requirement types and levels, and with design change management. Technological disconnects exist between the SE and DE tool chains due to lack of interoperability, digital workflows supporting requirements traceability and system definition review, preliminary design review and critical design review.

Timing delays refer to the late start of a process or delivery. Delays in information requirements specification and development processes will lead to late handover and structured transfer of digital deliverables from the acquisition phase to operational phase.

Resourcing requirements refers to the need for additional resources generally linked to the lack of budget allocated to support relevant requirements management activities and tools to support cyber and physical requirements management and information requirements management across the planning and acquisition phases. Lack of investment in requirements management software and training in requirements management skills and related software skills are the two main challenges identified.

To further analyse the pain points of requirements management practices from the lifecycle perspective, each challenge was mapped to corresponding phases of the asset lifecycle using the adapted Diamond model to visualise where these challenges impact complex rail transport projects (see Figure 5.9). Typical cyber and physical requirements management challenges are described below, while new information requirements management challenges are described above the model. Of the 22 challenges, 10 are active throughout the lifecycle of the asset. The majority of the process related challenges (6 out of 9) are located in or before the "specify" stage of the asset lifecycle, with their knock-on effects causing impacts on downstream verification activities. Further, although verification and validation issues identified are mapped to the "build" and "integrate" stages, these process challenges can largely be addressed in the earlier "specify" stage in the project specifications.

Similarly, most technology related challenges are located in or before the "specify" stage of the asset lifecycle and affect the downstream activities. Moreover, 6 out of 8 challenges exist in traditional requirements management activities, reflecting the immature status of technology supporting requirements management activities in the industry. The main challenges focus on the interoperability of requirements management software with 3D modelling software, disconnected digital workflows supporting traceability and requirements review, and lack of tools supporting requirements prioritisation, documentation, and automatic information requirements validation.

People related challenges focus on limited expertise and training on requirements management process and software tools, lack of clear roles and responsibilities for information requirements development and limited support from senior management for information requirements management. These challenges exist from the "need" or "plan" phases through to the "acquire" phase and some to the "operate and maintain" phase.

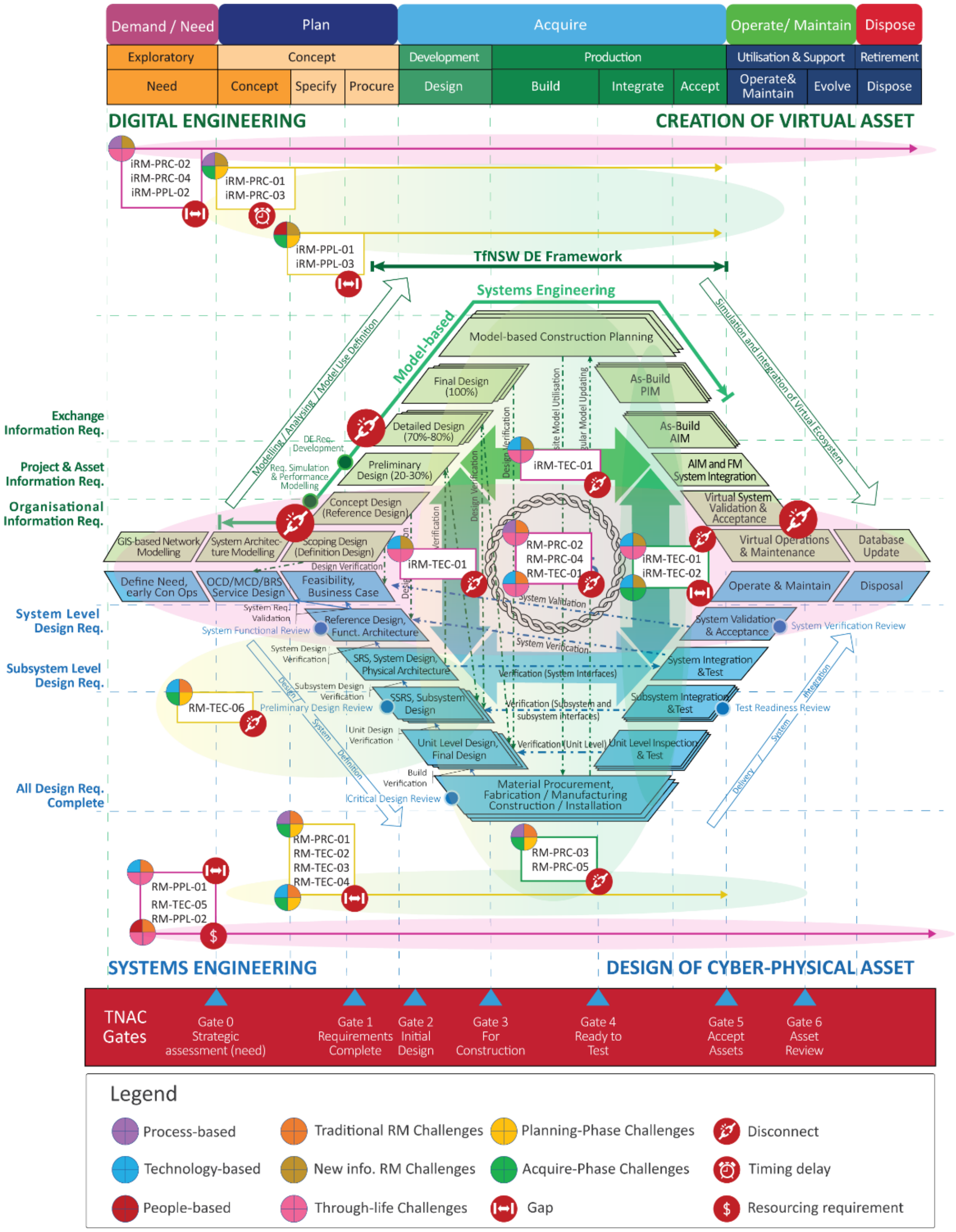


Figure 5.9 Challenges to requirements management mapped to Diamond model (Chen & Jupp, 2023a)

Disconnects in workflows and gaps in the technology supporting automated approaches to requirements validation exist in the core of the adapted Diamond model (Seal, 2018), reflecting that there is a lack of integrated development of asset, construction and assembly systems, and maintenance systems in the complex rail transport sector so as to support the achievement of a digital thread.

5.4.4 Main Challenges to Requirements Management in Complex Rail Transport Projects

Based on findings from both literature (Section 4.4) and interviews (Sections 5.4.1~5.4.2), the answers to research question Q2-4 are summarised in the tables below. Challenges to general requirements management and information requirements management practices on DE enabled complex rail transport projects are presented in Tables 5.4 and 5.5 respectively.

Table 5.4 Challenges to requirements management practices

Code	Challenge	Area
RM-PRC-01	Lack of collaborative requirements management processes across project team members in development stage	Process based Challenges
RM-PRC-02	Disconnect in requirements traceability workflows linking requirement types and levels	
RM-PRC-03	Disconnects between requirements traceability and design change management (change propagation)	
RM-PRC-04	Disconnects in distributed requirements processes across organisational units/ project disciplines with different levels of abstraction	
RM-PRC-05	Disconnects in process standards supporting physical, cyber and digital requirements verification and validation tasks	
RM-TEC-01	Disconnects between SE and DE tool chains due to lack of interoperability between requirements management and modelling software	Technology based Challenges
RM-TEC-02	Heterogeneous data inputs and outputs (e.g., different levels of detail, formats, units, etc.)	
RM-TEC-03	Limitations of software supporting the management of conflicting requirements during development stage	
RM-TEC-04	Lack of application of available configuration management software during development stage	
RM-TEC-05	Lack of investment in requirements management software throughout asset lifecycle	
RM-TEC-06	Disconnects in the digital workflows supporting requirements traceability and system definition review, preliminary design review and critical design review	
RM-PPL-01	Low levels of stakeholder expertise across diverse and distributed requirements development and management processes	People based Challenges
RM-PPL-02	Lack of investment in training in requirements management and related software skills	

Table 5.5 Challenges to information requirements management practices

Code	Challenge	Area
iRM-PRC-01	Delays in information requirements specification and development processes / incomplete information requirements	Process-based Challenges
iRM-PRC-02	Lack of agreed and consistent requirements language describing information requirements	
iRM-PRC-03	Delays in timely handover process supporting structured transfer of digital deliverables from acquisition phase to operational phase	
iRM-PRC-04	Lack of process standards supporting information requirements specification, development and management	
iRM-TEC-01	Disconnects in information requirements management due to SE and DE technical interfaces	Technology-based Challenges
iRM-TEC-02	Lack of automated approaches to information requirements validation	
iRM-PPL-01	Low levels of stakeholder expertise in information requirements development & management (especially supporting digital twin creation)	People-based Challenges
iRM-PPL-02	Lack of a clear description of roles and responsibilities supporting information requirements development and management	
iRM-PPL-03	Lack of support from senior management supporting information requirements development and management	

The complexity of rail transport requirements management processes is emphasised due to the number and type of system requirements, stakeholder requirements management interactions, and supporting requirements software tool chains. Requirements management challenges therefore increase in complex rail transport projects that must deliver a strategic approach to asset information lifecycle management as complexity resides in physical and cyber assets, their virtual replicas and their real-time behaviours in operations (Chen & Jupp, 2021).

In projects with strategic approaches to asset information management, challenges to complex rail transport requirements management processes stem from the "plan" phase of the asset lifecycle and can be linked to a lack of owner-developed AIRs supporting current and future operational scenarios, as well as deficiencies in the detail of required asset information to support asset management systems (Kasprzak, 2013). While the asset management sector undergoes this digital transformation, it is notable that only few owners have clearly articulated their actual information needs and how asset information will map to asset management systems (Chen & Jupp, 2023a).

In the transition from the "plan" phase to the "acquire" phase of the asset lifecycle, requirements specifications must make an important transition from system-level to project-level documentation formats (Chen & Jupp, 2023a). Requirements management efforts may be compromised during this exchange process due to the lack of detail about sub-system and unit-level AIRs, which affects the downstream information management capabilities of the project team (Chen & Jupp, 2023a). In what is largely a text-based exchange, insufficient specifications and documentation of the level of information (need), level of detail, and level of integration between systems, sub-systems and unit level design components all compound these difficulties (Chen & Jupp, 2023a).

From a process standpoint, requirements management complexity remains a critical challenge due to the many interdependent activities enacted in the elicitation, description and documentation of organisational and asset requirement types, as well as the decomposition, analysis and allocation of requirements across collaborating authorised engineering organisations (Chen & Jupp, 2021). The dynamic nature of complex rail transport projects also results in an intricate network of requirements change management activities, and challenges to this stem from deficiencies in requirements management tool chains, lack of software interoperability, imperfect or incomplete information exchange, and poor stakeholder interface management across the asset lifecycle (Chen & Jupp, 2021). Complexity in requirements management processes is, therefore, also embedded in the social challenges surrounding the presence, power and influence of project team members (i.e., people and supply chain) involved in (or absent from) requirements management activities (Chen & Jupp, 2023a). Technology maturity also plays a critical role in supporting integrated and collaborative requirements management processes among multiple stakeholders (Chen & Jupp, 2023a).

Requirements integration risks are therefore an important issue to tackle in complex rail transport projects and there is evidence of bespoke requirements management tool chain integration initiatives in complex rail transport projects (Roodt et al., 2020a, 2020b). However, they are predicated on the key assumption that information requirements are consistently developed in accordance with industry agreed data schemas providing a standard for asset system hierarchy (Chen & Jupp, 2019). Such approaches also demand that the value of requirements assurance, verification and validation processes extend beyond asset handover (Chen & Jupp, 2023a).

Requirements management complexity is exacerbated by a lack of maturity in collaborative information requirements management processes and the co-management of physical and digital assets. The maturity of integrated requirements management procedural methods is a critical barrier to advancing enterprise platform requirements management processes.

5.5 Summary

This chapter used a case study approach to investigate key requirements management capabilities, existing initiatives, and the challenges confronted by project teams when developing and managing complex and interdependent information requirements in complex rail transport projects to answer the second research question. Figure 5.10 illustrates the structure of this chapter.

This chapter outlined the scope and process of the case study, introducing the interview themes and interviewees. These interviewees were experts from both SE and DE disciplines, and their insights are essential for a comprehensive understanding of the research question.

The chapter summarised the capabilities that are key to information requirements management in complex rail transport projects as a response to sub-question Q2-1. These summaries are based on the insights gleaned from interview transcripts and project documentation recommended by interviewees. These key capabilities include i) process standards supporting information requirements management, ii) integrating DE within the SE process, iii) requirements verification process, and iv) a common data environment in complex rail transport projects. These capabilities were further explored as they are considered as the most important and essential capabilities for effective and efficient information requirements management in complex rail transport projects.

The chapter investigated and analysed initiatives that have been implemented within complex rail transport projects to improve effective requirements management and information requirements management to address sub-question Q2-2. Two specific case studies were scrutinised in detail: a light rail project that implemented DE, and a digital system program that adopted MBSE. The analysis explored the key advantages of these approaches to requirements management and information requirements management. The limitations associated with these approaches were also evaluated.

Challenges and open issues of general requirements management and information requirements management encountered by the project team in complex rail transport projects were investigated to answer sub-question Q2-3. The challenges identified through interviews and literature review (Section 4.4) were then combined and further analysed. In total, 13 general requirements management challenges and 9 information requirements management challenges were identified and categorised into process, technology and people related areas. These challenges were also tagged according to their nature (i.e., gap, disconnect, time delay, and resourcing requirement). These challenges were mapped in the requirements management and information requirements management processes using the Diamond model. Finally, the main challenges to requirements management in complex rail transport projects were summarised.

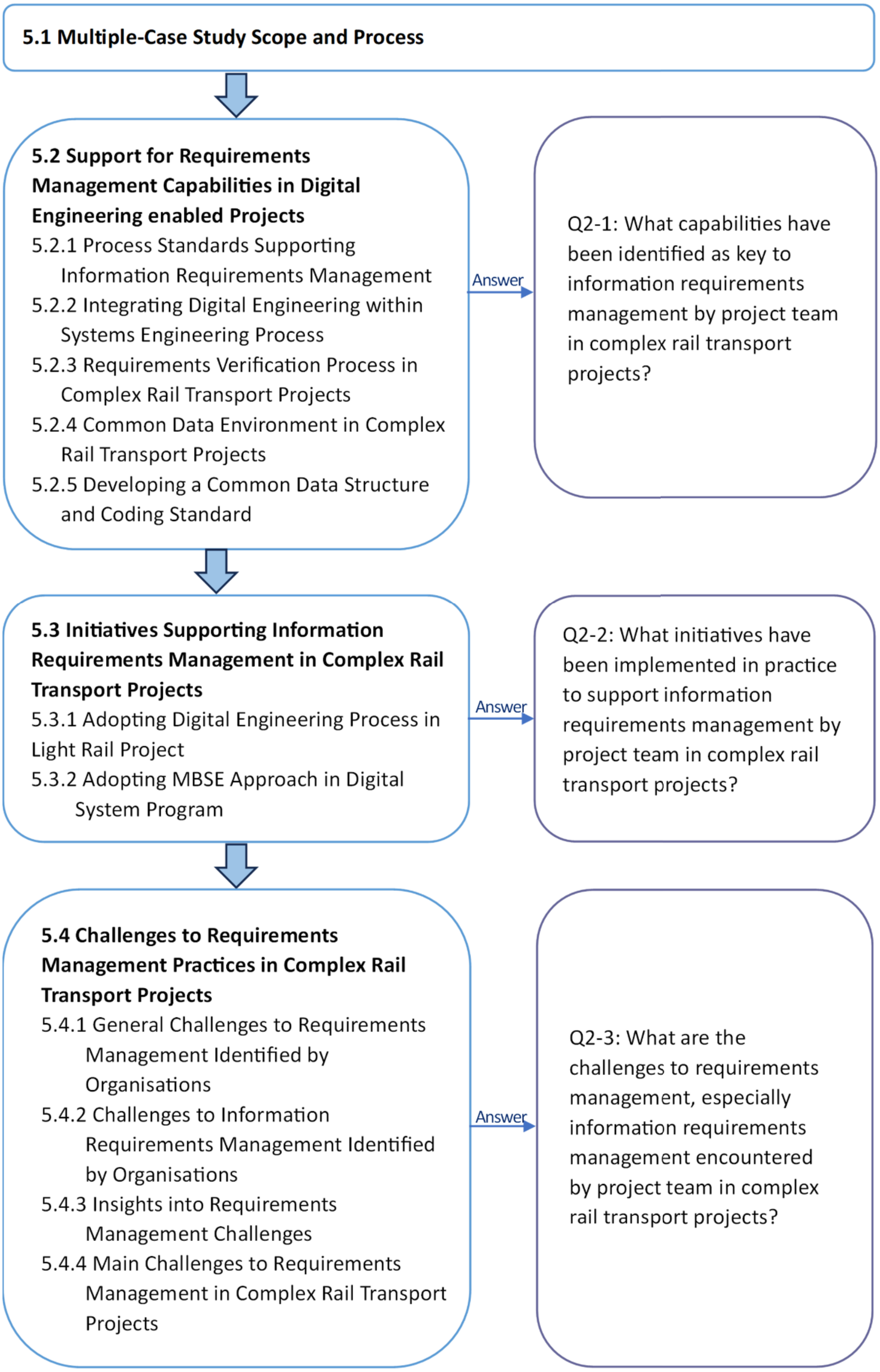


Figure 5.10 Structure of Chapter 5 content

Chapter 6 Requirements Management Practices in Complex Rail Transport Projects – Survey

This chapter addresses research question 2 and adopts a survey approach to investigate the current implementation status of standards supporting information requirements management enabled by digital engineering. It investigates the current maturity levels of capabilities supporting requirements engineering practices in the context of digital delivery methods of complex rail transport projects, and the significance of the challenges encountered by project teams when developing and managing complex and interdependent information requirements. Specifically, this chapter responds to research questions Q2-4, Q2-5 and Q2-6.

6.1 Introduction

An online survey was developed based on findings from the literature review (Chapter 4), semi-structured interviews and analysis (Chapter 5) stages of the research. Engineering and construction firms with high levels of organisational expertise in the civil infrastructure sectors were invited to participate in the online survey. The research survey specifically targeted organisations with established expertise and specifically those with specialisations in digital design management using digital engineering (DE) and Building Information Modelling (BIM), as well as professionals with specialisations in system engineering (SE) using model-based systems engineering (MBSE) methods and tools (Wymore, 2018) to identify the current implementation status of related standards, as well as the relative maturity level of requirements management processes, supporting technologies and resources in complex infrastructure projects. The significance of challenges to requirements management practices was also investigated.

A total of 36 valid responses were received. Due to the specialised nature of both SE and DE disciplines and their relative infancy in complex infrastructure projects, the number of professionals with the required domain expertise is small. The respondents listed a variety of DE/BIM related roles (e.g., digital engineer, digital integration consultant, digital strategist, BIM managers and consultants, etc.), as well as SE roles, and client-side design management roles. This provided a small sample, but a high level of expertise.

Survey responses were recorded from February to July 2022. Respondents were asked to choose their roles, sectors, their level of experience in the application of different methods and standards supporting information management, the levels of maturity in a range of capabilities supporting requirements management practices in their most recent projects, and the occurrence frequency of 47 challenges to requirements management practices. Survey data was extracted from the Qualtrics platform and analysed in multiple perspectives. The following sections analyse and discuss findings from the online survey.

6.2 Online Survey Development

The online survey had three main parts: respondents background information, current maturity status of requirements development and management practices, and prioritisation of challenges identified in the literature review and semi-structured interviews. The survey is in **Appendix E**.

6.2.1 Respondents Background Information

Part 1 of the survey collected the background information of respondents forming the foundation of analysis including survey respondents' AECO roles, sectors of construction, and level of experience in a variety of DE tasks including implementation of digital model-based methods and tools, production of 3D model-based deliverables, familiarity with Digital Engineering Execution Plan, use of asset information classification systems, application of BIM/DE process standards (e.g., ISO 19650, Australia Government DE standard) and data standards (e.g., IFC, OmniClass, Uniclass, etc.). These questions were used to form a general overview of DE and information requirements related standards implementation among complex infrastructure industry.

The next set of questions were on respondents' experience in the development, specification and management of technical system requirements (in the survey, the term "physical system requirements" was used with the same meaning as technical system requirements) and asset information requirements. These questions specifically focused on handling of different types of requirements.

6.2.2 Maturity Levels of Requirements Management Practices

Part 2 of the survey was developed to investigate the maturity of requirements management practices in industry. The requirements management capabilities included: i) process, ii) technology and iii) people supporting the development and management of different types of requirements (focusing on technical system requirements and asset information requirements (AIRs)). Although this study concentrates on AIRs related practices, it was necessary to understand the technical system requirements management practices to establish the baseline of the maturity status in the industry. A five-point Likert scale was used to describe the maturity levels. Requirements management capabilities and corresponding maturity levels are listed in Table 6.1.

Table 6.1 Capabilities and maturity levels of requirements management practice

Category	Capability	Maturity Levels
Process Capabilities	Requirements elicitation process	• Very poor • Poor • Fair • Well-defined • Very well-defined
	Requirements analysis and prioritisation process	
	Requirements allocation and verification process	
	Negotiation of conflicting requirements amongst stakeholders	
	Requirements change management process	
	Requirements validation process	
Technology Capabilities	Requirements documentation software	• Very poor • Poor • Fair • Good • Very good
	Requirements verification software	
	Requirements validation software	
	Integration of requirements management software with 3D modelling software	
People Capabilities	Formally defined roles and responsibilities for handling requirements in the planning phase	• Never • Rarely • Sometimes • Often • Always
	Formally defined roles and responsibilities for handling requirements in the acquisition phase	
	Training in requirements software in support of requirements handling in the planning phase	
	Training in requirements software in support of requirements handling in the acquisition phase	

Apart from the requirements management capabilities in Table 6.1, the importance of resources supporting successful requirements management implementation was also surveyed (see Table 6.2).

Table 6.2 Importance of supporting resources

Code	Resources	Importance Levels
RES01	Support from senior management	• Not Important • Slightly Important • Moderately Important • Very Important • Extremely Important
RES02	Clearly defined roles and responsibilities for requirements management	
RES03	Training in requirements management methods	
RES04	Training in requirements management software	
RES05	Investment in requirements management software licenses	
RES06	Clear Government Agency/Appointing Party standards and terms of contract covering the application of requirements management	

6.2.3 Prioritisation of Challenges to Requirements Management Practices

Part 3 of the survey focused on the prioritisation of challenges based on their frequency of occurrence. As presented in Table 6.3, the list of challenges was developed based on the findings of the literature review and initial round of semi-structured interviews. The 47 challenges were grouped into three categories (i.e., process, technology and people) and mapped to requirements management capabilities and resources which were identified in Section 6.2.2. Frequency was measured through five different levels: “Never”, “Rarely”, “Sometimes”, “Often” and “Always”.

Table 6.3 Capabilities and challenges to the requirements management practices

Category	Requirements Management Capability	No.	Challenges
Process	Requirements Elicitation	PC1	Poor **technical system requirements** elicitation, specification and/or documentation processes
	Requirements Elicitation	PC2	Poor **AIRs** elicitation, specification and/or documentation processes
	Requirements Elicitation	PC3	Disconnects between **system architecture requirements** (including network requirements) and **technical system requirements**
	Requirements Elicitation	PC4	Disconnects between **system architecture requirements** (including network requirements) and **AIRs**
	Requirements Elicitation	PC5	**Technical system requirements** not adequately elicited, specified, or documented in Planning Phase
	Requirements Elicitation	PC6	**AIRs** not adequately elicited, specified or documented in Planning Phase
	Requirements Verification	PC7	Poor **requirements verification and traceability** processes during Acquisition Phase
	Requirements Verification	PC8	Poor **management processes** supporting the handling of regulatory compliance documents during **requirements verification**
	Requirements Change Management	PC9	Disconnects between **design change management** and **AIRs traceability**
	Requirements Change Management	PC10	Disconnects between **requirements management processes** and **design change management** processes
	Requirements Change Management	PC11	Poor **AIRs change management**
	Requirements Validation	PC12	Poor **technical system requirements** validation processes
	Requirements Validation	PC13	Poor **AIRs** validation processes
	Collaboration across disciplines	PC14	Lack of collaborative **requirements management processes** during the **Planning Phase**
	Collaboration across disciplines	PC15	Lack of collaborative **requirements management processes** during the **Acquisition Phase**
	Interface Management	PC16	Poor **interface management** across requirement types

Category	Requirements Management Capability	No.	Challenges
	Interface Management	PC17	Lack of **interface management processes** supporting the handling of different requirement types throughout the Acquisition
	Guideline and Standards	PC18	Lack of **practical guidelines** supporting development and management of different and interdependent requirements processes
Technology	Requirements Elicitation	TC1	Lack of common language supporting definition of **technical system requirements** and **AIRs**
	Requirements Verification	TC2	Poor **utilisation of software** supporting the handling of regulatory compliance documents during **requirements verification**
	Requirements Verification	TC3	Limited use of requirements management software for **verification of technical system requirements**
	Requirements Verification	TC4	Limited use of requirements management software for **verification of AIRs**
	Requirements Validation	TC5	Limited use of requirements management software for **validation of technical system requirements**
	Requirements Validation	TC6	Limited use of requirements management software for **validation of AIRs**
	Interface Management	TC7	Lack of **interface management software** supporting the handling of different requirement types throughout the Acquisition Phase
	Legacy systems and CDE	TC8	Lack of **enterprise platforms** supporting integrated modelling and simulation, enabling digital continuity from concept to development to production
	Technology Integration	TC9	Lack of **integrated** requirements management software tools and 3D modelling software
	Technology Integration	TC10	Limited **interoperability** between requirements management software and 3D modelling software
	Configuration Management	TC11	Limited use of software to support **configuration management**
People	Stakeholder Involvement	PCC1	Absence of **Project-Client* participation** in Planning and/or Acquisition Phases
	Stakeholder Involvement	PCC2	Absence of **key Project Delivery Team* members** in Planning and/or Acquisition Phases
	Stakeholder Involvement	PCC3	Absence of **FM-Client* participation** in Planning and/or Acquisition Phases
	Stakeholder Involvement	PCC4	Absence of **FM-Customer* participation** in Planning and/or Acquisition Phases
	Stakeholder Involvement	PCC5	Absence of **End-User* participation** in Planning and/or Acquisition Phases
	Roles/Responsibilities	PCC6	Lack of a clear description of roles and responsibilities supporting **technical system requirements** development and management
	Roles/Responsibilities	PCC7	Lack of a clear description of roles and responsibilities supporting **AIRs** development and management

Category	Requirements Management Capability	No.	Challenges
	Senior Management Support	PCC8	Lack of understanding and support from senior management in general requirements management methods
	Senior Management Support	PCC9	Lack of understanding and support from senior management in handling **AIRs**
	Internal skills to deliver	PCC10	Lack of competency in **technical system requirements development** (Specification, documentation, allocation etc.)
	Internal skills to deliver	PCC11	Lack of competency in **AIRs development** (Specification, documentation, allocation etc.)
	Internal skills to deliver	PCC12	Lack of competency in **technical system requirements management** (change management, verification and traceability, and validation)
	Internal skills to deliver	PCC13	Lack of competency in **AIRs management** (change management, verification and traceability, and validation)
	Internal skills to deliver	PCC14	Lack of competency in the creation of digital deliverables comprising 3D models and supporting databases
	Capability/Training	PCC15	Lack of training in **requirements management** methods
	Capability/Training	PCC16	Lack of training in **requirements management** software
	Funding	PCC17	Insufficient investment in requirements management software licenses
	Collaboration across disciplines	PCC18	Poor collaboration and lines of communication between Project Delivery Team members handling different requirement types

Note:

* Project Client - meaning the organisation that procures the design and delivery of the asset as the main Appointing Party,

* Project Delivery Team - meaning the Appointed Parties in the delivery of the asset, e.g. design and engineering services, main contractor, sub-contractors, trades, manufacturers, fabricators, etc.,

* FM Client - meaning the organisation that procures facility services by means of a facility management (FM) agreement,

* FM Customer - meaning the organisational unit that specifies and orders the delivery of facility services within the conditions of a facility management (FM) agreement,

* End user - meaning the person receiving facility services.

6.3 Implementation of Process Standards and Data Standards

This section responds to research sub-question Q2-4: *What is the prevalence of use of digital engineering process standards and data standards in Australia?*

6.3.1 Overview of the Online Survey

The survey targeted two distinct professional disciplines: SE roles (n = 13) and DE roles (n = 23). These two groups are principally responsible for technical system requirements (SE roles) and information requirements (DE roles) management activities. Their responsibilities are designated as separate and distinct activities, however growing maturity in MBSE methods suggests an intersection of responsibilities on the validation activities of AIRs prior to handover.

Figure 6.1 shows the DE roles separated into subcategories based on three distinct responsibilities during project delivery and years of experience: digital engineers (1–5 years experience), DE managers (6–10 years experience) and DE strategic advisers (10+ years experience).

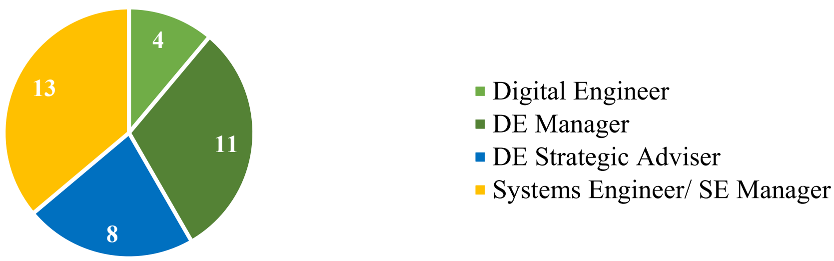


Figure 6.1 Respondents' roles in building and infrastructure projects (n=36)

As shown in Figure 6.2, the sectors represented by respondents varied, with more than half of the respondents (n = 24) having worked in multiple sectors. Rail infrastructure was the main sector represented, with the majority of respondents experienced in the delivery of rail projects (n = 31), followed by roads, bridges and highways (n = 19).

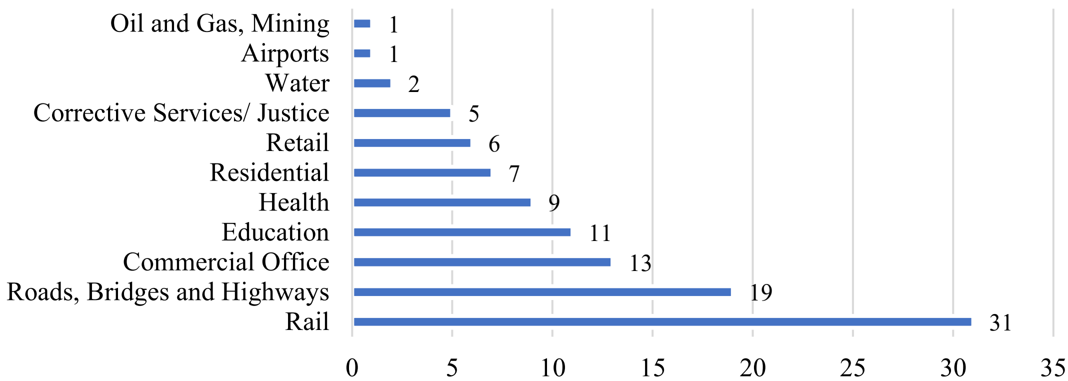


Figure 6.2 Respondents' involvement in industry sectors (n=36)

Figure 6.3 shows the level of experience in the use of digital model-based methods and tools to support a strategic approach to asset information lifecycle management. Digital model-based methods refer to a wide range of approaches and tools such as implementing BIM for facilities management, or COBie, or digital twin technologies, or MBSE approach. All of the respondents have some experience in implementing those model-based methods and tools, and 64% of the respondents have more than 6 years of experience which indicates the high level of expertise of the participants in this research.

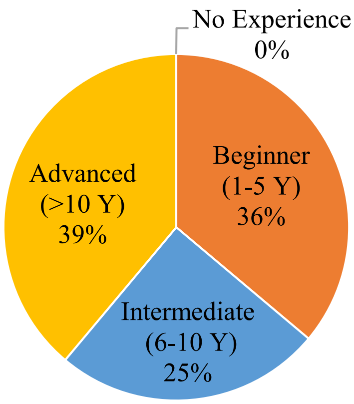


Figure 6.3 Level of experience in implementing digital model-based methods and tools (n=36)

Figure 6.4 reflects the level of experience in the production of 3D model-based deliverables required to support digital asset management. Three-quarters (73%) of respondents have 3D model-based deliverables experience and within those who did not, most of them (70%) are SE related roles and DE related roles as either facilities manager or digital service provider. The other SE related roles are all beginners in 3D model-based deliverables production indicating that DE implementation in infrastructure projects emerged within the last 5 years and is still in its infancy. Respondents with more than 5 years' experience are all DE related roles from multiple types of organisations, such as digital strategist, DE advisory consultant, client-side DE manager or construction BIM manager.

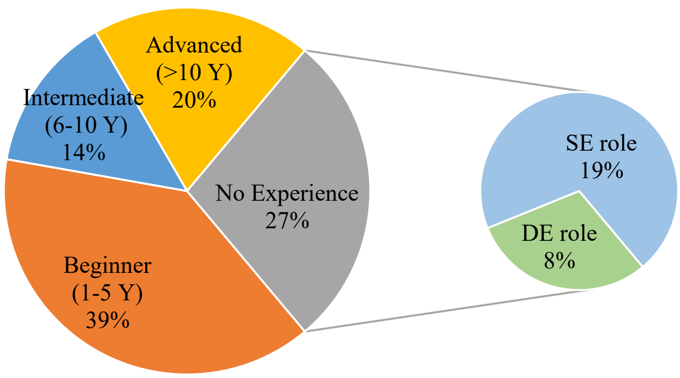


Figure 6.4 Level of experience in production of 3D model-based deliverables (n=36)

Figures 6.5 and 6.6 present respondents' level of experience in different requirements development activities supporting technical system requirements and AIRs. Similar to previous analysis, responses are divided into two groups – DE role and SE role. For technical system requirements related processes (as shown in Figure 6.5), more SE role respondents had working experience (92% ~ 100%) than DE role respondents (86%). There are larger ratios of respondents with over 6 years' experience in the technical system requirements related processes in the SE group (46%~54%) than the DE group (36%~41%). However, for AIRs related processes (as shown in Figure 6.6), the situation is totally opposite: 100% of DE respondents have working experience and 68%~73% of them have over 6 years' experience in AIRs related processes. In SE respondents, 78%~85% have practical experience and only 23% have over 6 years' experience in AIRs related processes.

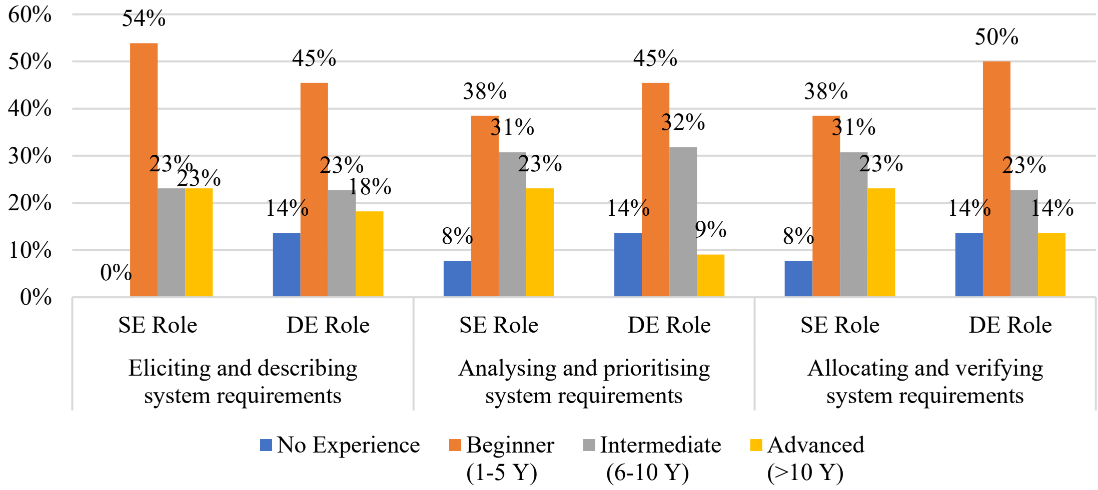


Figure 6.5 Level of experience in implementing management processes for technical system requirements (n=36)

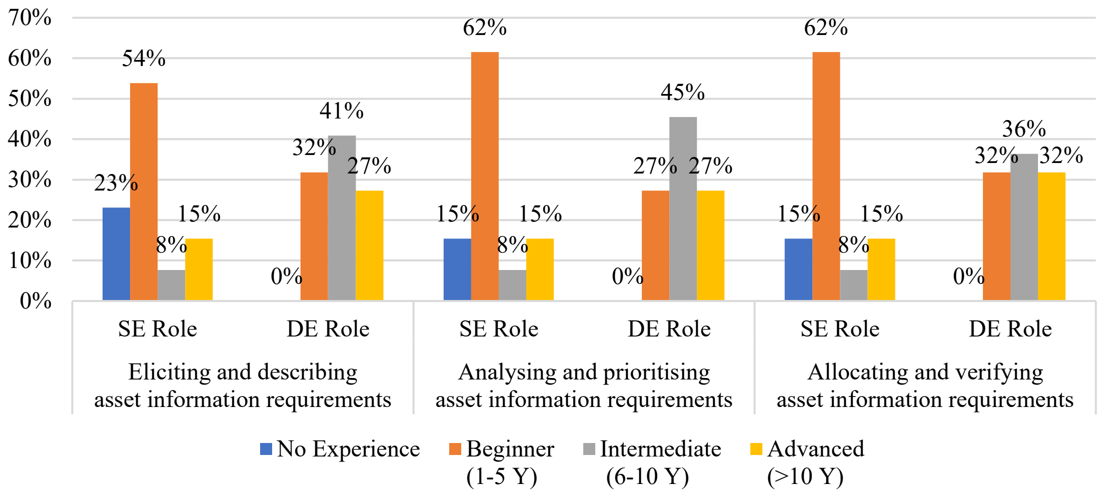


Figure 6.6 Level of experience of SE and DE roles in implementing management processes for AIRs (n=36)

6.3.2 Knowledge and Implementation of Process Standards

To support a consistent and structured information requirements management process across multiple stakeholders throughout the lifecycle of an asset, ISO 19650 standards and government state-based standards, such as the Transport for NSW DE framework and Victorian Digital Asset Strategy, are being implemented in Australian building and infrastructure sectors. Figure 6.7 presents an overview of respondents' level of experience in implementing ISO 19650 and state-based DE process standards. Considering these standards have only been published for less than 5 years, four levels were defined based on their understanding of and involvement in the implementation of those standards (rather than based on the number of years of experience): No Knowledge, Beginner, Intermediate and Advanced.

- **No Knowledge** – participant has not heard of the standard at all.
- **Beginner** – participant has a general understanding of concepts and principles of the standard but has not been involved in implementation.
- **Intermediate** – participant has an intermediate level working knowledge of the standard as a direct result of project-based experience.
- **Advanced** – participant has advanced working knowledge of the standard as a direct result of developing or implementing the standard.

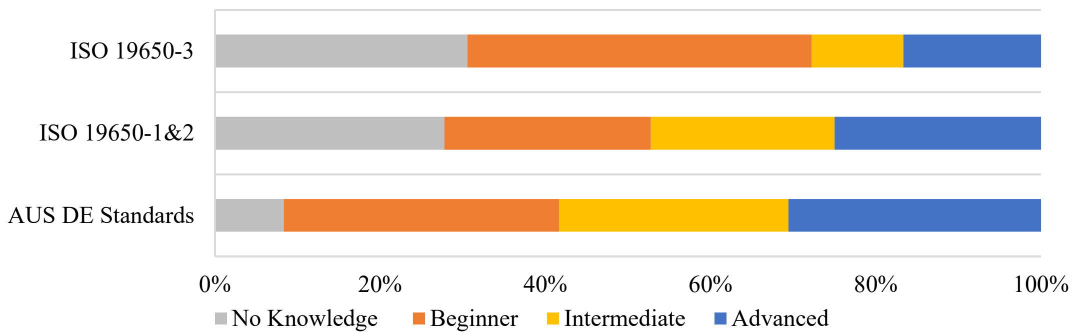


Figure 6.7 Overview of implementing ISO and government DE process standards (n=36)

An analysis of the survey findings for Q2-4, which sought to identify the prevalence of use of ISO 19650 and related DE process standards in Australia, is presented in Figure 6.7. Intermediate and Advanced levels show that 60% of respondents have a working knowledge of the standards and have been directly involved or responsible for the implementation of Australian (state-based) DE process standards on projects. ISO 19650 Part 3 also has a lower rate (30%) of implementation than Parts 1 and 2 (50%), as the current emphasis of DE implementation is still in the project delivery phases indicating a lower level of maturity in implementation of DE in the operation and maintenance (O&M) phase.

Further analysis is conducted to build a greater understanding of the related DE and SE roles relative to their responsibilities, and their respective levels of experience in information requirements management standards. As presented in Figure 6.8, state-based standards, including the Transport for NSW DE framework and the Victorian Digital Asset Strategy, are more commonly recognised and used on projects than the ISO 19650 standard. The respondents that have no to little knowledge of Australian DE standards were identified as systems engineers, who responded that they also do not have any, or limited, experience in DE related projects. During the early implementation of DE processes, those in SE roles have had limited to no understanding of international standards such as ISO 19650. Due to dependencies between technical system requirements management practices (traditionally led by SE roles) and new, evolving information requirements management practices (led by recent emergence of DE roles) a significant knowledge gap arises which presents substantial risk to requirements traceability. An awareness of Australian DE Standards was reported by the majority of SE roles in transport infrastructure sectors (refer to "Beginner" in Figure 6.8), indicating a low level of knowledge.

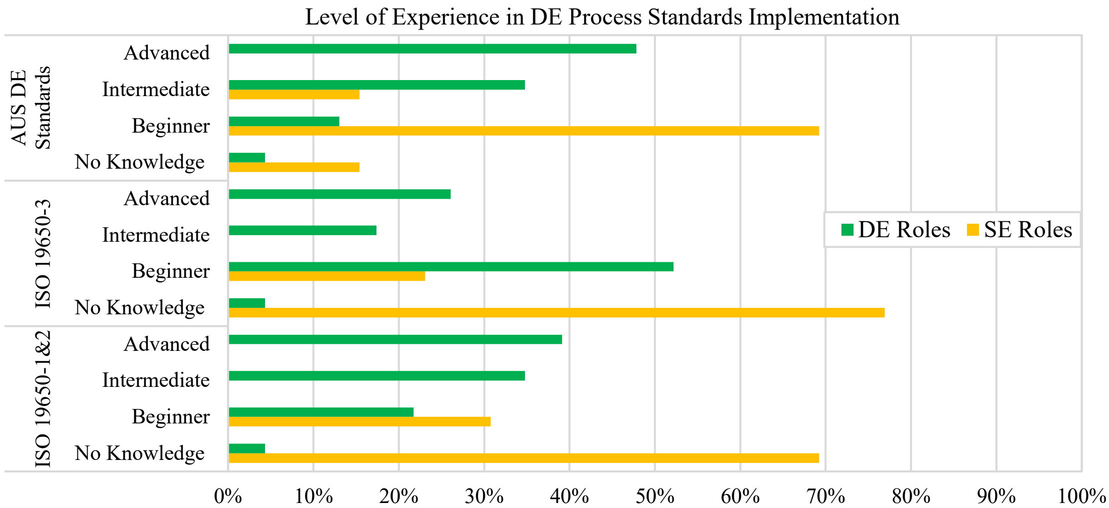


Figure 6.8 Respondents' level of experience in implementing DE process standards (n=36)

The most commonly used government agency DE framework or standard mentioned in the survey responses was the Transport for NSW DE Framework (61%) followed by the Victorian Digital Asset Strategy (11%) (see Table 6.4). Less than half of the SE respondents (46%) mentioned they have an understanding of a government agency DE framework or standard, indicating that there are potential opportunities for systems engineers to play a greater role in information requirements management processes. It also reveals opportunities for further transformation of SE roles in the use of model-based data during design review activities for requirements verification. The evolution of traditional SE competencies to MBSE competencies would assist in managing the interface between physical systems, functional and performance and information requirements.

Table 6.4 Most commonly used government agency DE framework

Government Agency DE Framework/ Standard	SE role (R=13)	DE role (R=23)	Total (R=36)
Transport for NSW DE Framework	38%	74%	61%
VDAS (Victorian Digital Asset Strategy)	8%	13%	11%
VBIS (Virtual Buildings Information System)	0%	4%	3%
Queensland Framework	0%	4%	3%
Metro exchange information requirements (EIR)	0%	4%	3%

6.3.3 Knowledge and Implementation of Data Standards

Figure 6.9 presents an overview of respondents' level of experience in implementing data standards including asset information classification systems (e.g., Uniclass, UniFormat, OmniClass), asset data models/standards for data exchange (e.g., COBie – Construction to Operations for Building information exchange, CONie – Construction to Operations for Network information exchange), ISO 16739-1: 2018 Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries – Part 1: Data schema, and ISO 23387:2020 Building information modelling (BIM) – Data templates for construction objects used in the lifecycle of built assets – Concepts and principles. The setup of the levels is similar to Section 6.3.2: No Knowledge, Beginner, Intermediate and Advanced.

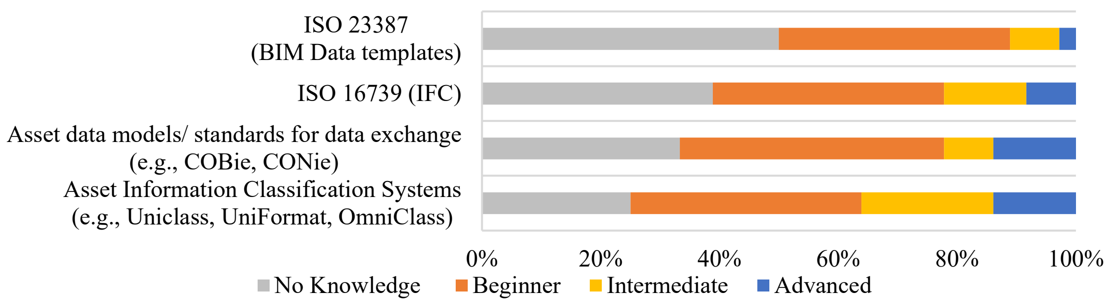


Figure 6.9 Overview of implementing data standards (n=36)

An analysis of the survey findings for the second part of Q2-4, which sought to identify the prevalence of use of asset data standards in Australia, is presented in Figure 6.10. Intermediate and Advanced levels show that 36% of respondents have a working knowledge of and have been directly involved in or responsible for the implementation of the asset information classification systems on projects, and only 22% have integrated asset data standards for data exchange (e.g., COBie) and ISO 16739 (IFC) standard in their working practices. ISO 23387:2020 (BIM data templates) is a relatively new standard, and only 11% of respondents have a work experience of it, again indicating a lower level of maturity in asset information lifecycle management.

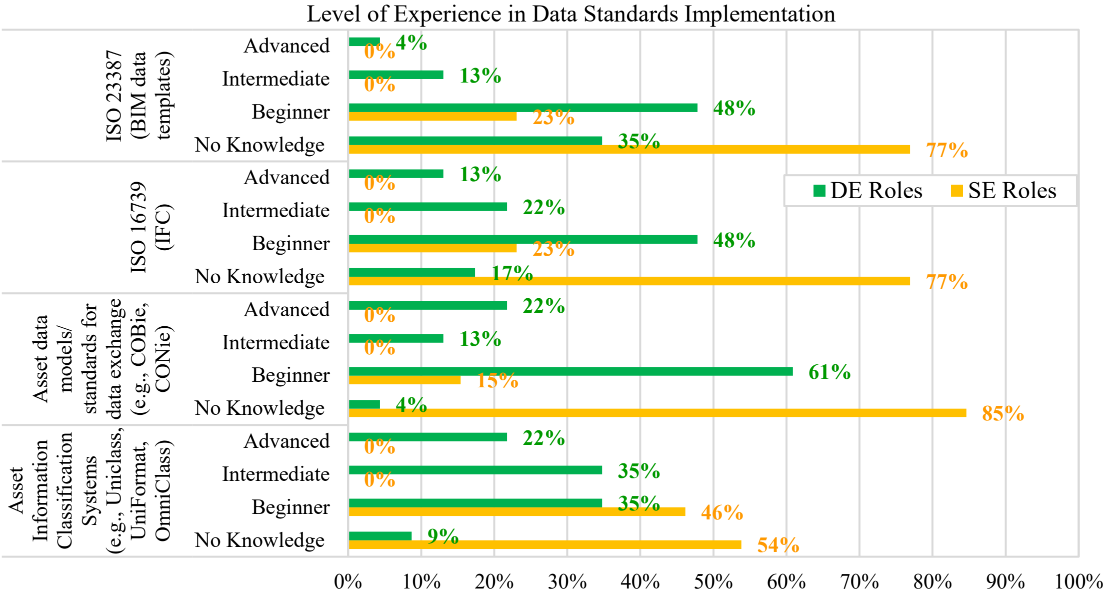


Figure 6.10 Respondents' level of experience in implementing data standards (n=36)

Further analysis is conducted to build a greater understanding of the related DE and SE roles relative to their responsibilities, and their respective levels of experience in data standards. As presented in Figure 6.10, SE role respondents either had no knowledge at all or had no working experience of the data standards (refer to "Beginner"). This reflects another knowledge gap for SE roles in data standards supporting DE implementation. Figure 6.10 also presents that the asset information classification system is more commonly recognised and implemented on projects supporting asset data handover to the operational stage.

As shown in Table 6.5, the most commonly used asset information classification system mentioned in the survey responses is Uniclass (61%) followed by OmniClass (17%). This finding is consistent with the findings from the semi-structured interviews. Uniclass is the most widely used and recognised asset classification system in the Australian infrastructure industry.

Table 6.5 Most commonly used asset information classification systems

Asset Information Classification Systems	SE role (R=13)	DE role (R=23)	Total (R=36)
Uniclass	46%	70%	61%
OmniClass	0%	26%	17%
MasterFormat	0%	9%	6%
UniFormat	0%	4%	3%
Transport for NSW/ASA Asset Classification	0%	4%	3%

6.4 Requirements Management Practices Maturity in Projects

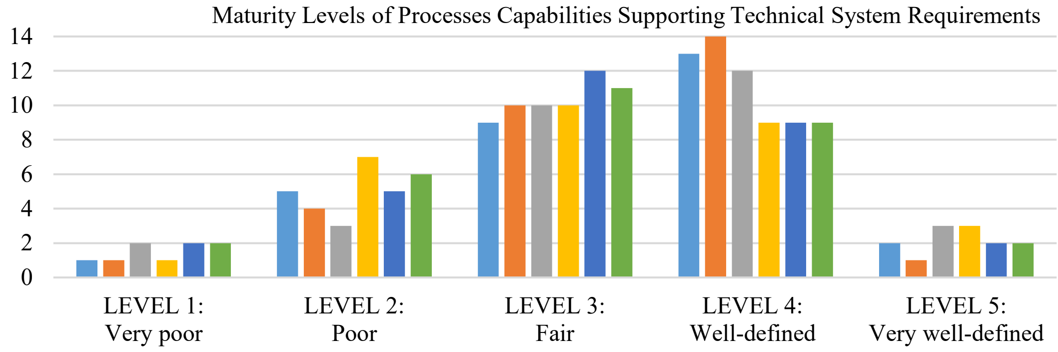
This section answers research sub-question Q2-5: *What are the current maturity levels of requirements management practices in complex infrastructure industry (process, technology, people)?*

6.4.1 Maturity Levels of Process Capabilities Supporting Requirements Management

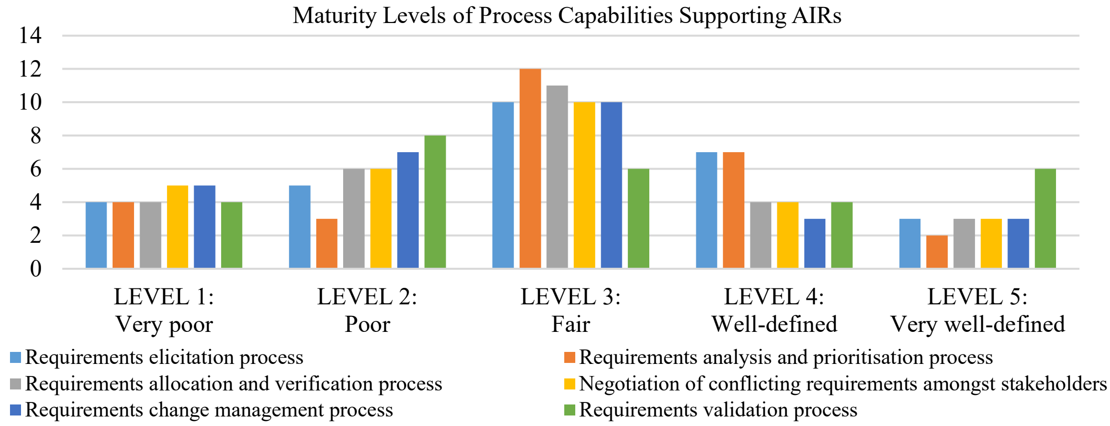
Figure 6.11 summarises analysis of results for the five areas of requirements management process capabilities surveyed relative to (a) technical system requirements versus (b) AIRs management activities. Five levels of maturity are defined for requirements management process capabilities:

- **Level 1: Very poor**. There is no formal process or protocol defined or implemented.
- **Level 2: Poor.** Ad hoc process and protocol is implemented during project delivery.
- **Level 3: Fair.** An organisational standard exists that describes a generic process.
- **Level 4: Well-defined**. Level 3 + Process is monitored, and performance assessed.
- **Level 5: Very well-defined**. Level 4 + Continuous process improvement.

Respondents scored the maturity levels of technical system requirements versus AIRs management processes differently, with the former scoring either "Well-defined" or "Fair" while AIRs were scored as "Poor" or "Fair". The responses indicate a higher level of capability maturity across each of the six areas of technical system requirements management process (i.e., requirements elicitation, requirements analysis and prioritisation, requirements allocation and verification, requirements negotiation, requirements change management, and requirements validation).



(a)



(b)

Figure 6.11 Maturity levels of process capabilities supporting the handling of requirements (n=36)

To illustrate the survey result in a more straightforward way, the maturity levels were scored from "1" to "5" where "1" is "Very Poor" and "5" is "Very Well-defined". The score of each process capability is calculated as the mean of all responses (as shown in Figure 6.12). Overall, processes supporting technical system requirements management have higher maturity levels than those supporting AIRs. Requirements allocation and verification reflects the largest gap (ΔScore=0.51) between technical system requirements and AIRs while requirements validation process has the smallest gap (ΔScore=0.1).

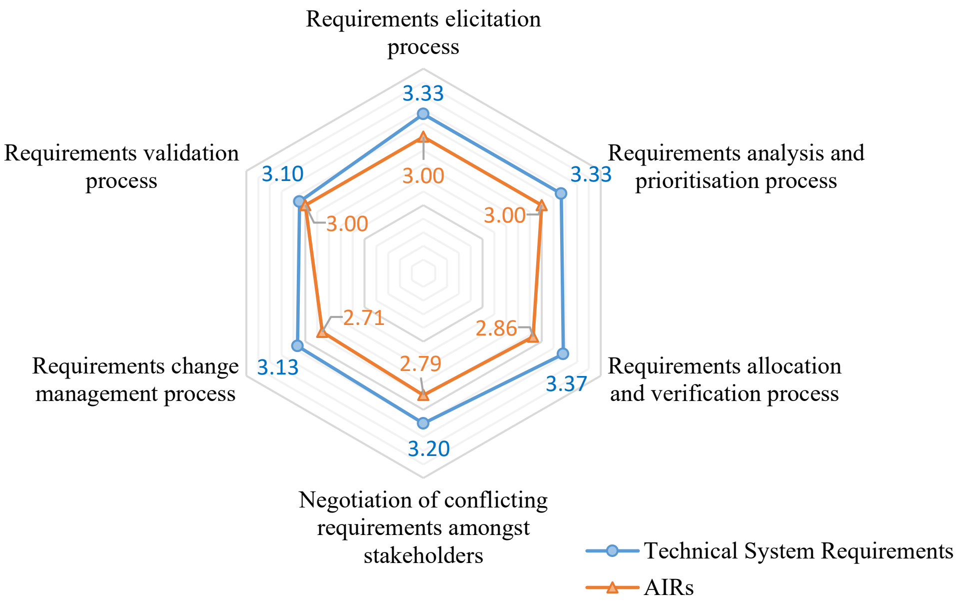


Figure 6.12 Maturity levels of process capabilities comparison – technical system requirements vs AIRs

Analysis was also undertaken to compare the responses relative to the two main disciplines of SE roles or DE roles. The maturity levels were scored from "1" to "5" where "1" is "Very Poor" and "5" is "Very Well-defined". The score of each process capability is calculated as the mean of all responses of each group with their standard deviations (SD) given (see Table 6.6).

Table 6.6 Maturity levels of process capabilities – SE and DE role perspectives

Process Capabilities	SE role				DE role			
	Technical System Requirements		AIRs		Technical System Requirements		AIRs	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Requirements elicitation process	3.45	0.82	2.44	1.17	3.26	1.05	3.32	1.11
Requirements analysis and prioritisation process	3.36	0.67	2.40	1.13	3.32	1.00	3.26	1.05
Requirements allocation and verification process	3.55	0.82	2.33	1.12	3.26	1.15	3.11	1.15
Negotiation of conflicting requirements amongst stakeholders	3.09	0.94	2.22	0.97	3.26	1.10	3.05	1.27
Requirements change management process	3.36	0.81	2.22	0.97	3.00	1.11	2.95	1.27
Requirements validation process	3.00	0.63	2.22	1.09	3.16	1.21	3.37	1.38

Note: Scored from 1 to 5, where 1 is Very Poor and 5 is Very Well-defined.

Figures 6.13 and 6.14 then plot the maturity levels of process capabilities supporting requirements management practices reported by the respondents according to their respective SE and DE roles. Figure 6.13 focuses on technical system requirements while Figure 6.14 focuses on AIRs. In Figure 6.13, the scores of requirements management processes surrounding technical systems requirements management from SE and DE roles are quite close (scores = 3~3.55). But the discrepancy lies in the difference between the perspectives of DE and SE roles relative to AIRs maturity in Figure 6.14, where AIRs maturity was ranked substantially lower by SE roles (scores < 2.5), indicating that they are not exposed to these activities, and therefore there is a lack of integration of AIRs in technical system requirements processes.

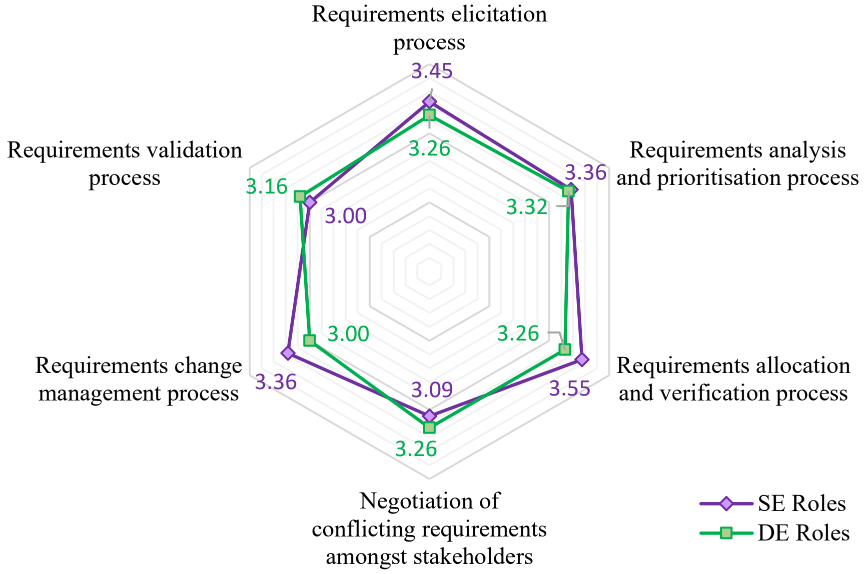


Figure 6.13 Maturity levels of process capabilities supporting technical system requirements

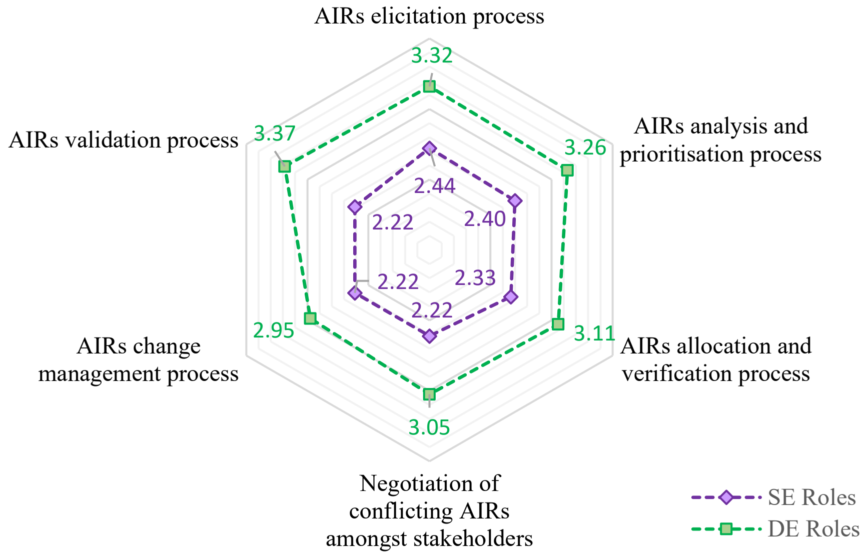


Figure 6.14 Maturity levels of process capabilities supporting AIRs

To understand the intensity of relationship between SE and DE roles, effect sizes are measured using the Cohen's D method (Cohen, 1988). Under the Cohen's D effect size method, there are three interpretations:

- Small size (0.2): Such an effect between the two groups is negligible and cannot be spotted with naked eyes.
- Medium size (0.5): This level of correlation is usually identified when the researcher goes through the data – medium size can have a reasonable overall impact.
- Large size (0.8 or greater): A large effect can be observed without using any calculator –the impact is significant in real-world scenarios.

Cohen's D Formula: $Effect\ Size = \frac{\mu 1 - \mu 2}{\alpha}$

Here, μ1 is the mean of the first population group (SE role),
μ2 is the mean of the second population group (DE role), and
σ is the standard deviation.

In Table 6.7, the effect size of each process capability maturity of technical system requirements and AIRs was calculated. This result reveals the intensity of the relationship between SE and DE roles. As shown in Table 6.7, the difference between the SE and DE perspectives for the maturity level of technical system requirements processes are negligible (|Effect size| < 0.5), while for AIRs management processes the difference is obvious (|Effect size| > 0.5). The negative effect size means DE roles recognised a high maturity level in process capabilities than SE roles.

Table 6.7 Effect size of process capabilities maturity levels from SE and DE role perspectives

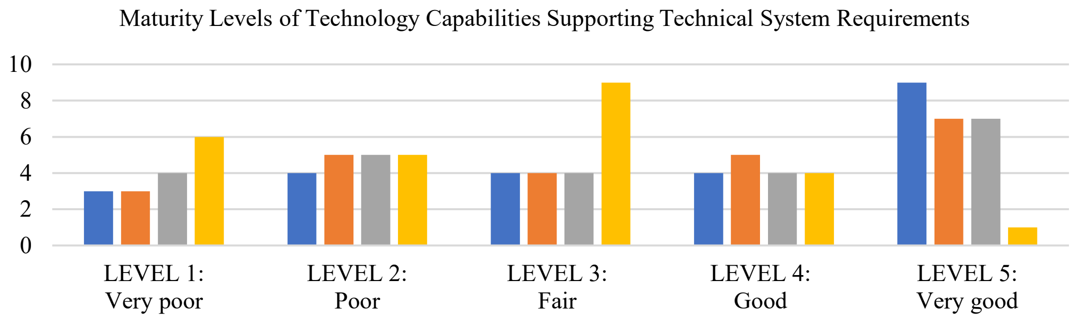
Requirements Processes	Technical System Requirements		AIRs	
	SD	Effect Size	SD	Effect Size
Requirements elicitation process	0.96	0.20	1.20	**-0.73**
Requirements analysis and prioritisation process	0.88	0.05	1.12	**-0.77**
Requirements allocation and verification process	1.03	0.28	1.18	**-0.66**
Negotiation of conflicting requirements amongst stakeholders	1.03	-0.16	1.23	**-0.67**
Requirements change management process	1.01	0.36	1.21	**-0.60**
Requirements validation process	1.03	-0.16	1.39	**-0.83**

6.4.2 Maturity Levels of Technology Capabilities Supporting Requirements Management

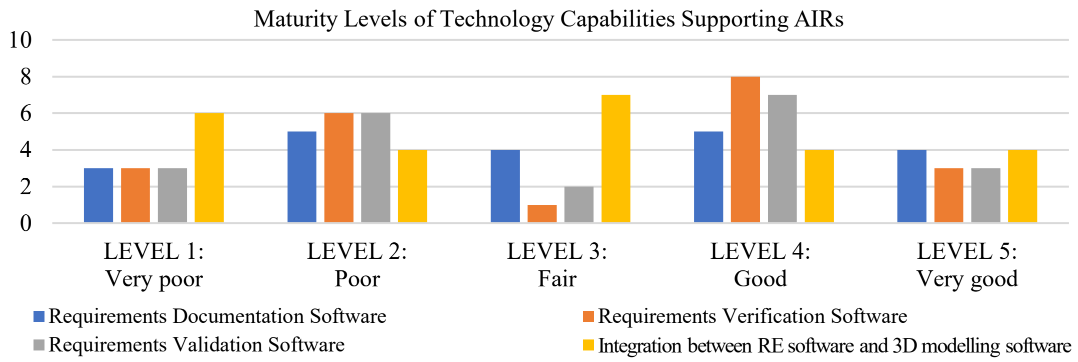
Figure 6.15 summarises the relative maturity of the technology used to support the handling of technical system requirements versus AIRs. Five levels of maturity of technology capabilities are defined as:

- **Level 1: Very poor**. There is no dedicated requirements software tool used by project delivery team organisations. Neither requirements management nor 3D modelling software is used.
- **Level 2: Poor.** Separate requirements software tools are used across the various project delivery team organisations. Requirements management related software is used but 3D modelling software is not.).
- **Level 3: Fair.** An integrated requirements software tool or platform is used by a minority of relevant project delivery team organisations. Separate and distinct requirements management and 3D modelling software are used, however there are no digital links between them.
- **Level 4: Good.** An integrated requirements software tool or platform is used by a majority of relevant project delivery team organisations. There is basic integration enabled between the requirements management and 3D modelling software used, e.g., providing spatially enabled requirements mapping, linking requirements with 3D objects, and automating a basic level of spatial requirements verification.
- **Level 5: Very good**. Level 4 + Requirements managed by a dedicated project role, e.g., requirements engineer, systems engineer, digital engineer, BIM manager. There is a high level of integration enabled between the requirements management and 3D modelling software used, supporting the use of configuration management to establish and maintain consistency of system performance, functional, and physical attributes with its requirements, design, and operational information.

As shown in Figure 6.15, the maturity levels of technology use in technical system requirements scored higher overall than for AIRs, with “Very Good” versus “Good”. However, the survey analysis identified a slightly higher level of integration between the use of tools supporting AIRs management and 3D modelling technologies. Most respondents reported only “Fair” levels of maturity in the integration between technical system requirements technologies and 3D modelling software. However, there was a lack of agreement, with fluctuation of maturity levels reflected in the use of requirements management software to support AIRs management and its interface with 3D modelling software. This reflects separate and distinct requirements management and 3D modelling software and workflows.



(a)



(b)

Figure 6.15 Maturity levels of technology capabilities supporting the handling of requirements (n=36)

To illustrate the survey result in a more straightforward way, the maturity levels were scored from "1" to "5" where "1" is "Very Poor" and "5" is "Very Good". The score of each technology capability is calculated as the mean of all responses (as shown in Figure 6.16). Overall, technologies supporting technical system requirements management have slightly higher maturity levels than those supporting AIRs. However, when it comes to the integration of requirements management software with 3D modelling software, AIRs related software (score = 2.84) has a slightly higher maturity score than technical system requirements (score = 2.56).

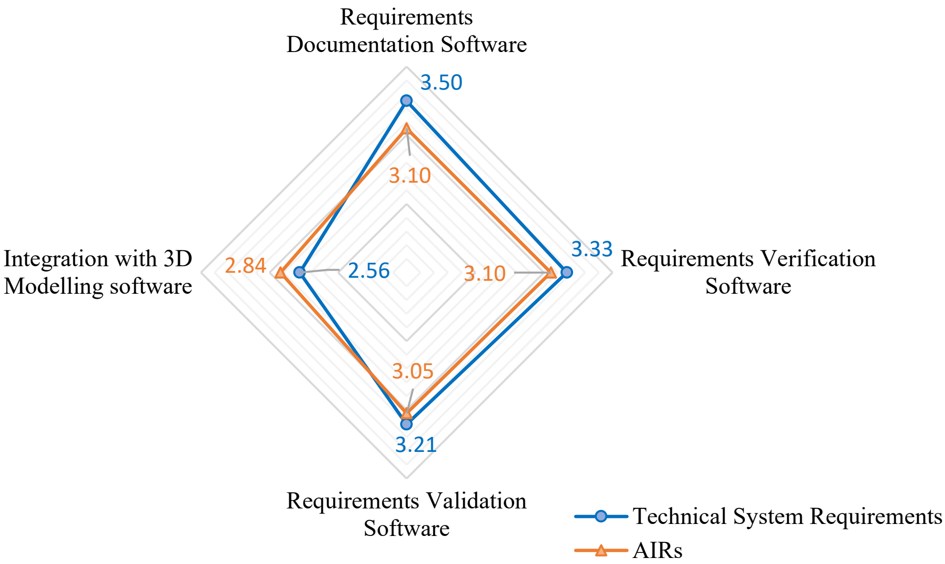


Figure 6.16 Maturity levels of technology capabilities comparison – technical system requirements vs AIRs

Discipline related analysis was then undertaken to compare responses relative to the two main disciplines, i.e., SE roles or DE roles. The score of each technology capability is calculated as the mean of all responses of each group with their standard deviations (SD) given (see Table 6.8).

Table 6.8 Maturity levels of technology capabilities – SE and DE role perspectives

Technology Capabilities	SE Role				DE Role			
	Technical System Requirements		AIRs		Technical System Requirements		AIRs	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Requirements documentation software	4.30	0.95	3.71	1.50	2.93	1.54	2.79	1.25
Requirements verification software	4.10	1.10	3.29	1.70	2.79	1.42	3.00	1.24
Requirements validation software	3.80	1.48	3.14	1.68	2.79	1.42	3.00	1.24
Integration of requirements management software with 3D modelling software	2.1	1.10	2	1.15	2.87	1.13	3.4	1.30

Note: Scored from 1 to 5, where 1 is Very Poor and 5 is Very Good.

Figures 6.17 and 6.18 plot the maturity levels of technology capabilities supporting requirements management practices reported by the participants according to their respective SE and DE roles. Figure 6.17 focuses on software implementation supporting technical system requirements while Figure 6.18 focuses on AIRs. In Figure 6.17, SE roles reported significantly higher maturity levels of the use of requirements management software (i.e., system requirements documentation software, system requirements verification software, and system requirements validation software) to support technical systems requirements management (scores = 3.8~4.3) than those by DE roles (scores = 2.79~2.93). This indicates that DE roles are not involved much in the implementation of requirements management software for technical system requirements. On the contrary, for integration of requirements management software with 3D modelling software, SE roles reported a substantially lower score (score = 2.1, referring to no 3D modelling software used in projects) than DE roles (score = 2.87). This is consistent with feedback from SE roles that they have limited experience in DE related activities and most projects they were involved in did not have an aspiration of digital deliverables. According to DE respondents, even in those projects where 3D modelling software was used in digital delivery, there are currently limited links between requirements management software and 3D modelling software.

In the technology supporting AIRs management, there was discrepancy between the perspective of DE and SE roles in software supporting documentation of AIRs and integration with 3D modelling software (see Figure 6.18). SE roles recognised a much higher maturity level of implementing documentation software for AIRs than DE roles while SE and DE roles have consistent responses as "Fair" software utilisation of software supporting verification and validation of AIRs. This reflects the timeline of appointment of different roles (i.e., SE and DE roles). When a digital engineer for design management has been appointed, they have not necessarily been involved in the identification and documentation of AIRs. A DE consultancy may be employed to do that, and those requirements could then be translated by a system engineer in documentation software. However, those AIRs might not be verified or validated in software in later stages by SE roles.

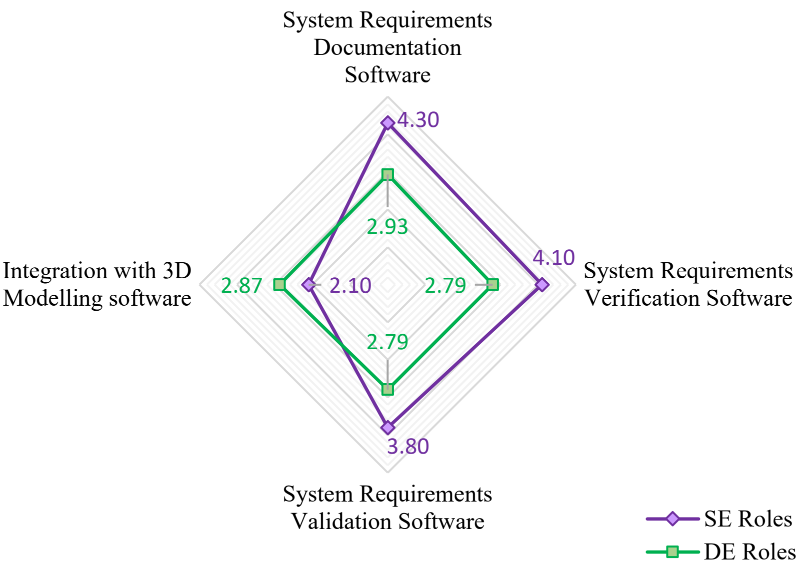


Figure 6.17 Maturity levels of technology capabilities supporting technical system requirements

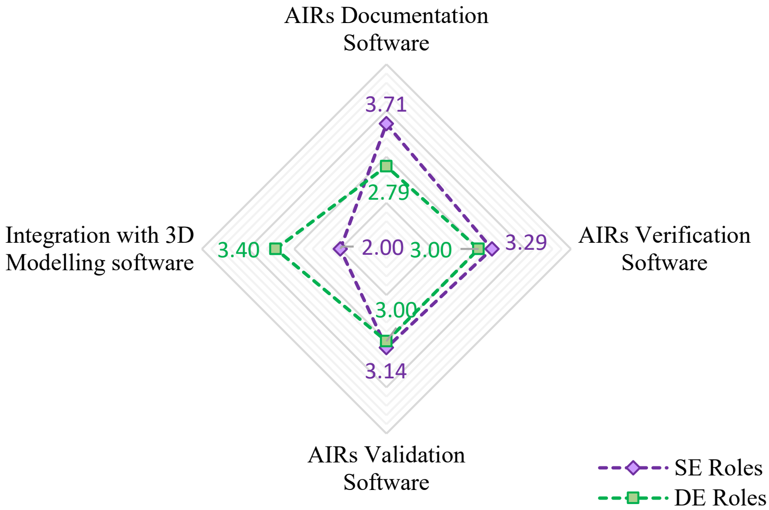


Figure 6.18 Maturity levels of technology capabilities supporting AIRs

In Table 6.9, the effect size of each technology capability maturity of technical system requirements and AIRs was calculated. This result reveals the intensity of the relationship between SE and DE roles. As shown in Table 6.9, significant differences of SE and DE perspectives are identified (|Effect size| > 0.5) in all four technology capabilities supporting technical system requirements and two supporting AIRs (highlighted as bold font in Table 6.9). The differences between SE and DE perspectives for two technology capability maturity levels are negligible including verification and validation software for AIRs (|Effect size| ≤ 0.2) which means that both SE and DE roles identified a moderate to low level of maturity in software implementation for AIRs verification and validation.

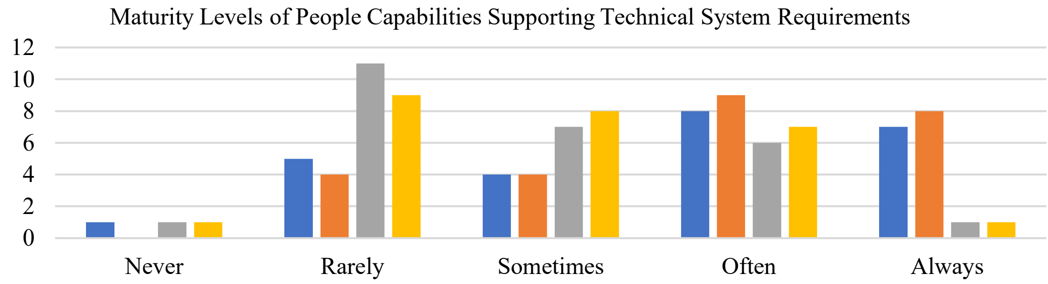
Table 6.9 Effect size of technology capabilities maturity levels from DE and SE role perspectives

Technology Capabilities	Technical System Requirements		AIRs	
	SD	Effect Size	SD	Effect Size
Requirements documentation software	1.47	**0.93**	1.37	**0.67**
Requirements verification software	1.43	**0.91**	1.37	0.21
Requirements validation software	1.50	**0.67**	1.36	0.10
Integration of requirements management software with 3D modelling software	1.16	**-0.67**	1.40	**-1.00**

6.4.3 Maturity Levels of People Capabilities Supporting Requirements Management

This section investigates the maturity levels of people and culture capabilities supporting the handling of technical system requirements and AIRs. As mentioned in Section 6.2.2, these capabilities are measured through frequency as “Never”, “Rarely”, “Sometimes”, “Often” and “Always”.

Figure 6.19 summarises the analysis of the perceived maturity levels of people and culture capabilities underpinning (a) technical system requirements and (b) AIRs management. Roles and responsibilities that are formally defined for the handling of technical system requirements were identified as “Often” and “Always” in the planning and acquisition phase while for roles and responsibilities in AIRs management they were identified as “Sometimes” and “Often”. The same trend is reflected in the training in requirements software where lower levels of training are reflected in the people responsible for AIRs management.



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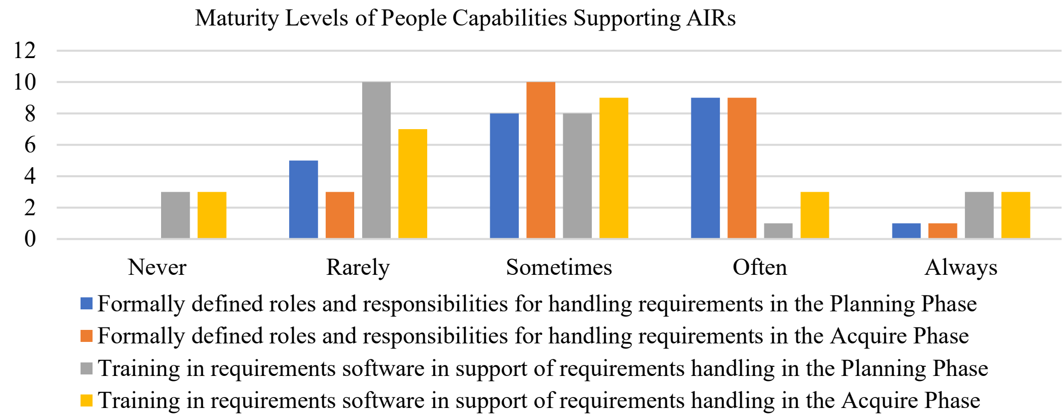

(b)

Figure 6.19 Maturity levels of people capabilities supporting the handling of requirements (n=36)

To illustrate the survey result in a more straightforward way, the maturity levels were scored from “1” to “5” where “1” is “Never” and “5” is “Always”. The score of each people and culture capability is calculated as the mean of all responses (as shown in Figure 6.20). In general, the maturity levels of people and culture capabilities supporting physical system requirements and AIRs are very close to each other. The respondents reflect a slightly higher maturity level of people related capabilities supporting physical system requirements than AIRs. They also reflect that the frequency of formally defined roles and responsibilities in the planning and acquire phases is “Sometimes” to “Often”. However, training in requirements management software happened “Rarely” or “Sometimes”.

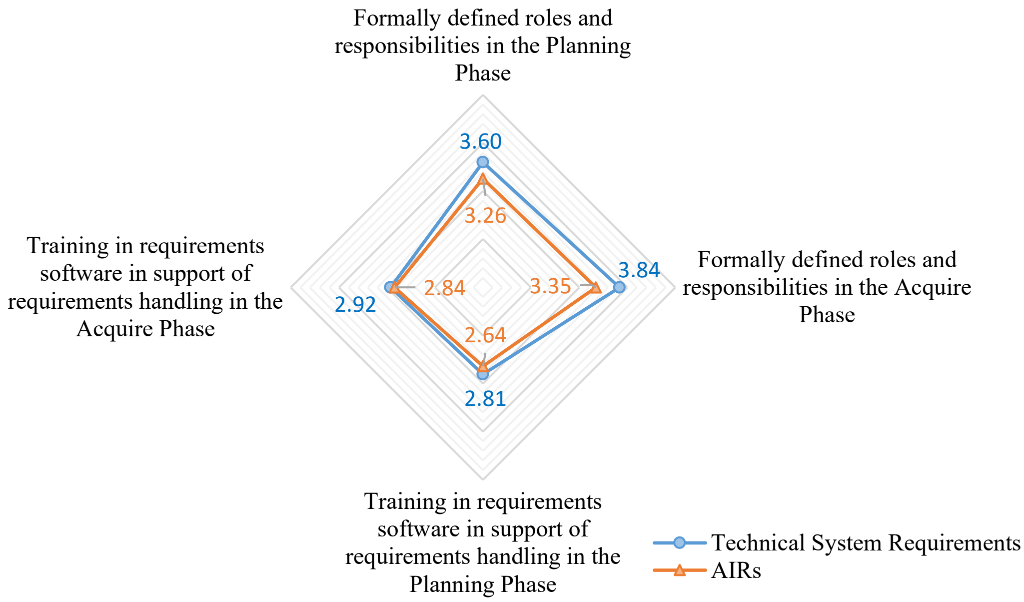

Figure 6.20 Maturity levels of people capabilities comparison – technical system requirements vs AIRs

Similarly, discipline related analysis was undertaken to compare the responses relative to the two main disciplines of SE roles or DE roles. The score of each people capability is calculated as the mean of all responses of each group with their standard deviations (SD) given (see Table 6.10).

Table 6.10 Maturity levels of people capabilities – SE and DE role perspectives

People Capabilities	SE Role				DE Role			
	Technical System Requirements		AIRs		Technical System Requirements		AIRs	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Formally defined roles and responsibilities in the Planning Phase	4.00	1.15	3.75	0.87	3.33	1.23	3.00	0.76
Formally defined roles and responsibilities in the Acquire Phase	4.30	0.95	3.75	0.87	3.53	1.06	3.13	0.64
Training in requirements software in support of requirements handling in the Planning Phase	2.60	0.97	2.22	1.09	2.94	1.00	2.88	1.15
Training in requirements software in support of requirements handling in the Acquire Phase	2.70	1.06	2.22	1.09	3.06	0.93	3.19	1.11

Figures 6.21 and 6.22 plot the maturity levels of people capabilities supporting requirements management practices reported by the participants according to their respective SE and DE roles. SE roles scored (scores = 3.75~4.3) higher maturity levels than DE roles (scores = 3~3.53) against "formally defined roles and responsibilities for the handling of requirements" in both planning and acquisition phases. "Training in requirements software in support of requirements handling" occurs less frequently in SE roles (scores = 2.22~2.7) than DE roles (scores = 2.88~3.19) in either the planning or acquisition phases.

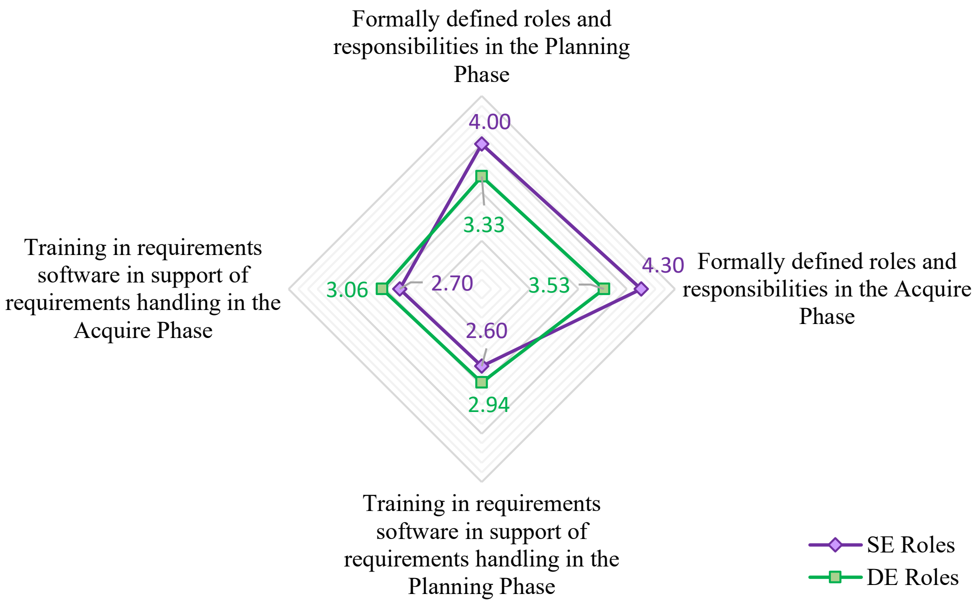

Figure 6.21 Maturity levels of people capabilities supporting technical system requirements

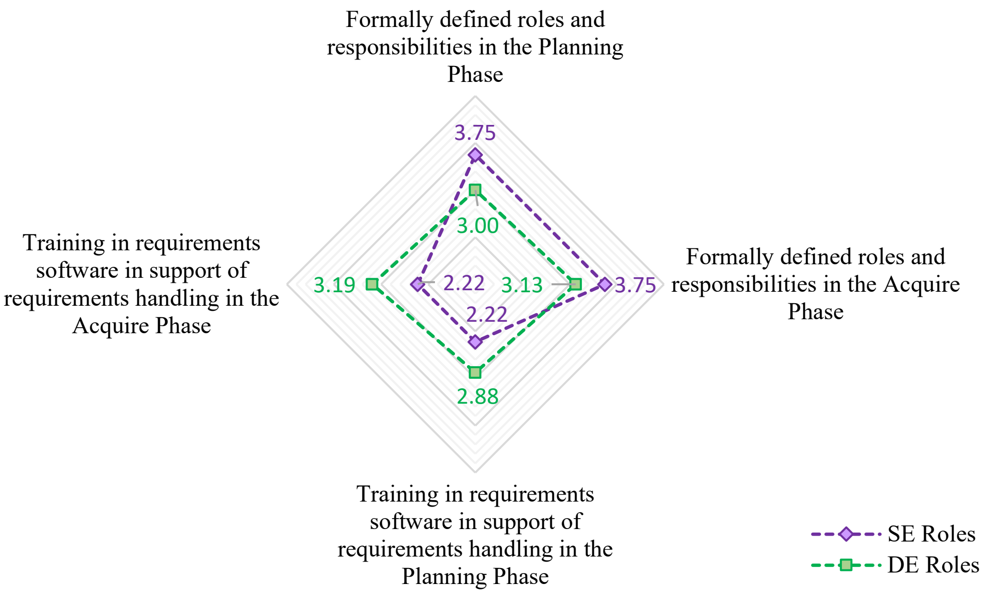

Figure 6.22 Maturity levels of people capabilities supporting AIRs

In Table 6.11, the effect size of each people related capability maturity of technical system requirements and AIRs was calculated. This result reveals the intensity of relationships between SE and DE roles. As shown in Table 6.11, significant differences between SE and DE perspectives are identified (|Effect size| > 0.5) in all four people capabilities supporting AIRs and two supporting technical system requirements (highlighted as bold font in Table 6.11). The difference between SE and DE perspectives for two people related capability maturity levels (i.e., training in requirements management software in planning and acquisition phases) are not obvious but could be identified through data analysis (0.2 <|Effect size| < 0.5).

Table 6.11 Effect size of people capabilities maturity levels from DE and SE role perspectives

People Capabilities	Technical System Requirements		AIRs	
	SD	Effect Size	SD	Effect Size
Formally defined roles and responsibilities in the Planning Phase	1.22	**0.55**	0.86	**0.87**
Formally defined roles and responsibilities in the Acquire Phase	1.07	**0.72**	0.78	**0.80**
Training in requirements software in support of requirements handling in the Planning Phase	0.98	-0.34	1.15	**-0.57**
Training in requirements software in support of requirements handling in the Acquire Phase	0.98	-0.37	1.18	**-0.82**

6.4.4 Resources Supporting Requirements Management Practices

The nature and importance of resources to support the successful implementation of requirements management are analysed in this section. Five levels of importance were defined in the survey as "Not Important", "Slightly Important", "Moderately Important", "Very Important" and "Extremely Important", scored from "1" for not important to "5" for extremely important. The overall score of each type of resource is calculated as the mean of responses, with their standard deviation given, see Table 6.12.

Table 6.12 shows "support from senior management" was scored as the most important resource (score > 4.5) for implementing more integrated requirements management approaches. This support could include funding, technical and human resources. This was closely followed by having "clear government agency/appointing party standards and terms of contract covering requirements management application" and "clearly defined roles and responsibilities for requirements management" with "Very Important" awarded (score > 4.0). The findings also show that "training in requirements management methods" and "investment in requirements management software licenses" were considered more important for the management of technical system requirements than for the management of AIRs.

Table 6.12 Importance of resources supporting requirements management practices

Resources supporting Requirements Management	Technical System Requirements		AIRs	
	Mean	SD	Mean	SD
Support from senior management	4.62	0.57	4.56	0.65
Clear Government Agency/Appointing Party standards and terms of contract covering requirements management application	4.38	0.90	4.08	0.61
Clearly defined roles and responsibilities for requirements management	4.35	0.69	4.28	1.00
Training in requirements management methods	4.19	0.63	3.52	1.00
Investment in requirements management software licenses	4.08	1.02	3.8	0.98
Training in requirements management software	3.62	0.98	3.72	1.00

The next section investigates the significance of challenges to requirements management practices identified from the literature survey (Chapter 4) and interview survey (Chapter 5). Identifying the most significant challenges on projects can then inform the development of core enablers of the requirements management Capability Improvement Framework in Chapter 7.

6.5 Significance of Challenges to Requirements Management Practices

This section answers the research sub-question Q2-6: *Of the challenges identified in the management of technical system requirements and asset information requirements, how significant are they and how should they be prioritised?*

6.5.1 Significant Challenges based on Frequency of Occurrence

Part 3 of the survey focused on investigating the significance of challenges identified from the literature survey and interview survey. Questions about the frequency of the occurrence of challenges are asked in three categories – process, technology and people. As mentioned in Section 6.2.3, five different frequency levels are adopted: “Never”, “Rarely”, “Sometimes”, “Often” and “Always”.

First of all, the respondents of these challenges’ frequency levels are grouped into “Negligible” (including “Never” and “Rarely”) and “Identifiable” (including “Always”, “Often” and “Sometimes”). The intention is to simplify the analysis of the severity of these challenges. Figures 6.23 to 6.25 present the overviews of these two groups of respondents relative to the frequency of occurrence of challenges to requirements management practices in these three categories: (a) Process, (b) Technology and (c) People.

To illustrate the survey result in a more straightforward way, the different levels are scored as “1” for “Never” to “5” for “Always”. Tables 6.13 to 6.15 reflect the parameters of 47 different challenges, including mean, standard deviation (SD) and Top 3 Box (T3B), and project phases. Mean is the average value of responses. SD describes the variability in the distribution, which equals the square root of the average squared deviations from the mean. The T3B score in this study represents the sum of percentages for the three highest responses of the frequency scale (i.e., “Often” and “Always”). Project phases refer to the phases of the project (i.e., planning and acquisition) which these challenge related activities are involved in. To identify the different significant levels of challenges to requirements management, T3B scores were used as the primary reference. Challenges with a T3B score equal to 100% were identified as **Critical challenges**, challenges with a T3B score from 90% to 99% were identified as **Important challenges**, and challenges with a T3B score lower than 90% were identified as **Moderate challenges**.

As presented in Figure 6.23 and Table 6.13, there are six critical challenges (T3B = 100%), 11 important challenges (90% ≤ T3B ≤ 99%), and 1 moderate challenge (T3B < 90%) related to requirements management processes. All these six critical challenges are related to AIRs management activities including those specific to AIRs and the interface between technical system requirements with AIRs. This is consistent with findings in Section 6.4.1, emphasising that the maturity levels of process capabilities supporting technical system requirements management are higher than those of information requirements management and the interface management across different requirement types is poor in practice. Survey respondents also raised that AIRs are not prioritised due to time pressure and financial drivers in most projects (see details in Section 6.5.2 iv).

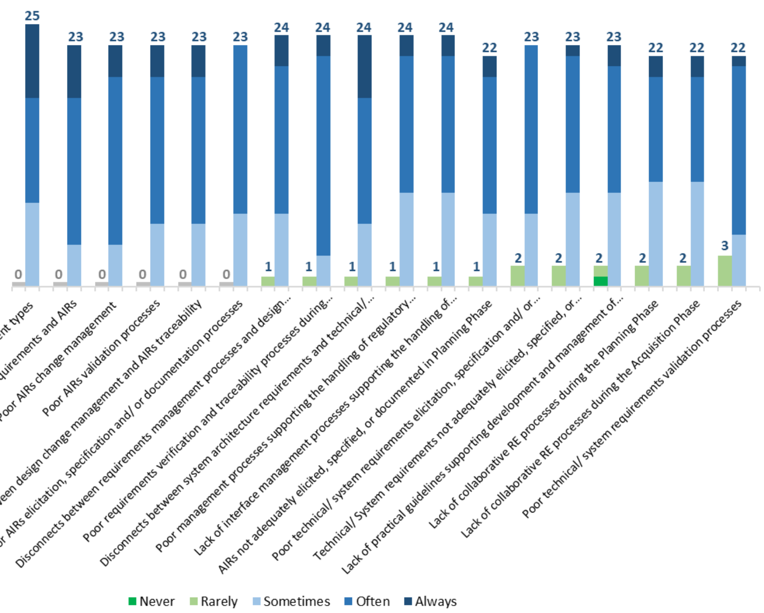

Figure 6.23 Frequency of process related challenges to requirements management practices

In terms of project phases, five out of six critical challenges are involved in the acquisition phase while only one challenge ("poor interface management across requirement types") is involved in both the planning and acquisition phases. This challenge reflects that the transition of requirements from the planning phase to the acquisition phase is poorly managed.

Table 6.13 Ranking of challenges based on frequency of occurrence – Process

No.	Process Related Challenges	Mean	SD	T3B	Project Phases
PC16	Poor interface management across requirement types	3.96	0.77	100%	Planning & Acquisition
PC4	Disconnects between system architecture requirements (including network requirements) and AIRs	4.04	0.62	100%	Acquisition
PC11	Poor AIRs change management	3.96	0.55	100%	Acquisition
PC13	Poor AIRs validation processes	3.87	0.61	100%	Acquisition
PC9	Disconnects between design change management and AIRs traceability	3.87	0.61	100%	Acquisition
PC2	Poor AIRs elicitation, specification and/or documentation processes	3.7	0.46	100%	Acquisition
PC10	Disconnects between requirements management processes and design change management processes	3.76	0.71	96%	Planning & Acquisition
PC7	Poor requirements verification and traceability processes during Acquisition Phase	3.88	0.59	96%	Acquisition
PC3	Disconnects between system architecture requirements (including network requirements) and technical system requirements	3.92	0.8	96%	Planning & Acquisition
PC8	Poor management processes supporting the handling of regulatory compliance documents during requirements verification	3.64	0.69	96%	Acquisition
PC17	Lack of interface management processes supporting the handling of different requirement types throughout the Acquisition Phase	3.64	0.69	96%	Acquisition
PC6	AIRs not adequately elicited, specified or documented in Planning Phase	3.7	0.69	96%	Planning
PC1	Poor technical system requirements elicitation, specification and/or documentation processes	3.56	0.64	92%	Planning
PC5	Technical system requirements are not adequately elicited, specified or documented in Planning Phase	3.52	0.7	92%	Planning
PC18	Lack of practical guidelines supporting development and management of different and interdependent requirements processes	3.52	0.85	92%	Planning & Acquisition
PC14	Lack of collaborative requirements management processes during the Planning Phase	3.5	0.76	92%	Planning
PC15	Lack of collaborative requirements management processes during the Acquisition Phase	3.5	0.76	92%	Acquisition
PC12	Poor technical system requirements validation processes	3.6	0.75	88%	Acquisition

As presented in Figure 6.24 and Table 6.14, technology related challenges occur either moving from planning to acquisition or in the acquisition phase. According to the T3B score, there are 2 critical challenges (T3B = 100%), 7 important challenges (90% ≤ T3B ≤ 99%) and 2 moderate challenges (T3B < 90%) relative to the technology supporting requirements management practices. Although the T3B score of "limited interoperability between requirements management software and 3D modelling software" and "lack of interface management software supporting the handling of different requirement types throughout the acquisition phase" is 96%, they have the highest mean scores (mean = 4.12 and 3.88) in technology challenges. Moreover, the only respondent responding "Rarely" had limited experience (1~2 years) in the use of digital model-based methods and tools to support asset information lifecycle management and had no experience in DE/BIM related project management activities. This indicated that these two answers from this respondent might not be able to reflect the real situation in practice because of limited working experience. In this circumstance, these two challenges are recognised as critical challenges.

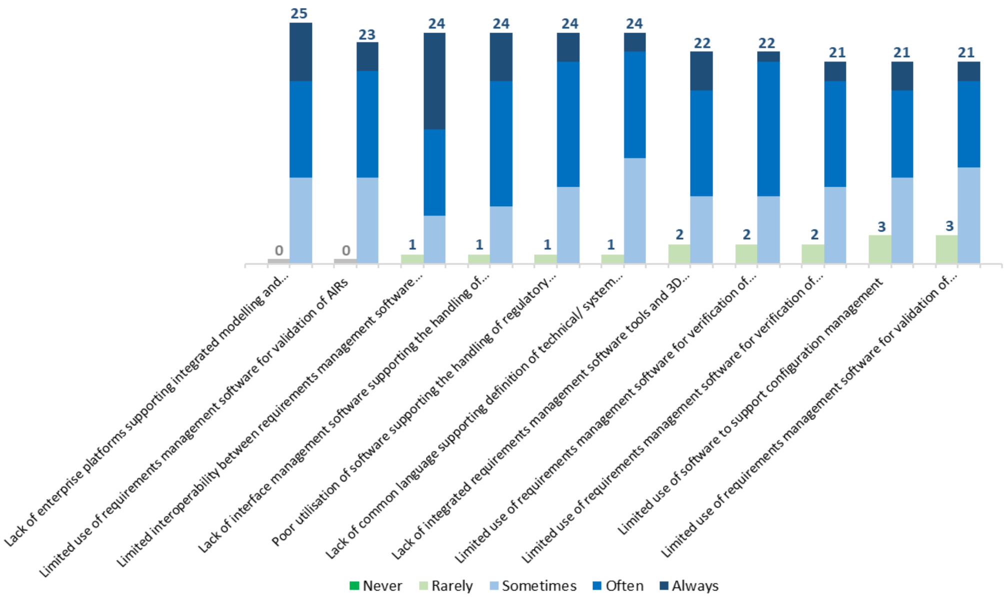

Figure 6.24 Frequency of technology related challenges to requirements management practices

Unlike "limited interoperability between requirements management software and 3D modelling software", "lack of integrated requirements management software tools and 3D modelling software" has a lower frequency of occurrence (T3B = 92%). This indicates that the interoperability across software is more important and practical than having one software which integrates requirements management and 3D modelling. This is also emphasised by survey respondents that instead of using one product integrating 3D modelling tools with MBSE tools, it is more realistic to use comparative data mapping to link system elements in MBSE with 3D model element data attributes via a common data exchange format (see details in Section 6.5.2 v).

Another frequently occurring challenge is the "lack of interface management software supporting the handling of different requirement types throughout the acquisition phase" (T3B = 96%). This is the technology issue supporting interface management across different requirement types mentioned in the process related challenge. In practice, the development of technical systems requirements and AIRs are usually conducted in parallel by two different work streams (Survey – Systems Engineer A, 2022), making the interface management across these requirements critical. However, effective interface management becomes challenging due to the lack of supporting guidelines and technology.

Table 6.14 Ranking of challenges based on frequency of occurrence – Technology

No.	Technology Related Challenges	Mean	SD	T3B	Project Phases
TC8	Lack of enterprise platforms supporting integrated modelling and simulation, enabling digital continuity from concept to development to production	3.88	0.77	100%	Planning & Acquisition
TC5	Limited use of requirements management software for validation of AIRs	3.74	0.67	100%	Acquisition
TC10	Limited interoperability between requirements management software and 3D modelling software	4.12	0.86	96%	Planning & Acquisition
TC7	Lack of interface management software supporting the handling of different requirement types throughout the Acquisition Phase	3.88	0.77	96%	Acquisition
TC2	Poor utilisation of software supporting the handling of regulatory compliance documents during requirements verification	3.72	0.72	96%	Acquisition
TC1	Lack of common language supporting definition of technical system requirements and AIRs	3.56	0.7	96%	Planning & Acquisition
TC9	Lack of integrated requirements management software tools and 3D modelling software	3.71	0.84	92%	Planning & Acquisition
TC3	Limited use of requirements management software for verification of technical system requirements	3.58	0.7	92%	Acquisition
TC4	Limited use of requirements management software for verification of AIRs	3.57	0.77	91%	Acquisition
TC11	Limited use of software to support configuration management	3.5	0.87	88%	Acquisition
TC5	Limited use of requirements management software for validation of technical system requirements	3.42	0.81	88%	Acquisition

As presented in Figure 6.25 and Table 6.15, 13 out of 18 people related challenges occur from planning and continue in the acquisition phase. According to the T3B score, there are 6 critical challenges (T3B = 100%), 5 important challenges (90% ≤ T3B ≤ 99%) and 7 moderate challenges (T3B < 90%) relative to the people and culture supporting requirements management practices. Although the T3B score of "lack of understanding and support from senior management in handling AIRs" is 96%, they have a relatively high mean score (mean = 3.83) in people and culture challenges. Moreover, the respondent responding “Rarely” for this challenge is a digital twin provider in the building and health sector where the development and management of AIRs is more mature than in the rail sector. In this circumstance, this challenge is categorised as a critical challenge. Of 7 critical challenges, 5 occurred in the planning phase and 4 of them continued in the acquisition phase. The rest of the critical challenges occurred in the acquisition phase. Of the 7 critical challenges, 4 of them are specifically related to AIRs.

“Poor collaboration and lines of communication between project team members handling different requirement types” (T3B = 100%) is related to interface management across different requirement types mentioned in both process and technology categories. “Lack of a clear description of roles and responsibilities supporting AIRs development and management” (T3B = 100%) is identified as a critical challenge while “lack of a clear description of roles and responsibilities supporting technical system requirements development and management” (T3B = 88%) is a moderate challenge. This is consistent with the findings of maturity levels of “formally defined roles and responsibilities” for AIRs and technical system requirements in Section 6.4.3 where technical system requirements are more mature than AIRs.

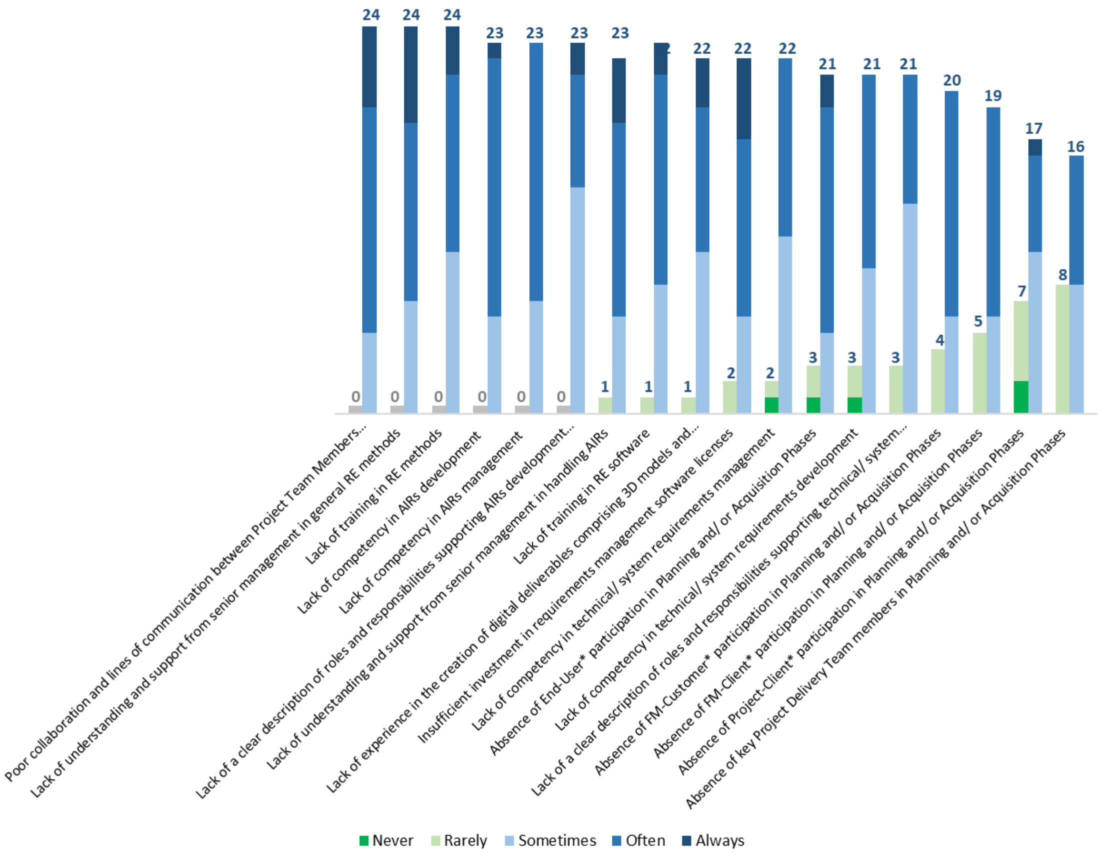

Figure 6.25 Frequency of people related challenges to requirements management practices

Table 6.15 Ranking of challenges based on frequency of occurrence – People

No.	People Related Challenges	Mean	SD	T3B	Project Phases
PCC18	Poor collaboration and lines of communication between Project Team Members handling different requirement types	4	0.65	100%	Planning & Acquisition
PCC8	Lack of understanding and support from senior management in general requirements management methods	3.96	0.73	100%	Planning & Acquisition
PCC15	Lack of training in requirements management methods	3.71	0.68	100%	Planning & Acquisition
PCC11	Lack of competency in AIRs development	3.78	0.51	100%	Planning
PCC13	Lack of competency in AIRs management	3.7	0.46	100%	Acquisition
PCC7	Lack of a clear description of roles and responsibilities supporting AIRs development and management	3.48	0.65	100%	Planning & Acquisition
PCC9	Lack of understanding and support from senior management in handling AIRs	3.83	0.76	96%	Planning & Acquisition
PCC16	Lack of training in requirements management software	3.67	0.69	96%	Planning & Acquisition
PCC14	Lack of competency in the creation of digital deliverables comprising 3D models and supporting databases	3.61	0.77	96%	Acquisition
PCC17	Insufficient investment in requirements management software licenses	3.79	0.87	92%	Planning & Acquisition
PCC12	Lack of competency in technical system requirements management	3.33	0.75	92%	Acquisition
PCC5	Absence of End-User participation in Planning and/or Acquisition Phases	3.58	0.91	88%	Planning & Acquisition
PCC10	Lack of competency in technical system requirements development	3.33	0.8	88%	Planning
PCC6	Lack of a clear description of roles and responsibilities supporting technical system requirements development and management	3.21	0.64	88%	Planning & Acquisition
PCC4	Absence of FM-Customer participation in Planning and/or Acquisition Phases	3.42	0.76	83%	Planning & Acquisition
PCC3	Absence of FM-Client participation in Planning and/or Acquisition Phases	3.33	0.8	79%	Planning & Acquisition
PCC1	Absence of Project-Client participation in Planning and/or Acquisition Phases	2.96	0.98	71%	Planning & Acquisition
PCC2	Absence of key Project Delivery Team members in Planning and/or Acquisition Phases	3	0.82	67%	Planning & Acquisition

6.5.2 Significant Challenges Highlighted by Respondents

This section highlights six challenges that are emphasised by survey respondents in the comments: i) poor implementation of requirements management process supporting system requirements; ii) a lack of system functional analysis and review process; iii) a lack of traceability between original business requirements to systems requirements; iv) AIRs are not prioritised due to time pressure and financial drivers; v) disconnect between DE authoring tools and requirements management tools; and vi) resistance to change due to the fragmented nature of the industry.

i. Poor implementation of requirements management process supporting system requirements

As mentioned by an experienced systems engineer in the rail sector, there are common processes standards existing in the industry (e.g., INCOSE standards). However, these process standards are loosely adopted in projects resulting in different requirements writing styles in each project. One participant (Survey – Digital Engineer A, 2022) also mentioned that “the processes are good, but the implementation is often poor”.

Another participant (Survey – Systems Engineer A, 2022) said: “In infrastructure and transport industries, requirements elicitation and development, including semantics and writing styles are often inconsistent. Due to the time constraints on procurement and delivery of projects (often driven by political timeframes), engineers often follow generic styles of writing requirements inspired from previous projects, and struggle to keep hierarchy of requirements clear (mixing of functional and physical requirements specifications).”

ii. A lack of system functional analysis and review process

In the survey, several participants mentioned that in most projects, the project team goes straight from business requirements to system design rather than doing operational and functional analysis and review. Usually, design solutions come out before system requirements have been specified. In this design-led circumstance, systems engineers have to derive requirements from the design. “As a result, the requirements set is not always coordinated and is written in discipline silos” (Survey – Systems Engineer B, 2022).

iii. A lack of traceability between business requirements and systems requirements

The traceability amongst different levels of requirements was mentioned in the survey as one of the most commonly occurring challenges (Survey – Systems Engineer C, 2022). This challenge was also mentioned frequently in previous interviews. Although there are software tools, such as IBM DOORs and dRofus, developed to support the effective traceability of requirements, the processes are still manually controlled by systems engineers in most projects.

Moreover, the knock-on effect of poor traceability management is reflected as poor assurance reporting (Survey – Systems Engineer D, 2022).

To support a more automatic way for requirements traceability throughout the lifecycle of the asset, an integration of MBSE and the DE approach has been raised in multiple domains (Pavalkis, 2016; Roodt et al., 2020a; Shirvani et al., 2020). There is also a prior project on digital systems in Transport for NSW aimed at solving this traceability problem by adopting the MBSE approach (Roodt et al., 2020a).

iv. AIRs are not prioritised due to time pressure and financial drivers

In practice, each party of stakeholders (e.g., designers or contractors) of complex infrastructure is always under time or financial pressure to meet their physical deliverables (e.g., drawings, schedules, reports or constructing the asset). When these pressures are too much, typically the asset information and the gradual development of this information is the first thing to be reduced in priority (Survey – DE Advisor A, 2022). In most cases, the value of data is poorly understood (Survey – Digital Engineer A, 2022).

v. Disconnect between 3D model authoring tools and requirements management tools

According to survey participants, information and quality management is poor throughout the construction sector. “There is a massive disconnect between the DE/BIM authoring tools and requirement management tools. Some tools such as dRofus (a buildings focused tool) are good at this but there is low capability in industry to use these types of tools. There is a real need to improve data management capabilities, rather than using BIM as a quicker CAD platform to produce faster drawings” (Survey – DE Advisor A, 2022). “Considering there is a difference between 3D models and models in MBSE, the approaches to ‘modelling’ and tool usage are usually independent from each other” (Survey – Systems Engineer A, 2022). “There are no real COTS products to integrate 3D modelling tools with MBSE tools (which include requirements management). This is usually done via comparative data mapping, linking system elements in MBSE with 3D model element data attributes via a common data exchange format. In the fixed infrastructure sector, the use of 3D models is often for information less for analytical modelling or parametric modelling via simulation whereas simulation of models is found in MBSE principles, and COTS products are more readily available” (Survey – Systems Engineer A, 2022). Some participants pointed out the causes of these situations: there is no selling of benefits of 3D models to asset management (Survey – Digital Engineer B, 2022); there is a lack of ability to correlate MBSE to 3D models (Survey – Systems Engineer C, 2022); and this approach is seldom funded since it is not mandated across industry or government projects, resulting in a piecemeal approach (Survey – Systems Engineer D, 2022).

vi. Resistance to technical system requirements and AIRs development and management processes

There is a higher maturity for the development of technical system requirements than for AIRs. However, there is a lower level of maturity for the management of both technical system requirements and AIRs. Because of the fragmented nature of the supply chain in the industry, "people tended to only be concerned about their part of responsibility in a project and not how change they make can improve the broader project" (Survey – DE Advisor B, 2022). Moreover, "performance and contracts are measured in silos leading to no incentive to work more collaboratively" (Survey – DE Advisor B, 2022). Thus, it is important to make sure the technical systems requirements and AIRs are contractual deliverables and each party within the supply chain is aware of the expectation of the client (Survey – DE Advisor A, 2022). There is an opportunity for greater awareness and training in the asset information and register requirements specification across all SE and DE stakeholders. As mentioned in Section 2.3.3, Transport for NSW has released the Asset Information Standard Part 1 as a component of the Transport for NSW DE Framework. This standard centres on the criteria for overseeing asset information to facilitate "the collection, governance and maintenance of accurate, complete and consistent asset information" (Transport for NSW, 2023, p. 7) pertaining to transport assets. It explicitly delineated the connection between AIR, asset register and asset information.

6.6 Relationship Analysis between Challenges and Requirements Management Practice Maturity

This section investigates the relationship between the frequency of challenges (including process and technology related challenges) with the maturity level of corresponding requirements management related practices. For people related challenges, analysis focused on the frequency and the importance of related resources. The scores of challenge frequency (mean value) and scores of requirements management activity maturity (mean value) relative to processes and technology of requirements management practice are both presented in Table 6.16.

Frequency scores of challenges are extracted from Section 6.5.1 while the scores of maturity levels of corresponding requirements management activities are extracted from Sections 6.4.1 and 6.4.2. However, there is no direct data from the survey respondents for "interface management" processes and technology, so the score of maturity level was generated based on interview findings. According to interviewees, there is a lack of interface management across different requirement types in industry, thus maturity scores of 2.5~2.55 were assigned to the relative requirements management practices (as highlighted in red italic font). Similarly, there is a lack of legacy systems and CDE enabling digital continuity from concept to development to production, and there is limited use of software supporting configuration management, thus the maturity scores of these two areas were both assigned as 2.5 (as highlighted in red italic font).

Table 6.16 Relationship analysis between challenges and maturity – Process and Technology

Category	Requirements Management Activity Type	No.	Challenges	Frequency	Maturity
Process	Requirements Elicitation	PC1	Poor **technical system requirements** elicitation, specification and/or documentation processes	3.56	3.33
	Requirements Elicitation	PC2	Poor **AIRs** elicitation, specification and/or documentation processes	3.70	3.00
	Requirements Elicitation	PC3	Disconnects between **system architecture requirements** (including network requirements) and **technical system requirements**	3.92	3.33
	Requirements Elicitation	PC4	Disconnects between **system architecture requirements** (including network requirements) and **AIRs**	4.04	3.00
	Requirements Elicitation	PC5	**Technical system requirements** not adequately elicited, specified or documented in Planning Phase	3.52	3.33
	Requirements Elicitation	PC6	**AIRs** not adequately elicited, specified or documented in Planning Phase	3.70	3.00
	Requirements Verification	PC7	Poor **requirements verification and traceability** processes during Acquisition Phase	3.88	3.11
	Requirements Verification	PC8	Poor **management processes** supporting the handling of regulatory compliance documents during **requirements verification**	3.61	3.11
	Requirements Change Management	PC9	Disconnects between **design change management** and **AIRs traceability**	3.87	2.71
	Requirements Change Management	PC10	Disconnects between **requirements management processes** and **design change management** processes	3.76	3.13
	Requirements Change Management	PC11	Poor **AIRs change management**	3.96	2.71
	Requirements Validation	PC12	Poor **technical system requirements** validation processes	3.60	3.10
	Requirements Validation	PC13	Poor **AIRs** validation processes	3.87	3.00
	Collaboration across disciplines	PC14	Lack of collaborative **requirements management processes** during the **Planning Phase**	3.50	*2.55*
	Collaboration across disciplines	PC15	Lack of collaborative **requirements management processes** during the **Acquisition Phase**	3.50	*2.50*
	Interface Management	PC16	Poor **interface management** across requirement types	3.96	*2.50*
	Interface Management	PC17	Lack of **interface management processes** supporting the handling of different requirement types throughout the **Acquisition Phase**	3.64	*2.50*
	Guideline and Standards	PC18	Lack of **practical guidelines** supporting development and management of different and interdependent requirements processes	3.52	3.25

Category	Requirements Management Activity Type	No.	Challenges	Frequency	Maturity
Technology	Requirements Elicitation	TC1	Lack of common language supporting definition of **physical system requirements** and **AIRs**	3.56	3.25
	Requirements Verification	TC2	Poor **utilisation of software** supporting the handling of regulatory compliance documents during **requirements verification**	3.72	3.22
	Requirements Verification	TC3	Limited use of requirements management software for **verification of physical system requirements**	3.58	3.33
	Requirements Verification	TC4	Limited use of requirements management software for **verification of AIRs**	3.57	3.10
	Requirements Validation	TC5	Limited use of requirements management software for **validation of physical system requirements**	3.42	3.21
	Requirements Validation	TC6	Limited use of requirements management software for **validation of AIRs**	3.74	3.05
	Interface Management	TC7	Lack of **interface management software** supporting the handling of different requirement types throughout the Acquisition Phase	3.88	*2.55*
	Legacy systems and CDE	TC8	Lack of **enterprise platforms** supporting integrated modelling and simulation, enabling digital continuity from concept to development to production	3.88	*2.50*
	Technology Integration	TC9	Lack of **integrated** requirements management software tools and 3D modelling software	3.71	2.70
	Technology Integration	TC10	Limited **interoperability** between requirements management software and 3D modelling software	4.12	2.70
	Configuration Management	TC11	Limited use of software to support **configuration management**	3.50	*2.50*
Note: the scores highlighted in red italic font came from the interviews.					

A priority matrix graph (Figure 6.26) was then developed according to these scores. In Figure 6.26, the X-axis represents the occurrence frequency of challenges relative to requirements management processes and technologies, while the Y-axis represents the maturity levels of relevant requirements management practices. Further examining these challenges in Figure 6.26, two areas are identified: i) challenges with frequency score ≥ 3.5 and maturity score ≤ 3.0, categorised as a **deficiency**; ii) challenges with frequency score < 4.0 and maturity score ≥3.0, categorised as an **inefficiency**. **Deficiency challenges** refer to challenges that occurred frequently and there are no established formal processes or dedicated software used to support relevant requirements management practices. **Inefficiency challenges** refer to challenges that occurred frequently where there are established formal processes or dedicated software used to support relevant requirements management practices, indicating there is inefficiency in existing processes or technologies. There are 9 process related and 4 technology related deficiency challenges, and 8 process related and 6 technology related inefficiency challenges.

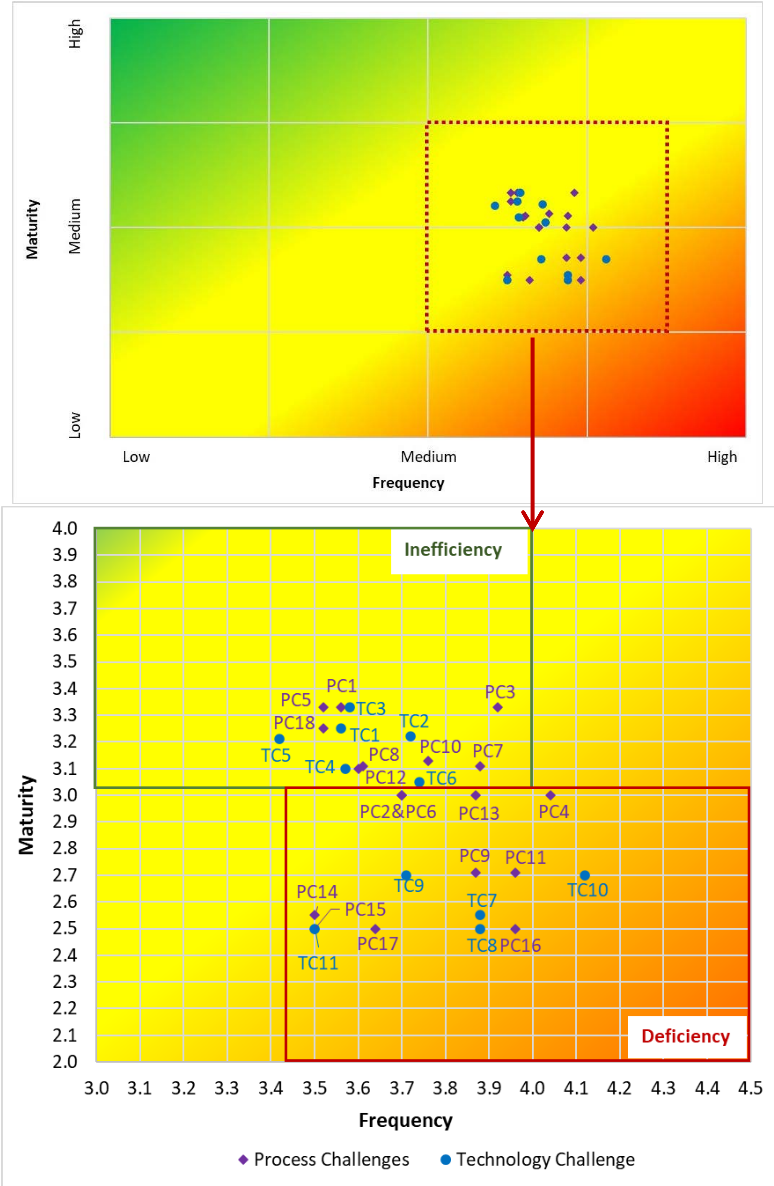

Figure 6.26 Priority matrix for challenges related to requirements management process and technology

As shown in Table 6.17, all AIRs related process challenges (i.e., PC2, PC4, PC6, PC9, PC11, PC13) are categorised as deficiency challenges (in red shade) while technical system requirements and general requirements management related process challenges (i.e., PC1, PC3, PC5, PC7, PC8, PC10, PC12, PC18) are inefficiency challenges (in green shade). Interface management related challenges are also identified as deficiency challenges. For technology related challenges, deficiency challenges include the interoperability amongst multiple software (TC9 and TC10), integrated platform (TC8) and interface management supporting software (TC7) while inefficiency challenges include silo implementation of supporting software (TC2–TC5). This result indicates that the technology supporting AIRs elicitation, verification and validation is ready, while the processes for AIRs development and management are lacking. Major gaps remain in the interface management among different requirement types, and technology integration supporting interoperability of multiple software tools.

Table 6.17 Significance of challenges – Process and Technology

Category	Requirements Management Activity type	No.	Challenges	Project Phase	Priority
Process	Requirements Elicitation	PC1	Poor **technical system requirements** elicitation, specification and/or documentation processes	Planning	Inefficiency
	Requirements Elicitation	PC2	Poor **AIRs** elicitation, specification and/or documentation processes	Acquisition	Deficiency
	Requirements Elicitation	PC3	Disconnects between **system architecture requirements** (including network requirements) and **technical system requirements**	Planning & Acquisition	Inefficiency
	Requirements Elicitation	PC4	Disconnects between **system architecture requirements** (including network requirements) and **AIRs**	Acquisition	Deficiency
	Requirements Elicitation	PC5	**Technical system requirements** not adequately elicited, specified or documented in Planning Phase	Planning	Inefficiency
	Requirements Elicitation	PC6	**AIRs** not adequately elicited, specified or documented in Planning Phase	Planning	Deficiency
	Requirements Verification	PC7	Poor **requirements verification and traceability** processes during Acquisition Phase	Acquisition	Inefficiency
	Requirements Verification	PC8	Poor **management processes** supporting the handling of regulatory compliance documents during **requirements verification**	Acquisition	Inefficiency
	Requirements Change Management	PC9	Disconnects between **design change management** and **AIRs traceability**	Acquisition	Deficiency
	Requirements Change Management	PC10	Disconnects between **requirements management processes** and **design change management** processes	Planning & Acquisition	Inefficiency
	Requirements Change Management	PC11	Poor **AIRs change management**	Acquisition	Deficiency
	Requirements Validation	PC12	Poor **technical system requirements** validation processes	Acquisition	Inefficiency
	Requirements Validation	PC13	Poor **AIRs** validation processes	Acquisition	Deficiency
	Collaboration across disciplines	PC14	Lack of collaborative **requirements management processes** during the **Planning Phase**	Planning	Deficiency
	Collaboration across disciplines	PC15	Lack of collaborative **requirements management processes** during the **Acquisition Phase**	Acquisition	Deficiency
	Interface Management	PC16	Poor **interface management** across requirement types	Planning & Acquisition	Deficiency
	Interface Management	PC17	Lack of **interface management processes** supporting the handling of different requirement types throughout the Acquisition Phase	Acquisition	Deficiency
	Guideline and Standards	PC18	Lack of **practical guidelines** supporting development and management of different and interdependent requirements processes	Planning & Acquisition	Inefficiency

Category	Requirements Management Activity type	No.	Challenges	Project Phase	Priority
Technology	Requirements Elicitation	TC1	Lack of common language supporting definition of **technical system requirements** and **AIRs**	Planning & Acquisition	Inefficiency
	Requirements Verification	TC2	Poor **utilisation of software** supporting the handling of regulatory compliance documents during **requirements verification**	Acquisition	Inefficiency
	Requirements Verification	TC3	Limited use of requirements management software for **verification of physical system requirements**	Acquisition	Inefficiency
	Requirements Verification	TC4	Limited use of requirements management software for **verification of AIRs**	Acquisition	Inefficiency
	Requirements Validation	TC5	Limited use of requirements management software for **validation of physical system requirements**	Acquisition	Inefficiency
	Requirements Validation	TC6	Limited use of requirements management software for **validation of AIRs**	Acquisition	Inefficiency
	Interface Management	TC7	Lack of **interface management software** supporting the handling of different requirement types throughout the Acquisition Phase	Acquisition	Deficiency
	Legacy systems and CDE	TC8	Lack of **enterprise platforms** supporting integrated modelling and simulation, enabling digital continuity from concept to development to production	Planning & Acquisition	Deficiency
	Technology Integration	TC9	Lack of **integrated** requirements management software tools and 3D modelling software	Planning & Acquisition	Deficiency
	Technology Integration	TC10	Limited **interoperability** between requirements management software and 3D modelling software	Planning & Acquisition	Deficiency
	Configuration Management	TC11	Limited use of software to support **configuration management**	Acquisition	Deficiency

Note:
Rows in green shade refer to Inefficiency challenges.
Rows in red shade refer to Deficiency challenges.

In the people related challenges, frequency of challenges and the importance of related resources are used as the X-axis and Y-axis attributes of the priority matrix. The scores of challenge frequency (mean value) and scores of resources importance (mean value) are both presented in Table 6.18. Frequency scores of challenges are extracted from Section 6.5.1 while the scores of resource importance are extracted from Section 6.4.3. However, because there is no direct data from the survey respondents for “stakeholder involvement”, “internal skills to delivery” or “collaboration across disciplines”, the importance score was generated based on open questions responses and interview findings.

According to an industry expert with more than 10 years' experience as digital strategist in a variety of sectors in Australia and overseas, the project client role should be "an internal resource supported by external consultant if it is a new process for them" to work on aligning the OIRs with AIRs to "ensure the scope of work is clear to the delivery-side stakeholders" (Survey – DE Advisor C, 2022). For the key project delivery team, it is important for them to "understand the uses of the information along with the information needs" (Survey – DE Advisor C, 2022) to better support the delivery of required datasets. The FM client role, or FM service provider, is "normally great at understanding the physical needs but are immature in the information requirements space" (Survey – DE Advisor C, 2022). "Many of them are charging extra to embed or manage the data requirements from their maintenance activities as they have not setup their systems to automate this process", thus it is important for them to be "heavily involved in procurement management to ensure costs aren't exacerbated by the slight change in information scope" (Survey – DE Advisor C, 2022). The FM customer role should be "built on absolute confidence in understanding how an asset is maintained" and should be involved in delivering OIRs which set "the performance needs and the AIRs" to help "establish the tiers of information requirements needed for things like maintenance contracts" (Survey – DE Advisor C, 2022). As the ones using digital delivery to benefit their asset performance, the end user is identified as the "glue to make digital delivery work" (Survey – DE Advisor C, 2022). However, a survey respondent who has 6~10 years' experience in DE in the transport infrastructure sector mentioned that if the "asset owner/maintainer define their asset information standards and assurance processes well, there should be limited need for them to be involved" (Survey – DE Advisor C, 2022) in requirements management related activities. Thus, importance scores of 3.6~3.8 were assigned to the involvement of different types of stakeholders (as highlighted in red italic font).

"Internal skills to delivery" include competency in requirements development and management as well as digital delivery. It is related to training in requirements management methods. Thus, importance scores of 4~4.1 were assigned to the competency related resources (as highlighted in red italic font). "Collaboration across disciplines" is identified as a very important area for requirements management practices as it is related to interface management. Thus, an importance score of 4.5 was assigned to the collaboration and communication between project team (as highlighted in red italic font).

Table 6.18 Relationship analysis between people related challenges and importance of resources

Category	Requirements Management Activity type	No.	Challenges	Frequency	Importance
People	Stakeholder Involvement	PCC1	Absence of **Project Client participation** in Planning and/or Acquisition Phases	2.96	3.8
	Stakeholder Involvement	PCC2	Absence of **key Project Delivery Team members** in Planning and/or Acquisition Phases	3.00	3.6
	Stakeholder Involvement	PCC3	Absence of **FM Client participation** in Planning and/or Acquisition Phases	3.33	3.8
	Stakeholder Involvement	PCC4	Absence of **FM Customer participation** in Planning and/or Acquisition Phases	3.42	3.8
	Stakeholder Involvement	PCC5	Absence of **End User participation** in Planning and/or Acquisition Phases	3.58	3.6
	Roles/Responsibilities	PCC6	Lack of a clear description of roles and responsibilities supporting **technical system requirements** development and management	3.21	4.35
	Roles/Responsibilities	PCC7	Lack of a clear description of roles and responsibilities supporting **AIRs** development and management	3.48	4.28
	Senior Management Support	PCC8	Lack of understanding and support from senior management in general requirements management methods	3.96	4.62
	Senior Management Support	PCC9	Lack of understanding and support from senior management in handling **AIRs**	3.83	4.56
	Internal skills to deliver	PCC10	Lack of competency in **technical system requirements development** (specification, documentation, allocation etc.)	3.33	4
	Internal skills to deliver	PCC11	Lack of competency in **AIRs development** (specification, documentation, allocation etc.)	3.78	4
	Internal skills to deliver	PCC12	Lack of competency in **technical system requirements management** (change management, verification and traceability, and validation)	3.33	4.1
	Internal skills to deliver	PCC13	Lack of competency in **AIRs management** (change management, verification and traceability, and validation)	3.70	4.1
	Internal skills to deliver	PCC14	Lack of competency in the creation of digital deliverables comprising 3D models and supporting databases	3.61	4
	Capability/Training	PCC15	Lack of training in **requirements management** methods	3.71	4.19
	Capability/Training	PCC16	Lack of training in **requirements management** software	3.67	3.50
	Funding	PCC17	Insufficient investment in requirements management software licenses	3.79	4.08
	Collaboration across disciplines	PCC18	Poor collaboration and lines of communication between Project Delivery Team members handling different requirement types	4.00	4.5

A priority matrix graph (Figure 6.27) was then developed according to these scores. In Figure 6.27, the X-axis represents the occurrence frequency of challenges related to people in requirements management practices, while the Y-axis represents the importance of relevant resources. Take a further deep look into these challenges in Figure 6.27, two areas are identified: i) challenges with frequency score ≥ 3.4 and importance score ≥ 4.0 are categorised as **emergency**; and ii) challenges with importance score < 4, or challenges with frequency score < 3.4 are categorised as **buffer**. **Emergency challenges** refer to challenges that occurred frequently and their corresponding resources are very important. **Buffer challenges** refer to challenges that occurred less frequently or their corresponding resources are moderately important. Therefore, there are 9 emergency challenges and 9 buffer challenges related to people.

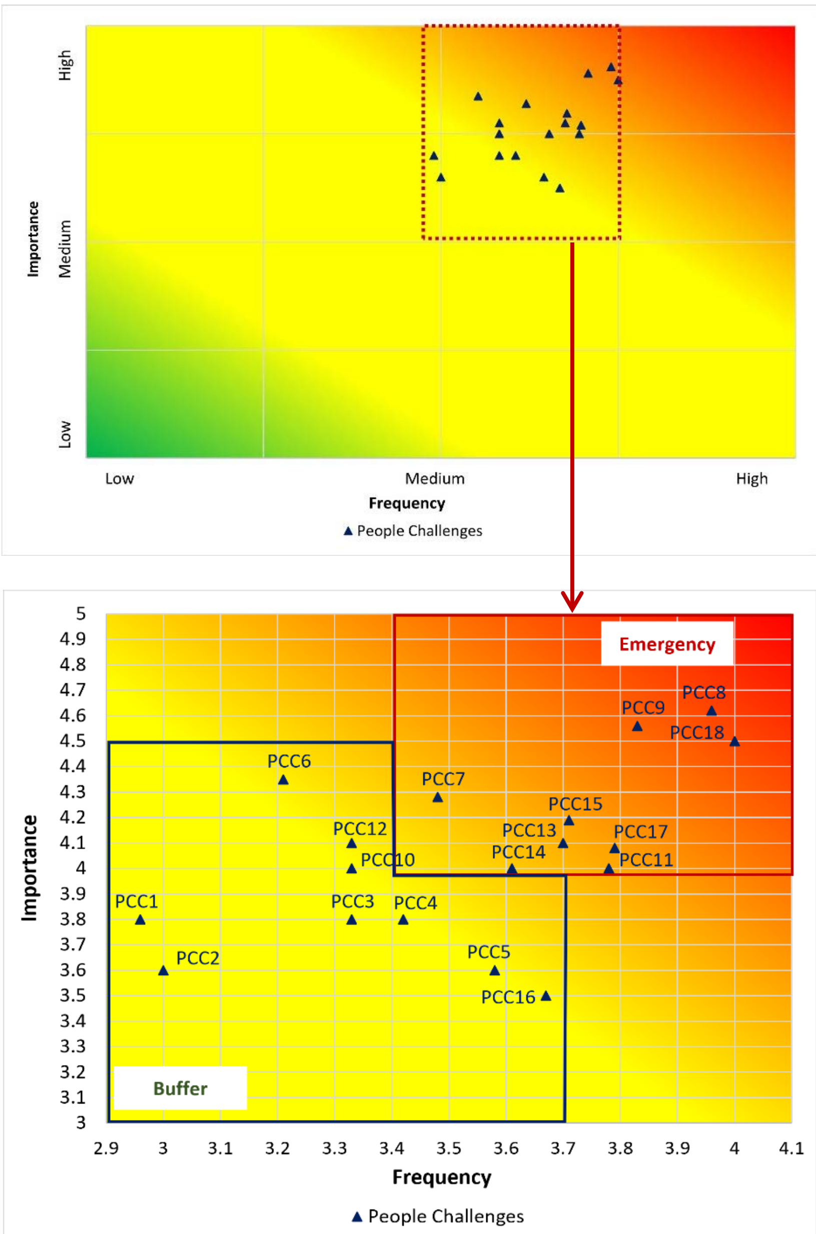

Figure 6.27 Priority matrix for challenges related to people in requirements management

As shown in Table 6.19, all AIRs related people challenges (i.e., PCC7, PCC9, PCC11, PCC13) are categorised into emergency challenges (in red shade) while physical system requirements related people challenges (i.e., PCC6, PCC10, PCC12) are buffer challenges (in green shade). Except for AIR related challenges, emergency challenges also include senior management's understanding and support for general requirements management methods (PCC8), competency in DE (PCC14), training in requirements management methods (PCC15), investment in requirements management software (PCC17) and collaboration across disciplines (PCC18). However, all stakeholders' involvement (PCC1–PCC5) and training in requirements management software (PCC16) are also identified as buffer challenges.

Table 6.19 Significance of people related challenges

Category	Requirements Management Activity type	No.	Challenges	Project Phase	Priority
People	Stakeholder Involvement	PCC1	Absence of **Project Client participation** in Planning and/or Acquisition Phases	Planning & Acquisition	Buffer
	Stakeholder Involvement	PCC2	Absence of **key Project Delivery Team members** in Planning and/or Acquisition Phases	Planning & Acquisition	Buffer
	Stakeholder Involvement	PCC3	Absence of **FM Client participation** in Planning and/or Acquisition Phases	Planning & Acquisition	Buffer
	Stakeholder Involvement	PCC4	Absence of **FM Customer participation** in Planning and/or Acquisition Phases	Planning & Acquisition	Buffer
	Stakeholder Involvement	PCC5	Absence of **End User participation** in Planning and/or Acquisition Phases	Planning & Acquisition	Buffer
	Roles/Responsibilities	PCC6	Lack of a clear description of roles and responsibilities supporting **technical system requirements** development and management	Planning & Acquisition	Buffer
	Roles/Responsibilities	PCC7	Lack of a clear description of roles and responsibilities supporting **AIRs** development and management	Planning & Acquisition	Emergency
	Senior Management Support	PCC8	Lack of understanding and support from senior management in general requirements management methods	Planning & Acquisition	Emergency
	Senior Management Support	PCC9	Lack of understanding and support from senior management in handling **AIRs**	Planning & Acquisition	Emergency
	Internal skills to deliver	PCC10	Lack of competency in **technical system requirements development** (specification, documentation, allocation etc.)	Planning	Buffer
	Internal skills to deliver	PCC11	Lack of competency in **AIRs development** (specification, documentation, allocation etc.)	Planning	Emergency
	Internal skills to deliver	PCC12	Lack of competency in **technical system requirements management** (change management, verification and traceability, and validation)	Acquisition	Buffer

Category	Requirements Management Activity type	No.	Challenges	Project Phase	Priority
	Internal skills to deliver	PCC13	Lack of competency in **AIRs management** (change management, verification and traceability, and validation)	Acquisition	Emergency
	Internal skills to deliver	PCC14	Lack of competency in the creation of digital deliverables comprising 3D models and supporting databases	Acquisition	Emergency
	Capability/Training	PCC15	Lack of training in **requirements management** methods	Planning & Acquisition	Emergency
	Capability/Training	PCC16	Lack of training in **requirements management** software	Planning & Acquisition	Buffer
	Funding	PCC17	Insufficient investment in requirements management software licenses	Planning & Acquisition	Emergency
	Collaboration across disciplines	PCC18	Poor collaboration and lines of communication between Project Delivery Team members handling different requirement types	Planning & Acquisition	Emergency
Note: Rows in green shade refer to Buffer challenges. Rows in red shade refer to Emergency challenges.					

6.7 Summary

This chapter investigated research questions Q2-4 to Q2-6 via an online survey, focusing on identifying i) the current status of requirements management and digital engineering related standard implementation, ii) the maturity levels of requirements management capabilities, and iii) the most significant challenges of requirements management practices in complex infrastructure sectors.

This chapter first described the structure and content of the online survey, which had three main parts: participant background information, current maturity status of requirements development and management practices, and prioritisation of challenges identified in the literature review (Chapter 4) and semi-structured interviews (Chapter 5). Two distinct professional disciplines were identified in this survey: systems engineering roles (responsible for systems requirements management activities) and digital engineering roles (responsible for information requirements management activities).

Responding to *Q2-4: What is the prevalence of use of digital engineering process standards and data standards in Australia?,* this chapter then investigated the application of and participation in international standards and other Australian state-based standards supporting the digital engineering process and data exchange in complex infrastructure projects (Section 6.3). Findings reflect variety in understanding and implementation of international standards as well as other related standards across different types of organisations. Government state-based standards are more commonly used and recognised than international standards. The findings reflected a low level of maturity in implementation of digital engineering in the operation and maintenance phase as well as asset information lifecycle management in the Australian infrastructure sector.

Responding to *Q2-5: What are the current maturity levels of requirements management practices in complex infrastructure industry (processes, technologies, people)?*, Section 6.4 investigated the status of requirements management practices and maturity levels in the delivery of complex infrastructure projects in Australia relative to three characteristics: process, technology, and people and culture. Findings reflect higher maturity levels of technical systems requirements than new information requirements management practices, particularly for asset information requirements. The section analysed two discipline-specific perspectives, from systems engineering and digital engineering roles, identifying the challenges related to the lack of knowledge and experience in managing system and information requirements concurrently and linking verification and validation workflows across requirement types to provide greater levels of assurance for digital deliverables. Key systems engineering and digital engineering roles involving systems design review and design coordination would benefit from increasing levels of process and technology integration, highlighting the need for mutual systems engineering and digital engineering responsibilities. The section also identified critical requirements management resources needed to increase the effectiveness and efficiency of integrated requirements management practices, including support from senior management, clearly defined roles and responsibilities for requirements management, and clear appointing party standards and terms of contract covering requirements management application.

In answer to *Q2-6: Of the challenges identified in the management of system requirements and information requirements, how significant are they and how should they be prioritised?*, Section 6.5 investigated the significance of challenges via the frequencies of occurrence of challenges and the emphasis from survey participants in the comments. Parameters including mean, standard deviation and Top 3 Box of survey responses were analysed and compared. As a result, 47 challenges were categorised into 16 critical challenges, 21 important challenges and 10 moderate challenges based on their Top 3 Box and mean scores. Of the 16 critical challenges, 14 are related to AIRs management activities, emphasising that the maturity levels of capabilities supporting technical system requirements management are higher than those of information requirements management. Further analysis was undertaken to categorise challenges based on their frequency of occurrence and the maturity levels of relevant requirements management activities (for process and technology challenges) or the importance of related resources (for people challenges). As a result, 13 deficiency challenges and 14 inefficiency challenges were identified for process and technology related challenges, and 9 emergency challenges and 9 buffer challenges related to people. The finding also highlighted that the capabilities (process, technology and people and culture) supporting interface management across different requirement types are poor in practices. Other than challenges listed in the survey, participants highlighted six critical challenges in practices: i) poor implementation of requirements management process supporting technical system requirements; ii) a lack of system functional analysis and review process; iii) a lack of traceability between original business requirements to systems requirements; iv) AIRs are not prioritised due to time pressure and financial drivers; v) disconnect between 3D model authoring tools and requirements management tools; and vi) resistance to technical system requirements and AIRs development and management processes. Table 6.20 reflects the final list of 22 challenges (13 deficiency challenges and 9 emergency challenges) that were identified as the highest priority.

Table 6.20 Highest priority challenges to requirements management practices

Category	Requirements Management Activity type	No.	Challenges	Project Phase	Priority
Process	Requirements Elicitation	PC2	Poor **AIRs** elicitation, specification and/or documentation processes	Acquisition	Deficiency
	Requirements Elicitation	PC4	Disconnects between **system architecture requirements** (including network requirements) and **AIRs**	Acquisition	Deficiency
	Requirements Elicitation	PC6	**AIRs** not adequately elicited, specified or documented in Planning Phase	Planning	Deficiency
	Requirements Change Management	PC9	Disconnects between **design change management** and **AIRs traceability**	Acquisition	Deficiency
	Requirements Change Management	PC11	Poor **AIRs change management**	Acquisition	Deficiency
	Requirements Validation	PC13	Poor **AIRs** validation processes	Acquisition	Deficiency
	Interface Management	PC14	Lack of collaborative **requirements management processes** during the **Planning Phase**	Planning	Deficiency
	Interface Management	PC15	Lack of collaborative **requirements management processes** during the **Acquisition Phase**	Acquisition	Deficiency
	Interface Management	PC16	Poor **interface management** across requirement types	Planning & Acquisition	Deficiency
	Interface Management	PC17	Lack of **interface management processes** supporting the handling of different requirement types throughout the Acquisition Phase	Acquisition	Deficiency
Technology	Interface Management	TC7	Lack of **interface management software** supporting the handling of different requirement types throughout the Acquisition Phase	Acquisition	Deficiency
	Legacy systems and CDE	TC8	Lack of **enterprise platforms** supporting integrated modelling and simulation, enabling digital continuity from concept to development to production	Planning & Acquisition	Deficiency

Category	Requirements Management Activity type	No.	Challenges	Project Phase	Priority
	Technology Integration	TC9	Lack of **integrated** requirements management software tools and 3D modelling software	Planning & Acquisition	Deficiency
	Technology Integration	TC10	Limited **interoperability** between requirements management software and 3D modelling software	Planning & Acquisition	Deficiency
	Configuration Management	TC11	Limited use of software to support **configuration management**	Acquisition	Deficiency
People	Roles/Responsibilities	PCC7	Lack of a clear description of roles and responsibilities supporting **AIRs** development and management	Planning & Acquisition	Emergency
	Senior Management Support	PCC8	Lack of understanding and support from senior management in general requirements management methods	Planning & Acquisition	Emergency
	Senior Management Support	PCC9	Lack of understanding and support from senior management in handling **AIRs**	Planning & Acquisition	Emergency
	Internal skills to deliver	PCC11	Lack of competency in **AIRs development** (specification, documentation, allocation etc.)	Planning	Emergency
	Internal skills to deliver	PCC13	Lack of competency in **AIRs management** (change management, verification and traceability, and validation)	Acquisition	Emergency
	Internal skills to deliver	PCC14	Lack of competency in the creation of digital deliverables comprising 3D models and supporting databases	Acquisition	Emergency
	Capability/Training	PCC15	Lack of training in **requirements management** methods	Planning & Acquisition	Emergency
	Funding	PCC17	Insufficient investment in requirements management software licenses	Planning & Acquisition	Emergency
	Collaboration across disciplines	PCC18	Poor collaboration and lines of communication between Project Delivery Team members handling different requirement types	Planning & Acquisition	Emergency

The next chapter focuses on the development of a capability maturity model supporting information requirements management based on findings from the literature review (Chapter 4), semi-structured interviews (Chapter 5) and online survey (Chapter 6). This maturity model was then revised and validated via feedback sessions with expert panels.

Chapter 7 Developing a Capability Improvement Framework for Information Requirements Management

This chapter addresses research question 3, which focuses on the development and validation of a Capability Improvement Framework for information requirements management. The three main contents of the improvement framework are a description of maturity levels, a checklist of information requirements management related activities, and an instrument for capability assessment. Interviews and workshops with industry experts were used to assess the key aspects of the framework in terms of clarity of maturity levels, comprehensiveness of information requirements management activities, and appropriateness of activity categorisation.

7.1 Overview of the Capability Improvement Framework

The research findings show the inherent complexity in managing information requirements across project delivery partners in an integrated process that supports traceability and change management processes implemented in traditional systems requirements management processes (and supporting software). To support improvement in planning processes, capability improvement frameworks have been shown to provide awareness and roadmaps that can overcome high levels of process complexity. Brinkkemper et al. (2008) outlined two process improvement approaches: capability-based, focusing on enhancing performance by increasing a company's capabilities; and problem-based, addressing underlying problems causing processes to underperform. As mentioned in Section 2.6, the capability-based approach is recommended in the context of complex transport infrastructure. The main clients are government agencies that develop numerous projects simultaneously. Focusing on specific problems encountered by different project teams is not efficient. Instead, improving the organisation's capability to manage requirements will benefit all future projects. The capability-based approach is more suitable for addressing the challenges faced by government agencies in managing complex rail transport projects, as it allows for improvements in overall capability.

In Section 2.5, a conceptual framework of a lifecycle in information requirements management in the infrastructure construction industry was proposed, forming the background foundation and context of this thesis. Then, based on the literature review and interviews conducted in Chapter 4 and Chapter 5, a Diamond model integrating digital engineering with systems engineering was developed in Section 5.2.2. Moreover, challenges to information requirements management were identified and mapped on the Diamond model in Section 5.4.3, highlighting the gaps in current digital and systems engineering supporting effective information requirements management. Based on the challenges identified in both literature and practice, a survey was conducted to further identify the most significant challenges in practice towards information requirements management. This forms the initial list of information requirements management activities in this framework. The structure of this framework was based on the integration of three existing maturity models (Solemon et al., 2012; Sommerville & Sawyer, 1997).

The main objective of the Capability Improvement Framework is to evaluate an organisation's current capability for managing information requirements and pinpoint areas that require improvement during the demand/need, plan and acquire phases in the project lifecycle. This framework has three components: maturity levels, information requirements management related activities, and assessment method.

7.2 Maturity Levels in Capability Improvement Framework

Considering the immaturity of information requirements management in the complex rail transport sector, the four maturity level style in the Requirements Engineering Process Assessment and Improvement Model (REPAIM) was adopted in this research (Solemon et al., 2012). The following paragraphs provide a detailed description of each maturity level.

Level 0: Incomplete. Similar to CMMI-DEV (Software Engineering Institute, 2010) and REPAIM (Solemon et al., 2012), information requirements management maturity at this stage is considered incomplete. At this level, information requirements management activities are either not performed at all or are only partially performed in an informal way (Rana et al., 2015).

Level 1: Performed. Consistent with maturity Level 1 in REPAIM, information requirements management maturity at this level is considered as "performed". At this level, information requirements are elicited, analysed, documented, verified and validated. Additionally, requirements changes are managed, and requirements traceability is maintained (Rana et al., 2015). However, there is no defined information requirements management process in the organisation, leading to poor requirements management, late delivery of products, and budget over-runs (Sommerville & Ransom, 2005). Moreover, information requirements management activities are performed individually in different projects based on the knowledge and preference of project managers.

Level 2: Managed. With a reduction in weakness compared to Level 1, information requirements management maturity at this level is classified as "managed", which is similar to the Requirements Engineering Good Practice Guide (REGPG). At this level, there are explicit standards for information requirements documents and information requirements management related policies and procedure in the organisation. Moreover, information requirements protocols are embedded within the project management protocols. Information requirements management is well-planned, relevant stakeholders are actively involved, the information requirements management activities are supervised and reviewed, and outputs from the information requirements management activities are verified and validated (Rana et al., 2015; Solemon et al., 2012).

Level 3: Integrated. Considering the unique nature of information requirements management, interoperability of data and software is the ultimate goal for information requirements management practice. This stage of information requirements management maturity is described as "integrated". At this level, information requirements management processes are documented, standardised and integrated into a standard process based on best practices. Importantly, a Common Data Dictionary or Master Classification Library is developed in the organisation to support a structured project data classification schema using a common data language. A common data environment is established in the organisation to enable a seamless data flow and data transition across different stakeholders and project phases. At this level, the information requirements management process clearly defines process objectives, assumptions, relevant standards, policies, performed activities, inputs and outputs, assigned resources, individuals responsible for each activity, and supporting tools for information requirements management processes (Rana et al., 2015; Solemon et al., 2012).

7.3 Information Requirements Management Activities in Capability Improvement Framework

In the REGPG maturity model, there were 66 practices covering eight requirements management process areas classified into *Basic*, *Intermediate* and *Advanced* practices. Similarly, in the improvement framework developed in this research, a checklist of the 82 information requirements management related activities was identified. These activities were developed according to either the existing SE and DE standards, and the finding from the literature review (Chapter 2), conceptual framework (Chapter 4), interviews (Chapter 5) and survey (Chapter 6) during earlier stages of this research project. The details of the checklist including the source of each activity is described in **Appendix F**.

One major difference from REGPG is that information requirements management related activities are grouped into seven stages of the project, consistent with the Diamond model developed in this research. These stages are 1) need, 2) concept, 3) specify, 4) procure, 5) design, 6) build and integrate, and 7) accept. The operate and maintain stage is not included in this framework considering the time constraints of the research and lack of support of relevant standards during this stage.

Two criteria have been set up to categorise the activities: a) Project level or Enterprise level, and b) Basic activity or Advanced activity. Each activity is also mapped to the corresponding requirements management capability areas identified during earlier research stages. The framework's implementation assumes concurrent systems engineering, digital engineering management, and project management processes. The activities in the framework are interconnected with those processes and their corresponding activities. Configuration management gates and review gates play a crucial role as they connect activities across various disciplines to ensure seamless coordination. To effectively implement the framework, it is important for the activities to be integrated with concurrent systems engineering, digital engineering management, and project management processes.

Figure 7.1 presents the overview of information requirements management activities during asset stages. This figure was built based on the project phases where each activity should occur in **Appendix F**. As shown in Figure 7.1, the concept and specify stages involved the most information requirements management activities. Almost 90% of the information requirements management activities happened before the "build" stage of a project. This further reflects the importance of the early planning phase of a project for effective information requirements management. The following sections present the information requirements management activities during each stage.

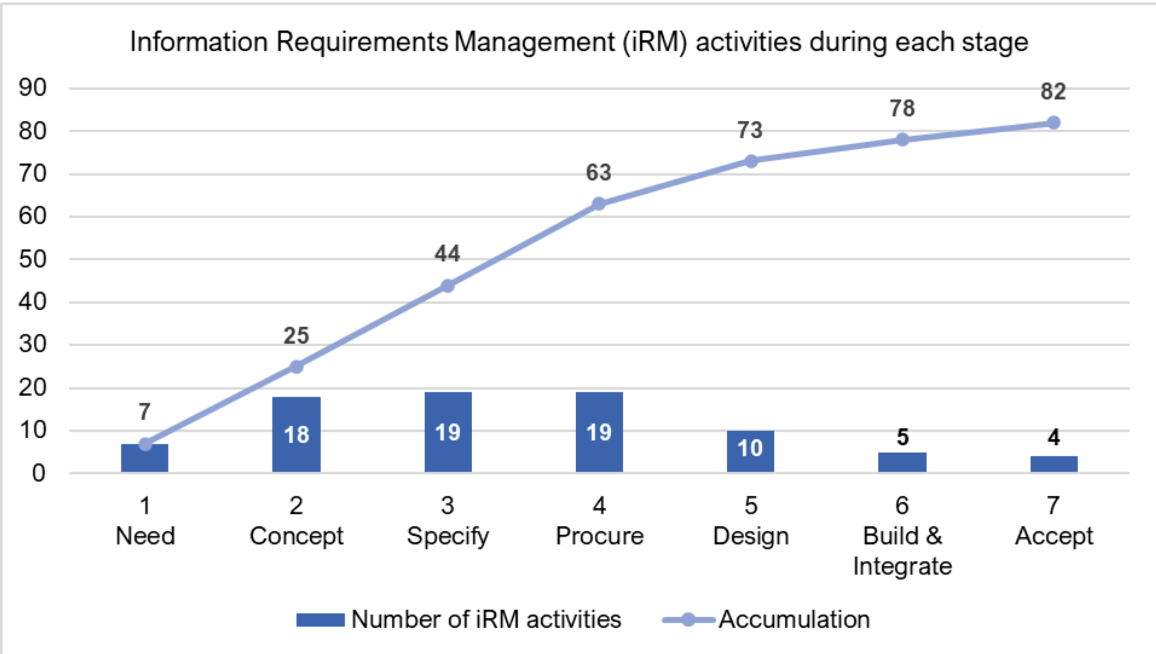

Figure 7.1 Information requirements management related activities during project lifecycle

7.3.1 Information Requirements Management Activities during "Need" Stage

There are seven information requirements management related activities during the "Need" stage (see Table 7.1). All these seven activities are at the enterprise level as, during this stage, the project has not been proposed yet. All these activities focus on the policy, strategy and organisational wide standard and plan development. The critical tasks highlighted in bold font in Table 7.1 to Table 7.7 are about linking and connecting the AIR management plan, the configuration management plan, updating processes of the Project Data Schema/AIRs and then their configuration in the client and project delivery team's CDEs.

Table 7.1 Information requirements management related activities (Need Stage)

Asset Lifecycle Stages (TfNSW, 2022a)	No.	Information Requirements Management (iRM) Activities	Project or Enterprise level (P/E)	Basic or Advanced activity (B/A)	RM capability area
1 Need	1.1	Prepare or review existing data and information asset management policy/strategy/standard, aligned to the asset management strategy	E	B	Requirements elicitation
	1.2	Establish or review existing/new organisational information requirements (OIRs) to ensure asset management activities are appropriately identified in the policy, strategy and plan	E	B	Requirements elicitation
	1.3	Identify asset/facilities managers as primary stakeholders and support the delivery team in understanding the operational service needs	E	B	Stakeholder involvement
	1.4	Understanding the asset managers' information requirements in the strategic and operational management of assets	E	B	Requirements elicitation
	1.5	Establish or review existing Concept of Operations (ConOps) or concept brief or service need	E	B	Requirements elicitation
	1.6	**Establish configuration management baselines and review gates for milestone delivery**	E	B	Configuration management
	1.7	**Establish and maintain the plan for performing information requirements management process (linked to configuration management baselines)**	E	A	RM protocol and language

Activity 1.4 is about the establishment of Concept of Operations (ConOps) which is a network level document stating the performance need for the rail network. Activities 1.1–1.6 are all basic activities for information requirements management as it is essential to develop the project level information requirements according to the organisational and network level policy and strategy about information asset management. Activity 1.6 is about establishing configuration management baselines and review gates for milestone delivery. Activity 1.7

focuses on the development of an information requirements management plan that is linked to a configuration management baseline and is defined as an Advanced activity as it supports a more effective way to manage information requirements throughout the project lifecycle stages. In terms of requirements management capability areas, these activities address requirements elicitation, stakeholder involvement, configuration management, and requirements management protocol and language. These enterprise level activities provide the foundation for future information requirements management practices at the project level.

7.3.2 Information Requirements Management Activities during "Concept" Stage

During the "Concept" stage which is also the first stage in the "Planning" phase, 18 information requirements management activities have been identified (see Table 7.2). Enterprise level activities during this stage focus on the development of the Master Classification Library (MCL) or Common Data Dictionary, Common Data Model – a standardised data model based on a top-down ontology, developed for the rail sector to exchange data in a connected digital ecosystem (RISSB, 2022) – which is also known as a Transport Data Building Block in the Transport for NSW DE Framework (Transport for NSW, 2022b), and the establishment of a client-side common data environment (CDE). These three activities are classified as *Advanced* activities and mapped into "requirements management protocol and language" and "integration/interoperability of tools" capability areas. Establishment of client-side CDE also goes to the project level depending on the scope of CDE established by the client.

Table 7.2 Information requirements management related activities (Concept Stage)

Asset Lifecycle Stages (TfNSW, 2022a)	No.	Information Requirements Management (iRM) Activities	Project or Enterprise level (P/E)	Basic or Advanced activity (B/A)	RM capability area
2 Concept	**2.1**	**Develop/update Master Classification Library (MCL)/Common Data Dictionary based on identified system or asset and locations using common corporate asset classification coding standard (e.g., Uniclass)**	E	A	RM protocol and language
	2.2	When developing and completing Operations Concept Definition (OCD) and Maintenance Concept Definition (MCD), ensure that O&M requirements are allocated to the appropriate corporate asset classification (e.g., complex, facility, system and/or asset, and asset location)	P	B	Requirements allocation
	2.3	Establish the DE project strategy (approach to DE implementation)	P	A	Senior management support

Asset Lifecycle Stages (TfNSW, 2022a)	No.	Information Requirements Management (iRM) Activities	Project or Enterprise level (P/E)	Basic or Advanced activity (B/A)	RM capability area
	2.4	**Establish/review data classification and referencing (include asset classification, asset references, location classification, location references – confirming the "Common Data Model" for the client/asset owner based on the MCL.) Buildings = COBie/ Infrastructure Transport Data Building Blocks (Uniclass + Project / Contract Info + Legacy Asset classifications)**	E	A	RM protocol and language
	2.5	**Based on DE project strategy and setup, establish the project data dictionary (In Transport this equates to the Project Data Building Blocks (PDBB))**	P	A	RM protocol and language
	2.6	Aligning with the Project Management Plan (PMP), specify asset information required for O&M (based on DE Framework and PDBB or OIRs), AKA asset information requirements (AIRs)	P	B	Requirements elicitation
	2.7	**Generate Project Data Schemas (PDS) based on functional requirements and AIRs, following the Master Classification Library (data dictionary) established in Activity 2.4**	P	A	RM protocol and language
	2.8	**Establish the Client-side Common Data Environment (CDE) which includes Enterprise Content Management, Scheduling Schemas, Cost Estimating Systems, etc., Workflow definition and management processes linked to design coordination and information requirements management activities to be established against the information requirements management plan (see "Need" Activity 1.6 and 1.7)**	E + P	A	Integration/ Interoperability of tools
	2.9	Embed Project Data Schemas/AIRs in the tender document (relative to other DE requirements including scope, draft DEXP, draft project data schema)	P	B	Integration of RM protocols with PM protocols
	2.10	Support the delivery team's tender response (Ensure alignment between information requirements/project data schemas, contract templates, technical disciplines and deliverables)	P	B	Integration of RM protocols with PM protocols

Asset Lifecycle Stages (TfNSW, 2022a)	No.	Information Requirements Management (iRM) Activities	Project or Enterprise level (P/E)	Basic or Advanced activity (B/A)	RM capability area
	2.11	**When conducting tender evaluation, include the requirement for an information requirements management plan aligned to ISO 19650 (e.g., TIDP, MIDP, DEXP), project data schema alignment in assessment criteria, and CDE workflow specifications supporting asset information requirements management plan**	P	A	Integration of RM protocols with PM protocols
	2.12	After awarding the contract, review and approve contractor's information requirements management plan which is included in DEXP against the tender document	P	A	Requirements change management
	2.13	After awarding the contract, review and approve contractor's final validation method to comply with project data schemas against the tender document	P	A	RM protocol and language
	2.14	**After awarding the contract, support the establishment of contractor's CDE which should include configuration of project data schemas (e.g., CAD, GIS, BIM, etc.) and specify the technology requirements to support information RM workflows (e.g., use of Solibri or Revizto for data validation), and integrate with the client CDE**	P	A	Integration/ Interoperability of tools
	2.15	**Update Project Data Schemas/AIRs to align with approved DEXP**	P	B	Requirements change management
	2.16	Validate the DE data (e.g., ECM data schema) in Strategic Business Case (SBC) (establish RVTM) submitted by Contractor against updated Project Data Schemas/AIRs in 2.15	P	B	Requirements verification and validation
	2.17	Validate the DE data (design model and data schema) in Options Design Model submitted by Contractor against updated Project Data Schemas/AIRs in 2.15	P	B	Requirements verification and validation
	2.18	**Model-based approaches are implemented to verify that Option Design deliverables are compliant with information requirements (AIRs, PIRs, EIRs) by contractor via CDE**	P	A	Requirements verification and validation

There are 15 project-level activities during the "Concept" stage with eight *Basic* activities and seven *Advanced* activities. Advanced activities at the project level mainly focus on establishment of DE project strategy, project data dictionary, project data schema and client's and contractor's CDE as well as the implementation of model-based approaches during design review.

The project level activities during this stage start from the development of an enterprise level Master Classification Library or Common Data Dictionary, followed by the development of Operation Concept Definition (OCD) and Maintenance Concept Definition (MCD). The key difference between OCD/MCD and ConOps is that OCD and MCD focus on the project level while ConOps focuses on the network level. Another important set of activities (Activities 2.9–2.14) during the "Concept" stage are embedding information requirements protocols within project management protocols during the tendering procedure. This set of activities is repeatable during the specify and procure stages. The main outputs during this stage are the Strategic Business Case (Activity 2.16) and Option Design Model (Activity 2.17). It is important to validate the DE data (including enterprise content management schema and design model) in these outputs against the asset information requirements (AIRs). The AIRs typically include the asset register; data schemas/standards; confirmation of how many information fields are required as a minimum in the asset register; costs associated with each item; whether a parent and child breakdown is required, and to what extent; managerial information; financial information; commercial information; technical information and legal information (Transport for NSW, 2022b).

7.3.3 Information Requirements Management Activities during "Specify" Stage

During the "Specify" stage which is also the second stage in the "Planning" phase, 19 information requirements management activities have been identified (see Table 7.3). All of them are at the project level with 11 *Basic* activities and 8 *Advanced* activities. Advanced activities at the "Specify" stage include develop system architecture frameworks using System Modelling Language (SysML) (Activity 3.6), review and update project data schemas/AIRs based on performance modelling simulation of business requirements (Activities 3.7 and 3.8), update project data schema within the CDE of both parties (Activities 3.9 and 3.15), embed AIRs within tendering evaluation criteria (Activity 3.12), review and approve contractor's final validation method to comply with project data schemas (Activity 3.14), and adopt model-based approaches during design review (Activity 3.19). Activities related to CDE have been highlighted in bold font as they are key enablers to support DE and requirements management.

At the beginning of the "Specify" stage, it is important to review and update the existing information requirements documents including organisation information requirements (OIR) and AIR. Based on this, information requirements are further decomposed into the next level. During this stage, the functional requirements defining the "What" (usually known as Business Requirements Specification or BRS) are established and are the base for developing the technical requirements defining the "How" (usually known as System Requirements

Specification or SRS). This is the key stage to transfer from "What" data is required to "How" to deliver the required data at the system level. AIRs at the corresponding levels should be embedded in the BRS and SRS documentation. Once the SRS is established, information requirements should then be embedded within the tendering documents and tender evaluation process. The main outputs during this stage are the Final Business Case (Activity 3.17) and Feasibility Design Model (Activity 3.18). It is vital to validate the DE data in these outputs against the updated AIRs.

Table 7.3 Information requirements management related activities (Specify Stage)

Asset Lifecycle Stages (TfNSW, 2022a)	No.	Information Requirements Management (iRM) Activities	Project or Enterprise level (P/E)	Basic or Advanced activity (B/A)	RM capability area
3 Specify	3.1	Elicit and analyse stakeholder information requirements with the support from asset and facilities management teams	P	B	•Requirements elicitation •Requirements analysis and prioritisation •Stakeholder involvement
	3.2	Clarify existing or planned operating information management systems/software, and identify legacy asset and location classification, and hierarchy requirements	P	B	Requirements analysis and prioritisation
	3.3	**After the approval of SBC, review and update OIRs and Project Data Schemas/AIRs against the context of the project (e.g., key decision points when information is required, level of information need, LOD, asset classification, asset location reference, asset attributes and data schemas, asset register, etc.)**	P	B	Requirements change management
	3.4	Embed information requirements of the OCD and MCD in the Business Requirements Specification (BRS)	P	B	Requirements elicitation
	3.5	When performing the feasibility study assessment on the preferred conceptual option, include the information requirements feasibility assessment	P	B	Requirements elicitation
	3.6	Develop the System architecture framework that draws together functional and performance requirements using SysML (make sure it aligns with the high-level DE assets classification hierarchy)	P	A	Systems architecture framework development
	3.7	**Review Project Data Schemas/AIRs based on outcomes of validation of business requirements using performance modelling simulations**	P	A	Requirements verification and validation

Asset Lifecycle Stages (TfNSW, 2022a)	No.	Information Requirements Management (iRM) Activities	Project or Enterprise level (P/E)	Basic or Advanced activity (B/A)	RM capability area
	3.8	**Update Project Data Schemas/AIRs which should be included in System requirements specification (SRS) (need to define interface between systems/technical requirements and information requirements)**	P	A	Requirements change management
	3.9	**Update client CDE (updates relative to revisions made to PDS and/or new contractor involvement)**	E + P	A	Integration/ Interoperability of tools
	3.10 – 3.15	// Repeat Activities 2.9 to 2.14	P	2B+4A	
	3.16	**Analyse and maintain project data schemas/AIRs in System Requirements Specification (update RVTM) for Final Business Case (FBC) (including review the integrity of AIR specifications, define the validation criteria for each AIR, allocate the AIRs to the relevant system or element, allocate the responsibility associated with each AIR, establish and maintain system level requirements traceability)**	P	B	•Requirements analysis and prioritisation •Requirements allocation •Requirements traceability •Requirements verification and validation
	3.17	Validate the DE data (e.g., ECM data schema) in Final Business Case submitted by Contractor against updated Project Data Schemas/AIRs in Activity 3.16	P	B	Requirements verification and validation
	3.18	Validate the DE data (design model and data schema) in Feasibility Design Model submitted by Contractor against updated Project Data Schemas/AIRs in Activity 3.16	P	B	Requirements verification and validation
	3.19	**Model-based approaches are implemented to verify that feasibility design deliverables are compliant with information requirements (AIRs, PIRs, EIRs) by contractor via CDE**	P	A	Requirements verification and validation

7.3.4 Information Requirements Management Activities during “Procure” Stage

During the “Procure” stage, which is also the third stage in the “Planning” phase, 19 information requirements management activities have been identified (see Table 7.4). An activity about updating client and project CDEs (Activity 3.9) occurs twice during this stage. The set of activities about tendering (Activities 2.9 to 2.14) also occur twice during this stage. All the other activities are project-level activities with four *Basic* activities and one *Advanced* activity. Advanced activities at the “Procure” stage focus on review and approve contractor’s final validation method to comply with project data schemas (Activity 4.8), update project data schema within the client and project team CDEs (Activities 4.2 and 4.13), embed AIRs within tendering evaluation criteria (Activities 4.6 and 4.16), the establishment of contractor’s CDE

(Activities 4.9 and 4.19), and the adoption of model-based approaches during design review (Activity 4.11).

Table 7.4 Information requirements management related activities (Procure Stage)

Asset Lifecycle Stages (TfNSW, 2022a)	No.	Information Requirements Management (iRM) Activities	Project or Enterprise level (P/E)	Basic or Advanced activity (B/A)	RM capability area
4 Procure	4.1	After the approval of FBC, update Project Data Schemas/AIRs which should be included in partly developed sub-system requirements specification (SSRS)/Scope and performance requirements specification (update RVTM)	P	B	•Requirements analysis and prioritisation •Requirements change management
	4.2	**// Repeat Activity 3.9**	E + P	A	Integration/ Interoperability of tools
	4.3	**Establish the Asset Register/ Asset Breakdown Structure according to the updated Project Data Schemas/AIRs**	P	B	RM protocol and language
	4.4 – 4.9	// Repeat Activities 2.9 to 2.14	P	2B+4A	
	4.10	Validate the DE data (design model and data schema) in Concept Design (also called Reference Design) Model submitted by Contractor against updated AIRs in 4.4	P	B	Requirements verification and validation
	4.11	**Model-based approaches are implemented to verify that concept design/reference design deliverables are compliant with information requirements (AIRs, PIRs, EIRs) by contractor via CDE**	P	A	Requirements verification and validation
	4.12	**After the approval of Concept design/Reference design, update Project Data Schemas specifying AIRs in partly developed sub-system requirements specification (SSRS)/Scope and performance requirements specification**	P	B	Requirements change management
	4.13	**// Repeat Activity 3.9**	E + P	A	Integration/ Interoperability of tools
	4.14 – 4.19	// Repeat Activities 2.9 to 2.14	P	2B+4A	

At the beginning of the "Procure" stage, the Sub-system Requirements Specification (SSRS) or Scope and Performance Requirements Specification (SPRS) is developed for the concept design or reference design at the sub-system level. In the meantime, the corresponding information requirements should also be developed at the sub-system level. Another important activity is establishing the asset register or asset breakdown structure. The main output during this stage is the Concept/Reference Design Model (Activity 4.10). It is crucial to validate the DE data including both design model and data schema in these outputs against the updated AIRs. At the end of this stage, the contract for preliminary design and critical design should be awarded.

7.3.5 Information Requirements Management Activities during "Design" Stage

During the "Design" stage, 10 information requirements management activities have been identified (see Table 7.5). 8 of these activities are at the project level with five *Basic* activities and three *Advanced* activities. The three project-level *Advanced* activities mainly focus on adding defined asset locations, and design/work packages in the data dictionary and data schema (Activity 5.3), and adopting model-based approaches during design review (Activities 5.8 and 5.10).

Activity 5.2 is at both the enterprise and project level, focusing on allocating updated Project Data Schemas/AIRs into design/work packages in collaboration with developing the commercial and procurement strategy and updating client and project CDEs and linked requirements management workflows. Another enterprise level activity during this stage is to issue an asset register to an enterprise asset management platform (Activity 5.11), which is also categorised as an *Advanced* activity.

At the beginning of the "Design" stage, the first activity is to develop information requirements in SSRS/SPRS at the unit level (Activity 5.1). After that, the information requirements are allocated to different design/work packages (Activity 5.2). The main outputs during this stage are the Preliminary Design Model (Activity 5.4) and Critical Design Model (Activity 5.6). It is important to validate the DE data (both design model and data schema) in these outputs against the updated AIRs. At the end of this stage, traceability of design elements to business, system and sub-system requirements should be demonstrated (Activity 5.10).

Table 7.5 Information requirements management related activities (Design Stage)

Asset Lifecycle Stages (TfNSW, 2022a)	No.	Information Requirements Management (iRM) Activities	Project or Enterprise level (P/ E)	Basic or Advanced activity (B/ A)	RM capability area
5 Design	5.1	Update Project Data Schemas/AIRs in sub-system requirements specification (SSRS) / Scope and performance requirements specification at the unit level (update RVTM with design verification evidence)	P	B	• Requirements analysis and prioritisation • Requirements change management
	5.2	**Allocate updated Project Data Schemas/AIRs in Activity 5.1 into design/work packages in collaboration with development of the commercial and procurement strategy and update client and project CDEs and linked requirements management workflows**	E + P	B	Requirements allocation
	5.3	Document defined asset locations, sub-systems/assets, design/work packages and work zones in the data dictionary and data schemas	P	A	RM protocol and language
	5.4	Validate the DE data (design model and data schema) in Preliminary Design Model (LOD 200, 20%–30% completion) submitted by Contractor against updated project data schemas/AIRs	P	B	Requirements verification and validation
	5.5	**Model-based approaches are implemented to verify that Preliminary design deliverables are compliant with information requirements (AIRs, PIRs, EIRs) by contractor via CDE**	P	A	Requirements verification and validation
	5.6	Validate the DE data (design model and data schema) in Critical Design Model (LOD 300) submitted by Contractor against updated project data schemas/AIRs	P	B	Requirements verification and validation
	5.7	**Model-based approaches are implemented to verify that Critical design deliverables are compliant with information requirements (AIRs, PIRs, EIRs) by contractor via CDE**	P	A	Requirements verification and validation
	5.8	**Issue the Critical design review asset register to Enterprise Asset Management (EAM) platform, aligning with the updated project data schemas/AIRs**	E	A	Requirements verification and validation
	5.9	Document additional systems and/or sub-systems identified during the design process in the SSRS, data dictionary and data schema, update project data schemas/AIRs	P	B	Requirements change management
	5.10	Demonstrate traceability of design elements to business, system, and sub-system requirements using the agreed requirements schema and specification	P	B	Requirements traceability

7.3.6 Information Requirements Management Activities during "Build" and "Integrate" Stages

During the "Build" and "Accept" stage, five information requirements management activities have been identified (see Table 7.6). Two of them are considered Advanced activities: implement model-based approaches during Approval for Construction (AFC) design review (Activity 6.2), and update verification and validation evidence in client and project CDEs (Activity 6.5). Before getting ready for test, it is crucial to validate the Work as Executed (WAE) asset register against the updated information requirements (Activity 6.4). After testing and commissioning, the information requirements should be updated with verification and validation evidence (Activity 6.5).

Table 7.6 Information requirements management related activities (Build and Integrate Stage)

Asset Lifecycle Stages (TfNSW, 2022a)	No.	Information Requirements Management (iRM) Activities	Project or Enterprise level (P/E)	Basic or Advanced activity (B/A)	RM capability area
6 Build and Integrate	6.1	After the approval of Critical Design, validate the DE data (design model and data schema) in the Approved for Construction (AFC) model submitted by Contractor against the updated project data schemas/AIRs	P	B	Requirements verification and validation
	6.2	**Model-based approaches are implemented to verify that Approved for Construction (AFC) design deliverables are compliant with information requirements (AIRs, PIRs, EIRs) by contractor via CDE**	P	A	Requirements verification and validation
	6.3	Conduct system verification review, making sure the DE data meets the updated project data schemas/AIRs	P	B	Requirements verification and validation
	6.4	Before getting ready for testing, validate the Work as executed (WAE) asset register against the updated project data schemas/AIRs (update RVTM with material procurement, manufacturing and installation verification evidence)	P	B	Requirements verification and validation
	6.5	**Update project data schemas/AIRs in RVTM with testing and commissioning and V&V evidence, update the client and project CDEs with V&V evidence**	E + P	A	Requirements verification and validation

7.3.7 Information Requirements Management Activities during "Accept" Stage

During the "Accept" stage, four information requirements management activities have been identified (see Table 7.7) with three *Basic* activities and one *Advanced* activity. During this stage, the focus of information requirements management is the validation of DE data (both design model and data schema) in the As-Built model (Activity 7.1) and during Physical Configuration Audit (PCA). Moreover, it is vital to review the EAM and as-built asset register to make sure that it is consistent with the updated information requirements (Activity 7.3). The asset/facility manager should perform final assurance of the asset information model against the AIRs during this stage (Activity 7.4).

Table 7.7 Information requirements management related activities (Accept Stage)

Asset Lifecycle Stages (TfNSW, 2022a)	No.	Information Requirements Management (iRM) Activities	Project or Enterprise level (P/E)	Basic or Advanced activity (B/A)	RM capability area
7 Accept	7.1	Validate the DE data (design model and data schema) in the As-Built model submitted by contractor against the updated project data schemas/AIRs	P	B	Requirements verification and validation
	7.2	Validate the DE data when conducting physical configuration audit (PCA) against the updated project data schemas/AIRs	P	B	Requirements verification and validation
	7.3	**Review EAM and as-built asset register and evidence, making sure it meets the updated project data schemas/AIRs**	E + P	A	Requirements verification and validation
	7.4	The asset/facilities manager/s performs final assurance of the AIM against the AIRs before assets are placed in service	P	B	Stakeholder involvement

7.4 Assessment Process in Capability Improvement Framework

The Capability Improvement Framework in this research employs a hybrid assessment approach, consisting of both organisational level and project level assessments. For assessing the organisational level maturity level, a style similar to REGPG (Sommerville & Sawyer, 1997) is adopted. This involves creating an assessment checklist for various activities and then assigning scores to each activity based on the level of standardised implementation (Standardised = 3, Normal use = 2, Discretionary = 1, Never = 0). When the framework is applied at the project level, it functions as a checklist of activities necessary for effective information requirements management, considering the available resources. It is advisable to customise these activities to suit the project's specific context and integrate them into the existing project management processes.

7.4.1 Organisational Level Assessment and Improvement Process

In the organisational level assessment process, a checklist consisting of the 82 information requirements management related activities is scored based on their implementation within the organisation. More specifically, there are four scenarios of implementation, following the framework proposed by Sommerville and Sawyer (1997) :

1) **Standardised**. This scenario involves activities that have a documented standard within the organisation and are consistently used in a standardised manner throughout the organisation. Score = 3.

2) **Normal use**. In this case, the activity is widely followed in the organisation but is not mandatory. Score = 2.

3) **Discretionary**. Some project managers may have introduced the activity, but it is not universally used across all projects. Score = 1.

4) **Never**. The activity is either never or very rarely applied within the organisation. Score = 0.

The maturity level is determined by summing the weighted scores for all implemented activities in Basic and Advanced categories, as outlined in Table 7.8. Within the 82 information requirements management activities, 48 are considered as *Basic* activities while 34 are considered as *Advanced* activities. The threshold levels and the scores associated with these levels as shown in Table 7.8 were determined according to a similar principle as the REGPG maturity model (Sommerville & Ransom, 2005). To transition from an Incomplete to a Performed level, an organisation should prioritise the establishment of a strong foundation of information requirements management activities. Moving from the Performed to the Managed level entails a focus on standardising the Basic information requirements management activities and introducing Advanced activities into the organisation's processes. For an organisation to progress from the Managed to the Integrated level, the key emphasis should be on standardising both Basic and Advanced information requirements management activities.

Table 7.8 Organisational maturity levels of Capability Improvement Framework

Maturity level	Scores of activities
Level 0: Incomplete	Score of below 48 in Basic Activities
Level 1: Performed	Score of above 47 in Basic Activities and below 34 in Advanced Activities
Level 2: Managed	Score of above 72 in Basic Activities and below 51 in Advanced Activities
Level 3: Integrated	Score of above 96 in Basic Activities and above 50 in Advanced Activities

As acknowledged in the CMMI-style approach, it is important to understand that the threshold levels in all discrete maturity models are arbitrary (Sommerville & Ransom, 2005), including the improvement framework developed in this research. These levels are defined to facilitate the assessment and improvement process, but the specific thresholds are not set in stone. They are meant to be customised and adapted to the specific needs and context of the organisation or project.

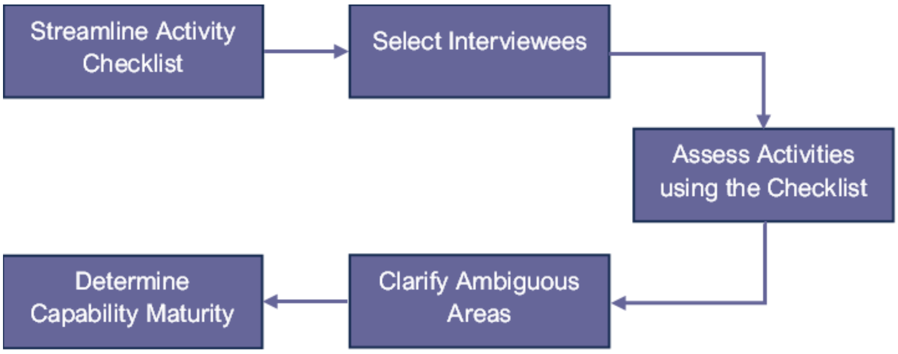

Figure 7.2 Requirements management capability maturity assessment process (adapted from Sommerville & Ransom, 2005)

The assessment of the capability maturity involves assessing the implementation of information requirements management activities within an organisation and using the results to ascertain the capability maturity level. The process to assess the maturity level consists of five steps (as shown in Figure 7.2) that are akin to the REGPG model (Sommerville & Ransom, 2005). These steps are (Sommerville & Ransom, 2005):

1) **Streamline activity checklist**. Efficiently identify practices that are not implemented by the organisation, such as formal methods, and remove the corresponding activities from the assessment to save time and avoid unnecessary discussions.
2) **Select interviewees**. Choose individuals within the organisation who have knowledge of the implemented activities and can provide valuable insights regarding their level of implementation.
3) **Assess activities using the checklist**. Evaluate each activity by conducting interviews with the selected individuals.
4) **Clarify ambiguous areas**. Once an initial set of scores is obtained, address any uncertainties through further discussions with stakeholders while ensuring consistency in scoring methodology.
5) **Determine capability maturity**. Calculate the overall score and assign a maturity level based on Table 7.8 as a reference point.

The maturity matrix, presented in Table 7.9, provides a summary of the assessments conducted on maturity levels. It displays the number of information requirements management activities used and gives an overall assessment of maturity. The maturity matrix consists of columns for both Basic and Advanced activity guideline categories, with each row presenting relevant details about these guidelines:

- Row 1 is the number of activities in each category that are actually used.

- Row 2 is the weighted score, which represents the level of standardisation in the organisational implementation of these activities.
- Row 3 is the maximum achievable score if all activities within a specific category are adhered to and standardised.
- Row 4 is the percentage of this maximum score actually achieved in this assessment.
- Lastly, Row 5 is an assessment of maturity level categorised as Incomplete, Initial, Managed or Integrated.

Table 7.9 Information requirements management maturity matrix

	Basic	Advanced
Activity Count	Basic Activity Count	Advanced Activity Count
Weighted Score	Basic Weighted Score	Advanced Weighted Score
Maximum Score	Max. score (Basic)	Max. score (Advanced)
Score %	Basic Score as a % of Maximum	Adv. Score as a % of Maximum
Maturity Level	Assessed maturity level	

The primary objective of this framework is to establish a roadmap for enhancing capability. The data in the maturity matrix serves as a foundational basis for discussing potential improvements (Sommerville & Ransom, 2005). By analysing the assessment results, we can pinpoint areas of weakness in information requirements management capability based on the scores assigned to each activity in the checklist.

Once areas of weaknesses have been identified, it is crucial to adopt a systematic approach to improve the organisation's capability in information requirements management. The capability improvement should be implemented incrementally and in a way that does not compromise the use of existing good practices. This ensures that the business goals are not threatened and that changes can be introduced without excessive costs. Furthermore, it is important to involve all stakeholders in the process improvement efforts. This includes project managers, team members, and other relevant stakeholders who can provide valuable insights and contribute to the improvement initiatives.

To achieve a successful capability improvement, several key factors need to be considered. First, the abilities, receptivity and experience of the personnel involved should be taken into account. It is important to assess their readiness and provide adequate training and support to ensure that they are equipped with the necessary skills and knowledge to implement the improvements effectively. Second, the time and resources available should be carefully considered. Implementing capability improvements requires allocating sufficient time and resources to the improvement initiatives. Additionally, the potential impact on business goals should be evaluated to ensure that the improvements align with the strategic objectives of the organisation. Finally, it is crucial to monitor and evaluate the effectiveness of the capability improvement efforts. Regular monitoring and evaluation allow for the identification of any challenges or barriers to success and enable the implementation of necessary adjustments.

In summary, the Capability Improvement Framework involves analysing assessment results, identifying areas of weakness, adopting a systematic approach to improvement, involving stakeholders, considering personnel readiness, allocating time and resources, aligning with business goals, and monitoring and evaluating the effectiveness of the improvement efforts.

7.4.2 Project Level Implementation of the Capability Improvement Framework

Regarding the project level, this Capability Improvement Framework serves as a checklist of essential activities for an effective and efficient information requirements management. The project team should review the list of activities, and allocate necessary resources required before starting the project. These activities should then be integrated into existing project management processes and protocols.

By implementing this Capability Improvement Framework, project teams can ensure that all necessary activities for effective information requirements management are addressed and properly allocated resources. This framework can also help in identifying any gaps or areas for improvement in current practices. The Capability Improvement Framework provides a structured approach to enhance the project team's ability to manage information requirements effectively.

The framework emphasises the importance of information requirements development and management processes in achieving project success. These processes ensure that accurate and complete information requirements are gathered, documented and effectively managed throughout the project lifecycle. By following this framework, project teams can improve their capability in identifying and addressing stakeholder needs, reducing risks related to incomplete or incorrect information requirements, and enhancing project outcomes through better information requirements management.

7.5 Validation of Capability Improvement Framework

To gather valuable input on the Capability Improvement Framework, we conducted a series of feedback sessions with industry experts. Based on the availabilities of the industry experts, two face-to-face feedback interviews, two online interviews, and one feedback via email were conducted. Each session involved one expert to minimise the influence from other experts. As mentioned in Section 2.6, the objectives of these feedback sessions were to assess specific aspects, including:

(1) **Clarity of maturity levels**: Ensuring clarity in the setup of maturity levels, accurately reflecting an organisation's level of maturity in information requirements management.

(2) **Comprehensiveness of information requirements management activities**: Confirming the comprehensiveness of information requirements management activities within the assessment area and ensuring that all relevant aspects are covered thoroughly.

(3) **Appropriateness of activity categorisation**: Evaluating whether the categorisation of information requirements management activities into basic and advanced is appropriate.

The five interviews followed the following guidelines:

1) At the beginning of each interview, the researcher provided a brief overview of the research background, objectives of the framework, key references used to develop the framework, and the intention for conducting the feedback sessions.

2) The researcher presented the structure of this framework (the content of each column as shown in **Appendix F**).

3) Then, the researcher went through each row of the framework (activities and the phases they belong to) with the interviewees. During this procedure, interviewees were encouraged to raise any questions and feedback. Further discussions were conducted on this feedback. Together with industry experts, the information requirements management activities were examined thoroughly.

Throughout this collaborative process, experts contributed valuable feedback by either expressing agreement or suggesting improvements to the order and description of these activities. Their invaluable insights have greatly enhanced the Capability Improvement Framework and paved the way for further advancements.

One of the key suggestions was to categorise the activities as either "enterprise level" or "project level". This categorisation suggestion provided by the industry experts is an important refinement of the Capability Improvement Framework. By distinguishing between activities at the enterprise level and those at the project level, we can better align the framework with the specific needs and context of organisations. This distinction acknowledges that different activities may be necessary depending on the scale and scope of the information requirements management efforts. It also allows organisations to prioritise and allocate resources effectively, focusing on activities that are most relevant to their specific context.

Other suggestions included adjusting the consequences of activities during the "need", "plan" and "specify" stages and refining the description of some activities. As emphasised by the expert who has a DE background in the infrastructure industry for more than 10 years with a deep understanding of implementing ISO 19650, it is a recommended way to align these activities with ISO 19650 to improve the generalisability of this artefact. According to ISO 19650, development of OIR is the first step to set up information requirements, followed by the development of AIR which must support the asset information model (AIM). Thus, AIM definition is critical before asking appointing parties to develop information that aligns with it. Moreover, the client-side information management function is critical, and may be an asset management or facility management or project management role that changes throughout the project.

Furthermore, during the feedback sessions, the experts highlighted the importance of considering the practical implementation of the framework. While the framework provides a comprehensive roadmap for improving information requirements management, it is essential to ensure that it is practical and feasible for organisations to implement. As a result, the Capability Improvement Framework was further refined to incorporate practical considerations and provide organisations with clear guidance on how to implement and apply the framework in real-world scenarios.

During the feedback sessions, additional feedback was received on the distinction between the Concept of Operations (ConOps) and Operation Concept Definition (OCD). The ConOps primarily addresses network level considerations, while OCD is more focused on project level details. Additionally, it was emphasised that ConOps should be established during the demand/need phase, whereas OCD typically takes shape during the planning phase.

In conclusion, the feedback sessions with industry experts were crucial in shaping and improving the Capability Improvement Framework for information requirements management. The feedback and suggestions led to important refinements, such as labelling activities as either "enterprise level" or "project level", which allows organisations to prioritise and allocate resources effectively. Aligning with ISO 19650 has enhanced the generalisability of the framework. Additionally, the emphasis on practical implementation and the incorporation of real-world scenarios have made the framework more feasible and applicable for organisations. The distinction between the ConOps and OCD has also been clarified, ensuring that they are addressed at the appropriate phases of the information requirements management process. The collaborative feedback sessions with industry experts were invaluable in enhancing and advancing the Capability Improvement Framework for information requirements management.

7.6 Summary

This chapter used a design science research approach to create a Capability Improvement Framework for information requirements management in the rail transport sector. The framework was reviewed and refined through feedback sessions with industry experts, aiming to address the third research question. Figure 7.3 depicts the structure of this chapter.

This chapter introduced the Capability Improvement Framework, outlining its key components such as maturity levels, information requirements management related activities, and assessment method. A detailed description of four maturity levels in this framework was provided: "Incomplete", "Initial", "Managed" and "Integrated". The information requirements management related activities were then identified and developed based on existing SE and DE standards, as well as previous research findings from interviews and surveys. A total of 82 information requirements management related activities were recognised across seven project stages. These activities were further categorised as a basic activity or advanced activity at either enterprise level or project level. Moreover, each activity was mapped to one or more information requirements management capability areas. The most critical activities highlighted in bold font are about linking and connecting the AIRs management plan and the configuration management plan, updating processes of the Project Data Schema/AIRs and then their configuration in the client and project delivery team's CDEs. By effectively linking and connecting the various management plans and processes, organisations can ensure that the necessary information and configurations are properly updated and integrated into their digital environments. In each table, there are basic activities and advanced activities, giving organisations the option to select the proper activities based on their resources and the context. Moreover, each activity was categorised as either a project level activity or enterprise level activity. The earlier the stage is, the more enterprise level activities are required.

The assessment and improvement process of this Capability Improvement Framework was presented at the organisational level, followed by its implementation at the project level. At the organisation level, assessment of capability maturity consists of five steps which are similar to the REGPG model. A final score for *Basic* and *Advanced* activities provides a foundation for discussing potential improvements. At the project level, this framework serves as a checklist of essential activities for effective information requirements management. The project team should tailor it based on the context of their specific project and integrate these activities into existing project management processes.

Industry professionals were invited to feedback sessions to offer their insights and recommendations for shaping and improving the framework. Their input significantly enhanced and refined the framework.

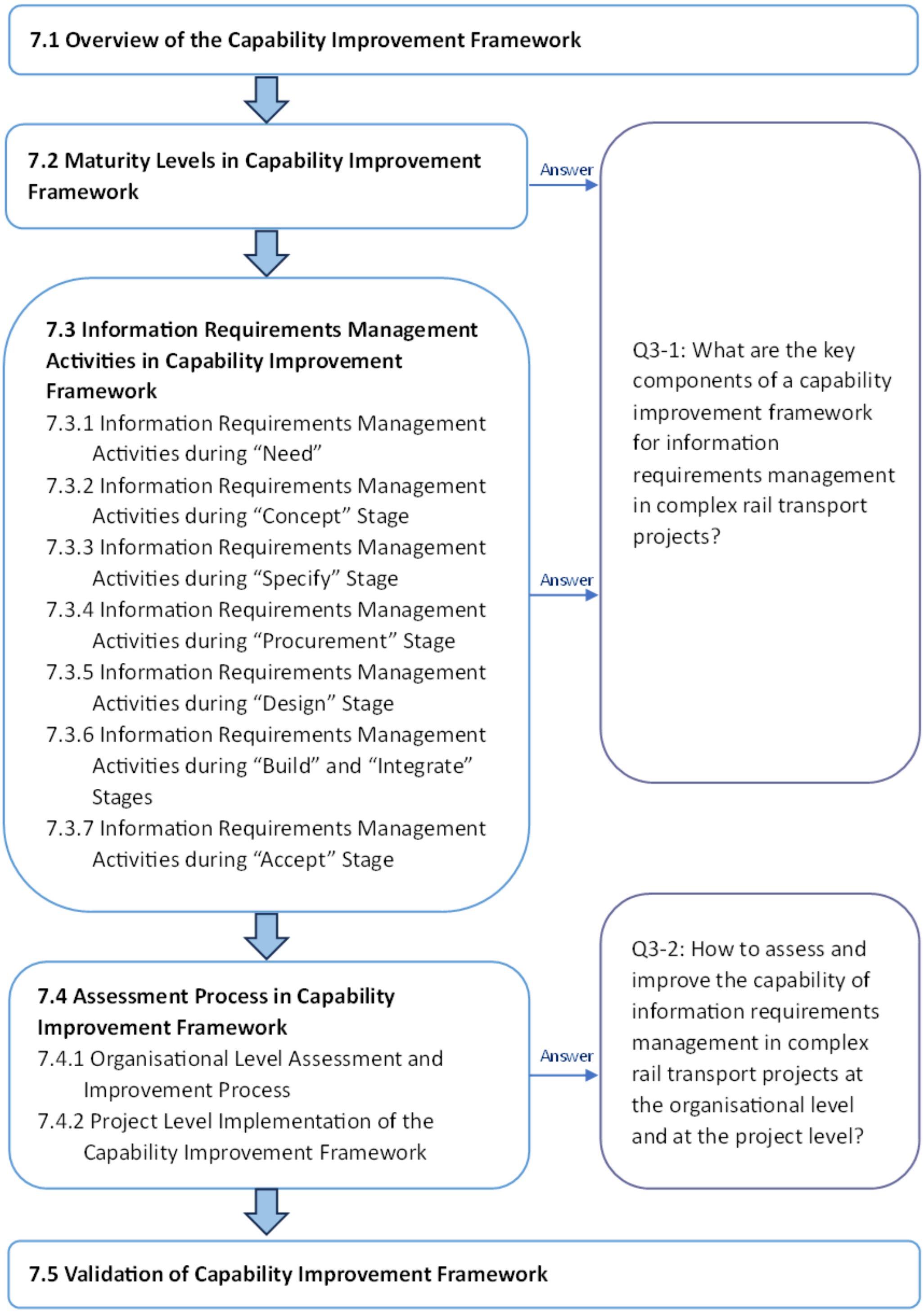

Figure 7.3 Structure of Chapter 7 content

Chapter 8 Conclusion and Recommendations

This concluding chapter reviews how the objectives of the research have been met and how the research questions have been addressed. This is followed by the contribution of the research in terms of the academic domain and practices. Limitations of this research are then discussed. This chapter ends with a discussion of future work as well as two important issues regarding significant gaps in the infrastructure tool ecosystem and the implementation of a cloud-based data warehouse approach for futureproofing infrastructure.

8.1 Summary of this Research

This research seeks to address the main question: *How are information requirements managed on complex rail transport projects, especially in terms of the implementation of digital engineering, and how can information requirements management practices be improved?* An initial literature review was conducted (Chapter 2), consolidating the existing knowledge regarding requirements management capability and the digital engineering backbones for lifecycle information management in architecture, engineering, construction and operations (AECO) sectors, to find potential gaps in the current body of research. Based on this review, it was evident that there is a lack of a whole-of-system and whole-of-life methodology and a lack of maturity with regards to the traceability and management of information requirements related to the creation of a digital twin.

To address these gaps, the design science research methodology was adopted and tailored based on the context of this research (articulated in Chapter 3). This methodology consists of three main research steps, with each step addressing one of the three sub-questions of this research:

1) Desktop-based research forming the "Knowledge base" of this thesis. This step responded to the first sub-question: "*In the context of complex project delivery, what is the current status of information requirements management and what capabilities are essential to the efficient and effective management of information requirements?*"

2) Multiple-case study providing the "Environment" of this research. This step addressed the second sub-question: "*In the specific context of complex rail transport projects implementing digital engineering approaches, what capabilities are essential to information*

requirements management and what is the current status of information requirements management practices in industry?"

3) Design science research acting as the core "design cycle" of this thesis. This step responded to the third sub-question: "*In the context of complex rail transport projects, what levels of capability can be identified to assess the relative maturity of information requirements management practices, and what activities are required to support the improvement of information requirements management?*"

8.1.1 Current Status of and Essential Capabilities for Information Requirements Management in Complex Project Delivery

In Chapter 4, the process of the desktop-based research was described in detail and the findings from a systematic literature review across multiple domains (i.e., AECO, infrastructure and manufacturing) were presented. As a result, 22 key capabilities of requirements management in digital engineering enabled projects were identified and categorised into *process*, *technology* and *people* dimensions. Initiatives proposed in these domains aimed at supporting information requirements management in digital engineering enabled projects were explored. These initiatives encompass methods and frameworks, with model-based systems engineering (MBSE) and digital engineering/product lifecycle management approaches being the most widely adopted. The relationships between these initiatives and key requirements management capabilities were further investigated. Additionally, challenges and open issues in general requirements management and information requirements management were identified and categorised into the same dimensions as capabilities. In summary, Chapter 4 provided a comprehensive review of the state-of-the-art requirements management methods and existing challenges to information requirements management in digital engineering enabled projects across multiple domains, forming the knowledge base of this thesis.

8.1.2 Current Status of and Essential Capabilities for Information Requirements Management in Complex Rail Transport Projects

This research sub-question was addressed by a multiple-case study approach, consisting of semi-structured interviews (findings presented in Chapter 5) and an online survey (findings presented in Chapter 6). In Chapter 5, a similar structure of findings as Chapter 4 was presented, regarding key capabilities of information requirements management identified by industry participants, initiatives that have been implemented in rail transport projects, and challenges encountered by project teams. The main difference from Chapter 4 is that findings in Chapter 5 focused on the complex rail transport context. Challenges to requirements management were mapped to the Diamond model which reflected the co-management process of technical system requirements and information requirements. Challenges of information requirements management for complex rail transport projects were analysed and summarised at the end of Chapter 5.

Chapter 6 presented the content and findings from the online survey. The objective of the online survey was to delve deeper into the information requirements management practices within the complex rail transport sector. The following results were analysed in this chapter: i) current status of requirements management and digital engineering related standard implementation, ii) the maturity levels of requirements management capabilities, and iii) the most significant challenges of requirements management practices in complex infrastructure sectors. Two distinct professional disciplines – system engineering roles (responsible for technical systems requirements management activities) and digital engineering roles (responsible for information requirements management activities) – were identified in this survey. The findings reflected a low level of maturity in implementation of digital engineering in the operations and maintenance (O&M) phase as well as asset information lifecycle management in the Australian infrastructure sector. Findings also reflected higher maturity levels of technical systems requirements than for new information requirements management practices, particularly for asset information requirements.

Critical requirements management resources needed to increase the effectiveness and efficiency of integrated requirements management practices were identified, including support from senior management, clearly defined roles and responsibilities for requirements management, and clear appointing party standards and terms of contract covering requirements management application. To prioritise challenges, of the full list of 47 challenges investigated, 22 challenges (13 deficiency challenges and 9 emergency challenges) were identified as the first priority based on the analysis of survey results.

8.1.3 Capability Improvement Framework for Information Requirements Management in Complex Rail Transport Projects

Based on findings in Chapter 4 to Chapter 6, a Capability Improvement Framework for information requirements management in the rail transport sector was developed and validated in Chapter 7. This framework consists of four maturity levels: "Incomplete", "Initial", "Managed" and "Integrated". As the core of this framework, a list of 82 information requirements management related activities were identified and developed based on existing systems engineering and digital engineering standards, as well as previous research findings from interviews and surveys. These activities were recognised across seven project stages.

This framework not only specifies which activities should be performed but also provides guidance on the timing of these activities. These activities are further categorised according to multiple criteria: a) project level or enterprise level, b) strategic, tactical or operational level, and c) basic activity or advanced activity. Each activity is mapped to one or more information requirements management capability areas. Overall, this framework can provide an implementation ready guideline for organisations to assess the capability of information requirements management, pinpoint the weaknesses, and provide a pathway for improvement. At the project level, this framework can serve as a checklist of essential activities for effective information requirements management by the project team by tailoring it based on the context of their specific project and integrating these activities into existing project management processes. Feedback sessions with industry professionals have been organised to enhance and refine the framework based on the feedback, suggestions and recommendations from experts.

8.2 Research Contributions

This section summaries the contributions of this research from the perspective of contributions to theory, methodology, practice and policy according to the literature and contributions from this research in Table 8.1 below.

8.2.1 Contributions to Theory

This research provides a contribution to the detailed description of the phenomenon surrounding the current rail transport sector that supports the application and the refinement of theoretical methods from other domains (i.e., systems engineering and requirement management theory) into a rail transport context. The refinement of theoretical methods can then enrich the current body of knowledge (both the requirements management discipline and information requirements management field in the rail infrastructure context).

In the requirements management discipline, this research extends current knowledge of requirements management processes, protocols and tools that have been developed and refined in advanced manufacturing disciplines and industries by redefining and testing existing approaches and applying them in a new rail transport-based context. For the rail transport domain, this research sheds new light on a systematic approach to information requirements management from a lifecycle perspective. This will further enhance the understanding of the relationships between information requirements management processes, protocols, toolsets and the current digital engineering related processes, specifications and data schemas and best practices in configuration management.

Table 8.1 Research contributions to theory, methodology, practice and policy

Area of Research Contribution	Status of Research in Extant Literature	Details of Contribution
RCI-1 Contributions of this research to the theories of systems engineering and requirements management	There are limited applications of systems engineering and requirements management theories in the literature in the complex rail transport sector in the digital engineering context.	An Addition: reviewed the system engineering and requirements management theory in the complex rail transport sector in the digital engineering context.
RCI-2 Contributions of this research to design science research methodology and mixed methods	There are detailed accounts in the literature of the application of design science research to a range of practical issues, although limited coverage in the complex rail transport sector.	An Addition: application of design science research to information requirements management in the complex rail transport sector.
RCI-3 Contributions of this research to the practice of requirements management	In the complex rail transport sector, requirements management practices focus on the technical system requirements. Approaches supporting the management of information requirements in the literature are limited and most of them focus on the advanced manufacturing sector or software sector. There is a lack of an integrated approach to support the interface management of different requirements in the transport sector.	An Advance: how to assess and improve the information requirements management capabilities in the transport sector. Identify key requirements management activities that fill the gaps between digital engineering and systems engineering disciplines. Linking between AIR specifications and schemas, CDE Setup and Configuration Management gates.
RCI-4 Contributions of this research to digital engineering policies	In the transport sector, there are standards and guidelines for systems engineering (managing technical systems requirements) and digital engineering management. However, there is limited coverage in terms of interface and interaction management of the digital engineering discipline and systems engineering discipline.	An Addition: digital engineering standards or guidelines to reflect how the information requirements management process is integrated with the existing project management process.

8.2.2 Contributions to Methodology

The design science research methodology developed for this research was based on Hevner's (2004) design science research conceptual framework to explore the improvement of information requirements management capability in the rail transport sector. This framework consists of three main cycles: relevance cycle, rigour cycle, and design cycle. The approach developed to undertake the design science research was adapted according to the context of the complex rail transport sector under digital transformation. Mixed methods were adopted to collect firsthand data via semi-structured interviews, online survey, and second-hand data via industry reports, standards and guidelines. Mixed methods provided an opportunity to incorporate every available source of data, qualitative and quantitative. This research contributes to the literature on design science research and incorporating mixed methods in its application to the capability improvement area and in the rail transport sector.

8.2.3 Contributions to Practice

One of the main contributions of this thesis is the development of the Capability Improvement Framework for information requirements management supporting the creation of digital twin deliverables in the rail transport sector. The contribution and novelty of this framework include:

- Filling the gap between the systems engineering process and digital engineering management process. This framework focuses on the interface management between systems engineering and the digital engineering process, to align the information requirements with technical systems requirements.
- Providing an activity-based and implementation-ready guideline for organisations seeking information requirements management capability improvement. Most current maturity improvement models for requirements management are at the general level and could not be directly implemented by an organisation or a project. This research fills this gap by providing a checklist of information requirements management related activities for complex rail transport projects. Organisations or project teams are able to use the checklist and embed these activities into their existing project management processes to support effective information requirements management.
- Identifying not only what activities should be conducted, but also when they should be conducted. Each information requirements management activity in this framework is mapped to the project stage as well as requirements management capability area.
- Providing links between AIR specifications and project data schemas, client and project common data environment setup and configuration management gates.

8.2.4 Contributions to Policy

In the complex rail transport sector, there are a range of standards and guidelines for systems engineering (managing technical systems requirements) and digital engineering management (focusing on information management of digital deliverables). However, there is limited coverage in terms of interface and interaction management of the digital engineering discipline and systems engineering discipline. The research highlighted the importance of early planning of information requirements management and integration with existing project management and digital engineering management processes. The framework can be reproduced in the form of a policy or guideline by government transport agencies in Australia as an extension of their existing standards for digital engineering management.

8.3 Limitations

Information requirements management is an area that has been neglected in this sector as it sits between the systems engineering process and the digital engineering management process. Thus, the information requirements management activities developed in this framework indicated an interactive process between systems engineering, digital engineering and project management activities. To support effective information requirements management, it is essential to perform the systems engineering, digital engineering and project management related activities in parallel with the information requirements management activities. As stated in Chapter 7, the practical way to implement the information requirements management activities is to integrate them into existing project management processes.

Due to the time constraints of this research project, the validation of this framework remained at feedback session level rather than implementation in real projects. Thus, the effectiveness of this improvement framework has not been supported by a real project application. Implementation of the framework in case studies and assessment of the effectiveness of this framework is a target of future work, to be conducted in postdoctoral studies.

The research and the requirements management activities within this framework focus on the client-side perspective and largely on client responsibilities to implement integrated processes and data frameworks in support of information requirements management. However, the activities conducted by contractors and sub-contractors are not addressed within the current scope of the framework. Extending the activity list to the whole supply chain could encourage wider implementation of this framework.

8.4 Future Work and Recommendations

Future research should focus on the following aspects: 1) future validating the framework via case study implementation, 2) developing information requirements management activities for the whole supply chain, 3) generalising the framework to the wider transport sector, and 4) simplifying the framework.

1) While the framework has been revised and improved based on feedback from industry experts via feedback sessions, real case study feedback is lacking. Future implementation in real projects could provide solid evidence on the effectiveness of the framework.

2) While the information requirements management activities developed in this framework support the client-side requirements management capability, guidance to contractors and sub-contractors is limited. Expanding the list to the whole supply chain could

support wider implementation of this framework and improve supply chains' capability of information requirements management.

3) The focus of this research is on the complex rail transport sector. However, there is a growing demand of capability improvement in other transport sectors such as roads. By identifying the main differences between these sectors, this framework could be tailored and implemented in other sectors.

4) The current framework is comprehensive, with 82 information requirements management activities covering 8 project stages. It may be challenging to convince an organisation or project team to add all of those activities to their existing processes. Thus, simplifying the improvement framework by grouping activities is an important direction of future work. For example, these activities could be categorised into strategic, tactical or operational level. The required supporting technology or software for each activity could be identified, as well as the linked documentation of each activity.

8.5 Further Discussion

This section explores fundamental barriers contributing to the substantial gap observed in the current infrastructure tool ecosystem. The viability and practicality of adopting a cloud-based data warehouse approach to futureproof infrastructure assets is examined.

8.5.1 Gap in Infrastructure Project Tool Ecosystems

Throughout this research project, it became evident that there is a significant gap in the current infrastructure tool ecosystem. It is worth exploring some of the underlying barriers caused by the dependency on software providers to implement application programming interfaces (APIs) between model authoring software, data warehouse platforms, and the common data environment where data specifications and schemas are configured. This creates challenges in establishing links between these software platforms and tools for system requirements verification and management, such as IBM Doors. The use of file-based information containers instead of a database-driven approach for asset data deliverables further complicates and fragments digital engineering practices. In the infrastructure construction sector, there is a lack of connected data capability within tool ecologies, which hinders the ability to establish links between:

(1) the various modelling tools themselves (e.g., BIM, CAD, GIS, etc.) and then between these tools

(2) collaboration platforms like the common data environment and Enterprise data management platforms

(3) the recent introduction of asset data verification capabilities through rule-based systems, such as Solibri

(4) the systems engineering tools like IBM Doors that facilitate traceability and verification of asset information requirements.

The gaps between (1), (2), (3) and (4) result in a misalignment of the systems and digital engineering delivery activities due to the incremental verification of information requirements management along with technical systems requirements (e.g., using IBM Doors), as illustrated in the Diamond model in Chapter 5.

8.5.2 Cloud-based Data Warehouse Approach for Futureproofing Infrastructure Assets

In recent years, there has been a growing emphasis on the management of information requirements and data integrity in the infrastructure construction sector, especially within the rail construction sector, and shifts towards a cloud-based data warehouse approach. For instance, Transport for New South Wales has adopted an enterprise approach to the Digital Engineering Framework that relies on project delivery partners adhering to a more strategic approach to asset lifecycle management through data-driven approaches. This means that to ensure that asset data generated during project stages can be validated effectively, it is essential for the software application/s involved in the (a) design coordination (e.g., common data environments), (b) data verification (e.g., Solibri), and (c) traceability/change management to seamlessly interface with the engineering and construction models as well as associated metadata. This interface should be real-time and enable smooth integration with BIM, CAD, GIS models and metadata. This will facilitate efficient project delivery within tight timelines.

To enhance their offerings, software vendors that provide common data environment, rule-based checking, and requirements traceability and verification capabilities should prioritise the development and integration of BIM/CAD/GIS connectors as plug-ins within these respective systems. These connectors will facilitate the extraction of asset information from the model's databases and enable seamless communication between different platforms. This requires the process to be initiated from the BIM/CAD/GIS side rather than from the common data environment, rule-based checking, requirements management end of the software – which poses a risk of potential inconsistencies between these systems (i.e., common data environment, rule-based checking, requirements management software) and the BIM/CAD/GIS data. The main challenge lies in the manual and static nature of the "connector" process, although this may vary depending on how the common data environment is configured. As a result, project IT teams, vendors of common data environments, rule-based checking tools, and requirements management software – and ultimately Transport for New South Wales – are therefore at the mercy of the BIM/CAD/GIS software companies who provide access to BIM/CAD/GIS APIs for the development of the connector software.

However, due to the considerable overlap between the digital engineering functions of government transport agencies like Transport for New South Wales, and product lifecycle management (PLM) functions[5]as well as enterprise resource planning (ERP) functions[6] in the engineering environment, BIM/CAD/GIS companies that are also common data environment and rule-based checking technology providers may be quite averse to licensing their APIs to other enterprise application providers. Additionally, since each BIM/CAD/GIS company uses a unique database and corresponding API, it would require companies like Autodesk, Bentley Systems and IBM Doors or others to develop multiple connectors for seamless multi-BIM/CAD/GIS data access in enterprise applications. However, it is uncertain whether the market is large enough for software companies to invest in these connectors at this time. Hence, the vision of employing a cloud-based data warehouse for seamless integration of data management is not feasible from a software development perspective. As a result, the industry currently relies on file-based information containers and will continue to do so until more comprehensive digital engineering frameworks are implemented globally.

To address these challenges, it is crucial for digital engineering as an enterprise initiative to develop innovative solutions that allow seamless access to BIM/CAD/GIS data from various systems, eliminating the need for APIs. A comprehensive solution would involve a single API that can be easily integrated into any enterprise application, enabling efficient data retrieval from multiple BIM/CAD/GIS platforms such as Revit, AutoCAD, OpenRoad, OpenRail, OpenTunnel and ArcGIS. This approach eliminates the necessity of acquiring individual licenses or creating separate connector software for each system. By developing a comprehensive solution that eliminates the need for APIs and allows seamless access to BIM/CAD/GIS data from various systems, the industry can significantly improve efficiency and productivity in data management processes.

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[5] PLM functions include management of design and process documents, product structure (bill of material) management, central data vault (electronic file repository), asset and document classification and metadata (“attribute”) management, materials content identification for environmental compliance, product-focused project task assignment, workflow and process management for approving changes, multi-user secured access, including "electronic signature” and data export for loading to downstream systems.

[6] ERP functions include accounting, procurement, project management, risk management and compliance, and supply chain operations, etc.

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Appendices

Appendix A: Publications Arising from this Research

Journal paper:

- Chen, Yu, and Julie R. Jupp, “Challenges to requirements management in complex rail transport projects”, *International Journal of Product Lifecycle Management*, 2023, 15, (2), pp.139-177.

Conference papers:

- Chen, Yu, and Julie R. Jupp, “Investigating Requirements Management Capabilities in Major Infrastructure Project Delivery”. *IEEE EI conference, 22-23 November 2023, Melbourne, Australia*.
- Chen, Yu, and Julie R. Jupp, “Exploring the Nexus between Digital Engineering and Systems Engineering and the Role of Information Management Standards”, *45th Australasian Universities Building Education Association Conference (AUBEA), 2022, Sydney, Australia.*
- Chen, Yu, and Julie R. Jupp, “Towards a Requirements Co-engineering Improvement Framework: Supporting Digital Delivery Methods in Complex Infrastructure Projects”. 19th *IFIP International Conference on Product Lifecycle Management, 10-13 July 2022, Grenoble, France.*
- Chen, Yu, and Julie R. Jupp, “Requirements Engineering in Complex Infrastructure: Challenges to the Development and Management of Rail Transport Requirements”. *44th Australasian Universities Building Education Association Conference (AUBEA), Deakin University, Melbourne, Australia* (2021): 120.
- Chen, Yu, and Julie R. Jupp, “Challenges to Asset Information Requirements Development Supporting Digital Twin Creation”. *IFIP International Conference on Product Lifecycle Management*, pp. 474-491. Springer, Cham, 2021.
- Chen, Yu, and Julie Jupp, “BIM and through-life information management: a systems engineering perspective”. *Advances in Informatics and Computing in Civil and Construction Engineering*, pp. 137-146. Springer, Cham, 2019.
- Chen, Yu, and Julie Jupp, “Model-based systems engineering and through-life information management in complex construction”. 18th *IFIP International Conference on Product Lifecycle Management*, pp. 80-92. Springer, Cham, 2018.

Poster presentation:

- Chen, Yu, “Improving Requirements Engineering in Transport Infrastructure Projects Supporting Digital Delivery”, Poster Presentation at TRANSW Symposium, 23 November 2022, Building 8, University of Technology Sydney, Australia.
- Chen, Yu, “Improving Requirements Engineering in Transport Infrastructure Projects Supporting Digital Delivery”, Poster Presentation at UTS FEIT Research Showcase, 29 November 2022, Building 11, University of Technology Sydney, Australia.

Appendix B: Glossary

AECO: Architecture, Engineering, Construction and Operations

AFC: Approval for construction

AHP: Analytic hierarchy process

AIM: Asset Information Model

AIRs: Asset Information Requirements

AMAF: Asset management accountability framework

BIM: Building Information Modelling

BRS: Business requirements specification

CAD: Computer Aided Design

CDE: Common Data Environment

CMIS: Content management interoperability services

CMM: Capability maturity model

CMMI: Capability maturity model for integration

COBie: Construction Operation Building Information Exchange

ConOps: Concept of operation

CPS: Cyber-Physical Systems

CPSoS: Cyber-physical system-of-systems

DAM: Digital data management

DE: Digital engineering

DSM: Digital system model

DSP: Digital system program

DEXP/DEEP: Digital engineering execution plan

DT: Digital twin

D&C: Design and construct

ECM: Enterprise content management

EDM: Enterprise document management

EIRs: Exchange Information Requirements

FM:	Facilities management
GIS:	Geographic Information System
IDM:	Information delivery model
IFC:	Industry Foundation Classes
IoT:	Internet of Things
LOD:	Level of Development
MBE:	Model-based engineering
MBSE:	Model-based systems engineering
MCD:	Maintenance concept definition
MCL:	Master classification library
MVD:	Model view definition
NASA:	National Aeronautics and Space Administration (US)
NLP:	Nature language processing
NSW:	New South Wales
OCD:	Operations concept definition
OIRs:	Organisational Information Requirements
O&M:	Operations and Maintenance
PAS:	Publicly Available Specification
PCA:	Physical configuration audit
PIM:	Project Information Model
PIR:	Project Information Requirements
PLM:	Product lifecycle management
QFD:	Quality function deployment
RAMS:	Reliability, availability, maintainability and safety
RCA:	Root cause analysis
R-CMM:	Requirements capability maturity model
REGPG:	Requirements engineering good practice guide
REPAIM:	Requirements engineering process assessment and improvement model

REPM: Requirements engineering process maturity

RM: Requirements management

RPMM: Requirements process maturity model

RISSB: Rail Industry Safety and Standards Board

RVB: Resource-based view

SD: Standard deviation

SE: Systems engineering

SEI: Software Engineering Institute

SLR: System literature review

SoS: System of systems

SPRS: Scope and performance requirements specification

SRS: System requirements specification

SSRS: Sub-system requirements specification

SysML: Systems Modelling Language

TfNSW: Transport for New South Wales

TIP: Technical information provider

VDAS: Victoria Digital Asset Strategy

V&V: Verification and validation

WAE: Work as executed

WBS: Work breakdown structure

Appendix C: Systematic Literature Review Article List

Authors	Title	Domain
1. (Baldauf et al., 2020)	Using Building Information Modelling to manage client requirements in social housing projects	AECO
2. (Succar & Poirier, 2020)	Lifecycle information transformation and exchange for delivering and managing digital and physical assets	AECO
3. (Gebru & Staub-French, 2019)	Leveraging data to visualize and assess space planning compliance	AECO
4. (Heaton et al., 2019)	A Building Information Modelling approach to the alignment of organisational objectives to Asset Information Requirements	AECO
5. (Soliman-Junior et al., 2019)	The role of Building Information Modelling on assessing healthcare design	AECO
6. (Arayici et al., 2018)	Interoperability specification development for integrated BIM use in performance based design	AECO
7. (Ashworth et al. 2017)	Employer's Information Requirements (EIR): A BIM case study to meet client and facility manager needs	AECO
8. (Cavka et al., 2017)	Developing owner information requirements for BIM-enabled project delivery and asset management	AECO
9. (Jallow et al., 2017)	An enterprise architecture framework for electronic requirements information management	AECO
10. (Jupp & Awad, 2017)	BIM-FM and Information Requirements Management: Missing links in the AEC and FM interface	AECO
11. (Kubler et al., 2016)	Building lifecycle management system for enhanced closed loop collaboration	AECO
12. (Parsanezhad et al., 2016)	Formalized requirements management in the briefing and design phase, A pivotal review of literature	AECO
13. (Patacas et al., 2016)	Supporting building owners and facility managers in the validation and visualisation of asset information models (AIM) through open standards and open technologies	AECO
14. (Navendren et al., 2015)	An examination of clients and project teams developing information requirements for the Asset Information Model (AIM)	AECO
15. (Jallow et al., 2014)	An empirical study of the complexity of requirements management in construction projects	AECO
16. (Baldauf et al., 2013)	Using BIM for modeling client requirements for low-income housing	AECO
17. (Kelly et al., 2013)	BIM for facility management: A review and a case study investigating the value and challenges	AECO
18. (Yu et al., 2010)	Managing employers' requirements in construction industry: experiences and challenges	AECO
19. (Arayici et al., 2006)	A requirements engineering framework for integrated systems development for the construction industry	AECO
20. (Johnson et al., 2021)	Informing the information requirements of a digital twin: A rail industry case study	INF
21. (Shirvani et al., 2020)	An architecture framework approach for complex transport projects	INF
22. (Ramos, 2018)	Requirements management - How 110,000 requirements are managed on Northwest Rapid Transit	INF
23. (Fucci et al., 2018)	Needs and challenges for a platform to support large-scale requirements engineering - a multiple-case study	INF
24. (Tolmer et al., 2017)	Adapting LOD definition to meet BIM uses requirements and data modeling for linear infrastructures projects: using system and RE	INF

25.	(Arnaut et al., 2016)	A Requirements Engineering and Management Process in concept phase of complex systems	INF
26.	(Scott et al., 2016)	Case study: A MBSE framework for characterising transportation systems over the full life cycle	INF
27.	(Nekvi & Madhavji, 2014)	Impediments to regulatory compliance of requirements in contractual systems engineering projects: A case study	INF
28.	(Koltun et al., 2017)	Model-Document coupling in aPS engineering: Challenges and requirements engineering use case	MANF
29.	(Wiesner et al., 2017)	Integrating requirements engineering for different domains in system development – lessons learnt from industrial SME cases	MANF
30.	(Pavalkis, 2016)	Towards industrial integration of MBSE into PLM for mission-critical systems	MANF
31.	(Holt et al., 2015)	A model-based approach for requirements engineering for systems of systems	MANF
32.	(Berkovich et al., 2014)	A requirements data model for product service systems	MANF
33.	(Papinniemi et al., 2014)	Challenges in integrating requirements management with PLM	MANF
34.	(Penzenstadler & Eckhardt, 2012)	A requirements engineering content model for cyber-physical system	MANF

Note: AECO – Architecture, Engineering, Construction and Operations, INF – Infrastructure; MANF – Manufacturing

Appendix D: Semi-structured Interview Questions (Sample)

No.	Theme
1	Background Information
1.1	Could you please briefly introduce your background (qualifications) e.g. How many years of work experience do you have?
1.2	Could you describe your current role and responsibilities in your organisation?
2	Experience in project
2.1	You're at the policy and strategy setting/ systems architecture level, how familiar are you with model-based/ BIM/ DE methods…? Have you been involved in many construction/ heavy rail/ or other large infrastructure projects that have implemented BIM/ DE methods...? Have they been ad-hoc implementations within certain organisations, or have they involved a wider more strategic and integrated approach to BIM/ DE across all project stakeholders...?
2.2	Can you tell us more about you experience in MBSE/DE methods relative to requirements management?
3	Challenges of RM in rail industry
3.1	Relative to MBSE and the requirements management methods and tools that are available, what are the main challenges to implementing these approaches in heavy rail projects…?
3.2	What is the current challenge for managing the requirements (both technical/system and information) effectively and efficiently?
3.3	What is the main challenges for the implementation of SE and/or MBSE in support of requirements management?
3.4	Requirements management process – interface of information requirements with technical/system requirements

Appendix E: Online Survey

Welcome to the UTS survey on

Challenges to Information Requirements Development and Management

This survey is designed to understand the **challenges** facing AECO practitioners during the **development and management of information requirements** on projects that use model-based methods and tools to support a strategic approach to **asset information lifecycle management**. The survey builds on earlier research conducted at UTS on the creation of cyber-physical systems and **digital twins** that identified key challenges to the development and management of different requirement types relating to **process, technology, and people & organisational issues**.

All information collected will remain **confidential**. Your answers will be **anonymous** and used for **research purposes only**. Participants who complete the survey and submit their email addresses at the end of this survey will receive a report of the survey findings at the close of the survey period. This survey takes approximately 20 to 30 minutes to complete as it presents a comprehensive picture of the requirements engineering problems impacting the handling of asset information requirements.

Additional information on the survey's background is provided on the next screen. Should you require further information or wish to be involved in the subsequent research interview phase, please contact **Yu Chen** (PhD Candidate) or **Associate Professor Julie Jupp**.

Yu.Chen-4@student.uts.edu.au Julie.Jupp@uts.edu.au

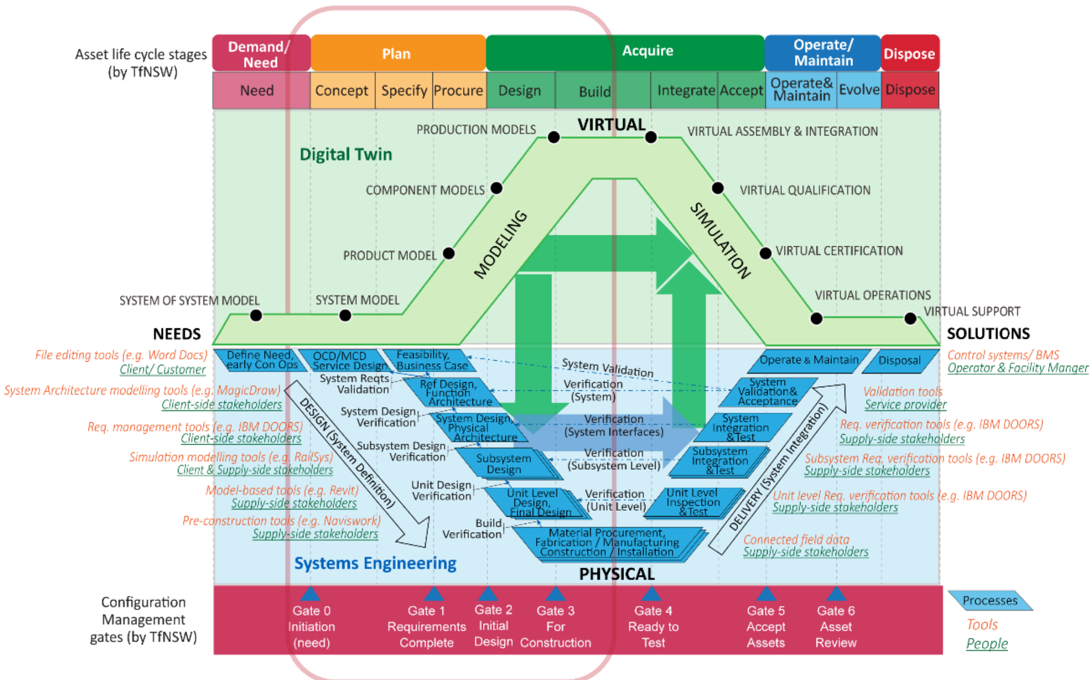
Thank you for your participation.

Survey Background

The use of Digital Engineering methods, and in particular building information modelling (BIM) has played a key role in developing strategic approaches to asset information lifecycle management and the recent creation of Digital Twins to support delivery and operations. During the creation of complex built assets, requirements describing physical systems, their virtual replicas, and real-time behaviours must be developed and managed throughout their digital delivery. Yet, often due to issues related to the scale, complexity, and emergent properties of the physical and cyber systems being developed, developing and managing evolving requirements is increasingly difficult for current engineering practices to handle.

Researchers at the University of Technology Sydney previously conducted research investigating the challenges encountered by project stakeholders during the handling of information requirements on complex infrastructure projects. Using an in-depth literature review and data collected from semi-structured interviews with AECO experts, the research highlighted a range of challenges in the development and management of interdependent requirement types which impact how asset information requirements themselves are handled. This survey continues the research by further exploring and verifying the challenges, and measuring their significance.

The figure below illustrates the general processes, tools and people involved in the planning, acquisition, and operations of an asset using a traditional Systems Engineering view of the asset life cycle, illustrated in the classic V-model, with the Digital Engineering view reflected to create a ‘diamond model’ that allows us to represent the practices of developing the digital twin and associated asset information requirements. The focus of this research looks at how Requirements Engineering is enacted and how information requirements are handled **between Gate 0 and Gate 3.** It also explores the interfaces between requirement types and the impact of associated challenges on downstream Gates.



PART 1: Participant Background Information

Which of the following best describes your role in the AECO industry?

- **Architect**
- **Structural Engineer**
- **Services Engineer**
- **Civil Engineer**
- **Mechanical Engineer**
- **Systems Engineer**
- **Geotechnical Engineer**
- **Environmental Engineer**
- **BIM Coordinator/ BIM Manager**
- **Digital Engineer**
- **Quantity Surveyor**
- **Project Manager**
- **Site Engineer/ Site Manager**
- **Services Subcontractor/ Manufacturer**
- **Facility / Building / Asset Manager**
- **Digital Services Provider** (e.g., 3D animation, 3D scanning, lidar, etc)
- **Client – Public Agency**
- **Client – Private Developer**
- **Academic**
- **Other, please specify**

Over the past 5 years, which sector/s of construction have you been involved with? Please select all that apply.

- **Residential**
- **Retail**
- **Commercial Office**
- **Health**
- **Education**
- **Corrective Services/ Justice**
- **Rail**
- **Roads, Bridges and Highways**
- **Other, please specify**

What is your **level of experience** in the use of digital model-based methods and tools to support a strategic approach to asset information lifecycle management?

For example, implementing building information modelling for facilities management, COBie, digital twin technologies.

- **No Experience**
- **Beginner** (1-5 years experience)
- **Intermediate User** (6-10 years experience)
- **Advanced User** (Over 10 years experience)

What is your **level of experience** in the production of 3D model-based deliverables required to support digital asset management?

- **No Experience**
- **Beginner** (1-5 years experience)
- **Intermediate User** (6-10 years experience)
- **Advanced User** (Over 10 years experience)

What is your **level of experience** in the use of a Digital Execution Plan / BIM Execution Plan which specify asset information requirements?

- **No Experience**
- **Beginner** (1-5 years experience)

- **Intermediate User** (6-10 years experience)
- **Advanced User** (Over 10 years experience)

What is your **level of experience** in the use of asset information classification systems?

For example, Uniclass 2015, UniFormat, MasterFormat, Omniclass, Cuneco, Coclas, etc.

- **No Experience**
- **Beginner** (1-5 years experience)
- **Intermediate User** (6-10 years experience)
- **Advanced User** (Over 10 years experience)

Please specify asset information classification systems most commonly utilised.

What is your **level of experience** in the use of asset data models/ standards for building data exchange to support product data handover from construction to operations?

For example, the COBie (Construction to Operations for Building information exchange), or CONie (Construction to Operations for Network information exchange) standard.

- **No Experience**
- **Beginner** (1-5 years experience)
- **Intermediate User** (6-10 years experience)
- **Advanced User** (Over 10 years experience)

Please specify asset data models/ standards most commonly utilised.

What is your **level of experience** in the use of Australian government infrastructure agency Digital Engineering Frameworks / BIM Standards?

For example, Transport for NSW's Digital Engineering Framework, or the Victorian Digital Asset Strategy (VDAS).

- **No Knowledge** - I have not heard of any government infrastructure agency's Digital Engineering Framework / BIM Standard.
- **Beginner** - I have a general understanding of the concepts and principles of government infrastructure agency Digital Engineering Frameworks / BIM Standards, but have not been directly involved in their implementation on a public project.
- **Intermediate** - I have an intermediate level working knowledge of at least one government infrastructure agency Digital Engineering Framework / BIM Standard and have been directly involved in its implementation on two or more public projects.
- **Advanced** - I have advanced working knowledge of at least one government infrastructure agency Digital Engineering Framework / BIM Standard and have been directly involved in its implementation on three or more public projects.

Please specify Government Agency DE Framework/ BIM Standard most commonly utilised.

What is your **level of experience** in the application of **Parts 1 and 2 of the ISO 19650 BIM Standard**?

I.e., ISO 19650-1: 2018 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling —

Part 1: Concepts and principles *and* ISO 19650-2 2018 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling — Part 2: Delivery phase of the assets.

- **No Knowledge** - I have not heard of the standards.
- **Beginner** - I have a general understanding of the concepts and principles of the standards, but have not been directly involved in their implementation on a project.
- **Intermediate** - I have an intermediate level working knowledge of the standards and have been directly involved in projects implementing the standards.
- **Advanced** - I have advanced working knowledge of the standards and have been responsible for the implementation of the standards.

What is your **level of experience** in the application of **Part 3 of the ISO 19650 BIM Standard**?

I.e., ISO 19650-3: 2020 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling — Part 3: Operational phase of the assets.

- **No Knowledge** - I have not heard of the standards.
- **Beginner** - I have a general understanding of the concepts and principles of the standards, but have not been directly involved in their implementation on a project.
- **Intermediate** - I have an intermediate level working knowledge of the standards and have been directly involved in projects implementing the standards.
- **Advanced** - I have advanced working knowledge of the standards and have been responsible for the implementation of the standards.

What is your **level of experience** in the application of **ISO 12006-2:2015 Building construction — Organization of information about construction works — Part 2: Framework for Classification**?

- **No Knowledge** - I have not heard of the standards.
- **Beginner** - I have a general understanding of the concepts and principles of the standards, but have not been directly involved in their implementation on a project.
- **Intermediate** - I have an intermediate level working knowledge of the standards and have been directly involved in projects implementing the standards.
- **Advanced** - I have advanced working knowledge of the standards and have been responsible for the implementation of the standards.

What is your **level of experience** in the application of **ISO 23387:2020 Building information modelling (BIM) - Data templates for construction objects used in the life cycle of built assets - Concepts and principles**?

- **No Knowledge** - I have not heard of the standards.
- **Beginner** - I have a general understanding of the concepts and principles of the standards, but have not been directly involved in their implementation on a project.
- **Intermediate** - I have an intermediate level working knowledge of the standards and have been directly involved in projects implementing the standards.

- **Advanced** - I have advanced working knowledge of the standards and have been responsible for the implementation of the standards.

What is your **level of experience** in the application of **ISO 16739-1:2018 Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries - Part 1: Data schema**?

- **No Knowledge** - I have not heard of the standards.
- **Beginner** - I have a general understanding of the concepts and principles of the standards, but have not been directly involved in their implementation on a project.
- **Intermediate** - I have an intermediate level working knowledge of the standards and have been directly involved in projects implementing the standards.

  Advanced - I have advanced working knowledge of the standards and have been responsible for the implementation of the standards.

PART 2: Working with Different Requirement Types

Different types of requirements about the physical and cyber systems of complex built assets must be developed and managed throughout the Planning and Acquisition Phases of complex infrastructure projects. Requirement types include, amongst others; high-level capability requirements defining system architecture capabilities; current and future operational requirements; system-, sub-system-, and unit- level requirements spanning functional, physical and performance-based needs; and business case requirements.

To support more strategic approaches to digital asset management, during the Acquisition Phase, asset information requirements describing physical systems, their virtual replicas, and real-time behaviours must also be developed and managed.

ISO 19650 Part 1 defines **Asset information requirements** (AIRs) relative to three additional **information requirement types**, which include: Organisational information requirements (OIRs); Project information requirements (PIRs), and Exchange information requirements (EIRs). The relationships between different types of information requirements are illustrated in the figure below:

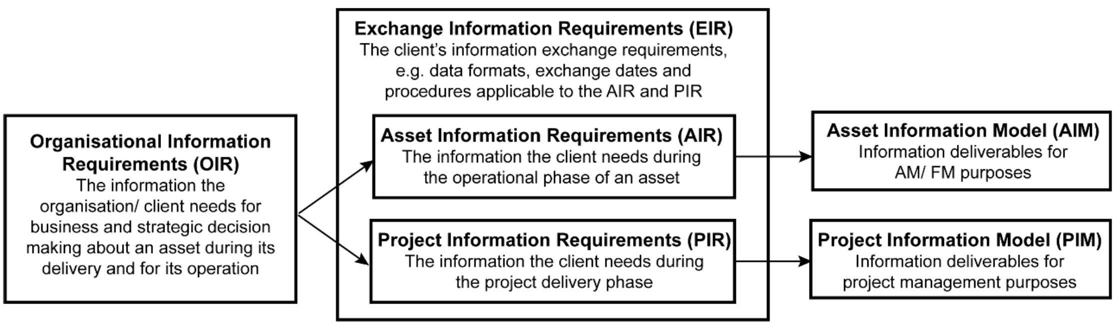


Figure: Relationships between information requirements (source: NATSPEC 2018, 2022)

For more information please refer to the following sources: https://bim.natspec.org/documents/iso-19650-documents and https://bim.natspec.org/documents/abab-air-guide

Please describe **how often** you are involved with the development and/or management of the following types of requirements**.**

	Never	**Less than once per week**	**About once per week**	**More than once per week**	**Most days**
Business case requirements					
System architecture requirements					
Current and future operations requirements					
Physical system requirements					
Performance requirements					
Organisational information requirements					
Project information requirements					
Asset information requirements					
Exchange information requirements					

Please describe your level of experience in the use of **physical system requirements** relative to the following requirements engineering activities**.**

	No Experience	**Beginner** (1-5 years experience)	**Intermediate User** (6-10 years experience)	**Advanced User** (Over 10 years experience)
Eliciting and describing **physical system requirements**				
Analysing and prioritising **physical system requirements**				
Allocating and verifying **physical system requirements**				

Please describe your level of experience in the use of **asset information requirements** relative to the following requirements engineering activities**.**

	No Experience	**Beginner** (1-5 years experience)	**Intermediate User** (6-10 years experience)	**Advanced User** (Over 10 years experience)
Eliciting and describing **asset information requirements**				
Analysing and prioritising **asset information requirements**				
Allocating and verifying **asset information requirements**				

In the past 5 years, have you participated in one or more complex (transport or building facility) infrastructure projects?

- o Yes (Please answer the next question)
- o No (Please click the Next button)

If **Yes**, were you (or your organisation) required by the Appointing Party to produce digital deliverables in support of a strategic approach to asset management in operations?

- o Yes (Please answer the next question)
- o No (Please click the Next button)

If **Yes**, was a Government Agency Digital Engineering Framework or BIM Standard a contractual requirement of the Appointing Party?

For example, from TfNSW's DE Framework or Victorian Digital Asset Strategy (VDAS).

- o Yes (Please answer the next question)
- o No (Please click the Next button)

If **Yes**, was an information classification schema utilised in the delivery of asset information?

	YES	**NO**
OMNICLASS		
UNICLASS 2015		
MASTERFORMAT		
UNIFORMAT		
CUNECO		
COCLAS		

In the past 5 years, have you participated in other Non-Government Agency projects and utilised Digital Engineering/ BIM methods and tools to generate digital deliverables for an Appointing Party?

- o Yes
- o No

PART 3: Requirements Development and Management Practices –

UNDERSTANDING PROCESSES & PROTOCOLS

Please choose the description that best represents the **nature of the processes and protocols*** supporting the handling of **physical system requirements** on your most recent project/s.

* As specified either by the Appointing Party or developed by your own or collaborating party.

	LEVEL 1: Very poor/ no process or protocol (There is no formal process or protocol defined or implemented)	LEVEL 2: Poor formal process and protocol (An ad hoc process and protocol is implemented during project delivery)	LEVEL 3: Fair processes and protocols (An organisational standard exists that describes a generic process)	LEVEL 4: Well-defined processes and protocols (Level 3 + Process is monitored, and performance is assessed)	LEVEL 5: Very well-defined processes and protocols (Level 4 + Continuous process improvement enabled by performance feedback loop)
Physical systems requirements					
Requirements elicitation process					
Requirements analysis and prioritisation process					
Requirements allocation and verification process					
Negotiation of conflicting requirements amongst stakeholders					
Requirements change management process					
Requirements validation process					

Do you have any specific comments about the **handling of physical system requirements** relative to **processes or protocols**?

Please choose the description that best represents the **nature of the processes and protocols*** supporting the handling of **asset information requirements** on your most recent project/s.

* As specified either by the Appointing Party or developed by your own or collaborating party.

	LEVEL 1: Very poor to no formal process or protocol (There is no formal process or protocol defined or implemented)	LEVEL 2: Poor formal process and protocol (An ad hoc process and protocol is implemented during project delivery)	LEVEL 3: Fair processes and protocols (An organisational standard exists that describes a generic process)	LEVEL 4: Well-defined processes and protocols (Level 3 + Process is monitored, and performance is assessed)	LEVEL 5: Very well-defined processes and protocols (Level 4 + Continuous process improvement enabled by performance feedback loop)

Asset Information Requirements (AIRs)					
Requirements elicitation process					
Requirements analysis and prioritisation process					
Requirements allocation and verification process					
Negotiation of conflicting requirements amongst stakeholders					
Requirements change management process					
Requirements validation process					

Do you have any specific comments about the **handling of asset information requirements** relative to **processes or protocols**?

Please choose the description that best represents the use of a **recognised standard** to support the definition and specification of **physical system requirements** and **asset information requirement** on your most recent project/s.

	LEVEL 1: **Very poor - No standard utilised** (There is no standard used to define and specify requirements)	**LEVEL 2:** **Poor – Delivery team standard utilised** (Standards supporting definition and specification of requirements based on individual delivery-side stakeholder approach)	**LEVEL 3:** **Fair – Industry sector standard utilised** (An industry sector-specific standard is used to define and specify requirements)	**LEVEL 4:** **Good – Government Agency standard utilised** (A standard specified by the Government Agency/ Client is used to define and specify requirements)	**LEVEL 5:** **Very Good - International standard utilised** (E.g., ISO Standard used to define and specify requirements)
Physical system requirements					
Asset information requirements					

PART 3: Requirements Development and Management Practices –

UNDERSTANDING PROCESSES & PROTOCOLS (Continued)

Stakeholder involvement in requirements development is a desirable project goal and a contributing factor in determining the successful production of digital deliverables to support digital asset management. Stakeholders include:

- **Project Client** - meaning the organisation that procures the design and delivery of the asset as the main Appointing Party,
- **Project Delivery Team** - meaning the Appointed Parties in the delivery of the asset, e.g. design and engineering services, main contractor, sub-contractors, trades, manufacturers, fabricators, etc.,
- **FM Client** - meaning the organisation that procures facility services by means of a facility management (FM) agreement,
- **FM Customer** - meaning the organisational unit that specifies and orders the delivery of facility services within the conditions of a facility management (FM) agreement,
- **End user** - meaning the person receiving facility services.

Please choose the description that best represents the **level of Project Client-side involvement** in eliciting and analysing **physical system requirements** and **asset information requirements** on your most recent project/s.

	Very poor involvement	Poor involvement	Fair involvement	Good involvement	Very good involvement
Project Client involvement in…					
Physical system requirements elicitation and analysis processes					
Asset information requirements elicitation and analysis processes					

* **Project Client** - meaning the organisation that procures the design and delivery of the asset as the main Appointing Party.

Please choose the description that best represents the **level of Project Delivery Team involvement** in eliciting and analysing **physical system requirements** and **asset information requirements** on your most recent project/s.

	Very poor involvement	Poor involvement	Fair involvement	Good involvement	Very good involvement
Project Delivery Team involvement in…					
Physical system requirements elicitation and analysis processes					
Asset information requirements elicitation and analysis processes					

* **Project Delivery Team** - meaning the Appointed Parties in the delivery of the asset, e.g. design and engineering services, main contractor, sub-contractors, trades, manufacturers, fabricators, etc.

Please choose the description that best represents the **level of FM Client involvement** in eliciting and analysing **physical system requirements** and **asset information requirements** on your most recent project/s.

	Very poor involvement	Poor involvement	Fair involvement	Good involvement	Very good involvement
FM Client involvement in…					
Physical system requirements elicitation and analysis processes					
Asset information requirements elicitation and analysis processes					

* **FM Client** - meaning the organisation that procures facility services by means of an FM agreement.

Please choose the description that best represents the **level of FM Customer involvement** in eliciting and analysing **physical system requirements** and **asset information requirements** on your most recent project/s.

	Very poor involvement	Poor involvement	Fair involvement	Good involvement	Very good involvement
FM Customer involvement in…					
Physical system requirements elicitation and analysis processes					
Asset information requirements elicitation and analysis processes					

* **FM Customer** - meaning the organisational unit that specifies and orders the delivery of facility services within the conditions of an FM agreement.

Please choose the description that best represents the **level of End User involvement** in eliciting and analysing **physical system requirements** and **asset information requirements** on your most recent project/s.

	Very poor involvement	Poor involvement	Fair involvement	Good involvement	Very good involvement
End User involvement in…					
Physical system requirements elicitation and analysis processes					
Asset information requirements elicitation and analysis processes					

*** End user** - meaning the person receiving facility services.

Please choose the description that best represents the level of **continuity of stakeholders involvement** in the ongoing requirements engineering processes relative to **physical system requirements** and **asset information requirements** on your most recent project/s.

	Very poor continuity	Poor continuity	Fair continuity	Good continuity	Very good continuity
Continuity of Project Client-side stakeholder involvement in…					
Physical system requirements engineering processes					
Asset information requirements engineering processes					
Continuity of Project Delivery-side stakeholder involvement in…					
Physical system requirements engineering processes					
Asset information requirements engineering processes					
Continuity of FM Client-side stakeholder involvement in…					
Physical system requirements engineering processes					
Asset information requirements engineering processes					
Continuity of FM Customer-side involvement in…					
Physical system requirements engineering processes					
Asset information requirements engineering processes					
Continuity of End User-side involvement in…					
Physical system requirements engineering processes					
Asset information requirements engineering processes					

Do you have any comments about the **interfaces** or **key fusion points** between the processes for handling **physical system requirements** and **asset information requirements**?

PART 4: Requirements Development and Management Practices – UNDERSTANDING TECHNOLOGY & PEOPLE

Please describe how often you are involved with software tools to support requirements development and management**.**

	Never	Less than once per week	About once per week	More than once per week	Most days
Documentation of **physical system requirements**					
Verification of **physical system requirements**					
Validation of **physical system requirements**					
Documentation of **asset information requirements**					
Verification of **asset information requirements**					
Validation of **asset information requirements**					

Please choose the description that best represents the **nature of the software tools*** supporting the development and management of different types of requirements on your most recent project/s.

* Tools may include system architecture modelling tools (e.g. MagicDraw, GENESYS, Innoslate) as well as project-level requirements management tools (e.g. IBM DOORs, dRofus, Excel).

	LEVEL 1: **Very poor or no software utilisation** (There is no dedicated requirements software tool utilised by project delivery team organisations)	LEVEL 2: **Poor software utilisation** (Separate requirements software tools are utilised across the various project delivery team organisations)	LEVEL 3: **Fair software utilisation supporting an integrated approach** (An integrated requirements software tool/ platform is **used by a minority** of relevant project delivery team organisations)	LEVEL 4: **Good software utilisation supporting an integrated approach** (An integrated requirements software tool/ platform is **used by a majority** of relevant project delivery team organisations)	LEVEL 5: **Very good software utilisation supporting a highly integrated approach** (Level 4 + Requirements managed by a dedicated project role, e.g., requirements engineer, systems engineer, digital engineer, BIM manager)
The use of a **dedicated requirements management software** supporting…					
Documentation of **physical system requirements** Please specify if applicable					
Verification of **physical system requirements** Please specify if applicable					
Validation of **physical system requirements** Please specify if applicable					
Documentation of **asset information requirements** Please specify if applicable					
Verification of **asset information requirements** Please specify if applicable					
Validation of **asset information requirements** Please specify if applicable					

Please choose the description that best represents the **level of integration** of **requirements management software** with **3D modelling software** to support the handling of Physical system requirements and Asset information requirements on your most recent project/s.

	LEVEL 1: Very poor – No software utilised (Neither requirements management nor 3D modelling software is used)	**LEVEL 2: Poor – Only requirements management software utilised** (Requirements management software is used but 3D modelling software is not)	**LEVEL 3: Fair – Requirements management and 3D modelling software utilised** (Separate and distinct requirements management and 3D modelling software is used, however there are no digital links between them)	**LEVEL 4: Good – Partially integrated requirements management and 3D modelling software utilised** (There is basic integration enabled between the requirements management and 3D modelling software utilised, e.g., providing spatially-enabled requirements mapping, linking requirements with 3D objects, and automating a basic level of spatial requirements verification)	**LEVEL 5: Very good – Fully integrated requirements management and 3D modelling software utilised** (There is a high level of integration enabled between the requirements management and 3D modelling software utilised, supporting the use of configuration management to establish and maintain consistency of system performance, functional, and physical attributes with its requirements, design, and operational information)
Physical system requirements					
Asset information requirements					

Do you have any comments about the **integration** or **key fusion points** between **physical system requirements/ asset information requirements** and **model-based interfaces** relative to supporting software capabilities?

PART 5: Requirements Development and Management Practices –

UNDERSTANDING ORGANISATION & PEOPLE

Please choose the description that best represents the **nature of the people and organisational capabilities** supporting the development and management of different types of requirements on your most recent project/s.

Based on your previous project experiences, what was the **frequency** of formally defined requirements engineering **roles and responsibilities** in the Planning and Acquire Phases for handling physical systems requirements and asset information requirements?

	Never	Rarely	Sometimes	Often	Always
Formally defined roles and responsibilities for handling **physical system requirements** in the **Planning Phase**					
Formally defined roles and responsibilities for handling **physical system requirements** in the **Acquire Phase**					
Formally defined roles and responsibilities for handling **asset information requirements** in the **Planning Phase**					
Formally defined roles and responsibilities for handling **asset information requirements** in the **Acquire Phase**					

Based on your previous project experiences, what is the **importance** of clearly and formally defined requirements engineering **roles and responsibilities** in the Planning and Acquire Phases for handling physical systems requirements and asset information requirements?

	Not At All Important	Slightly Important	Moderately Important	Very Important	Extremely Important
Formally defined roles and responsibilities for handling **physical system requirements** in the **Planning Phase**					
Formally defined roles and responsibilities for handling **physical system requirements** in the **Acquire Phase**					
Formally defined roles and responsibilities for handling **asset information requirements** in the **Planning Phase**					
Formally defined roles and responsibilities for handling **asset information requirements** in the **Acquire Phase**					

Based on your previous project experiences, what was the **frequency** of **training in requirements modelling and/or management software** in the Planning and Acquire Phases for handling physical systems requirements and asset information requirements?

	Never	**Rarely**	**Sometimes**	**Often**	**Always**
Training in requirements software in support of **physical system requirements** handling in the **Planning Phase**					
Training in requirements software in support of **physical system requirements** handling in the **Acquire Phase**					
Training in requirements software in support of **asset information requirements** handling in the **Planning Phase**					
Training in requirements software in support of **asset information requirements** handling in the **Acquire Phase**					

Based on your previous project experiences, what is the **importance** of **training in requirements modelling and/or management software** in the Planning and Acquire Phases for handling physical systems requirements and asset information requirements?

	Not At All Important	**Slightly Important**	**Moderately Important**	**Very Important**	**Extremely Important**
Training in requirements software in support of **physical system requirements** handling in the **Planning Phase**					
Training in requirements software in support of **physical system requirements** handling in the **Acquire Phase**					
Training in requirements software in support of **asset information requirements** handling in the **Planning Phase**					
Training in requirements software in support of **asset information requirements** handling in the **Acquire Phase**					

How important are the following **resources** in supporting **a project's successful implementation** of requirements engineering in support of **physical system requirements** handling?

	Not At All Important	Slightly Important	Moderately Important	Very Important	Extremely Important
Resources supporting physical system requirements development and management					
Support from senior management					
Clearly defined roles and responsibilities for physical system requirements					
Training in requirements engineering methods					
Training in requirements modelling software (e.g. MagicDraw, GENESYS, Innoslate, etc.)					
Training in requirements management software (e.g., dRofus, IBM DOORS, etc.)					
Investment in requirements modelling software licenses					
Investment in requirements management software licenses					
Clear Government Agency/ Appointing Party standards and terms of contract covering the application of requirements engineering					
Please list other resources that you think are important:					

How important are the following **resources** in supporting **a project's successful implementation** of requirements engineering in support of **asset information requirements** handling?

	Not At All Important	Slightly Important	Moderately Important	Very Important	Extremely Important
Resources supporting Asset information requirements development and management					
Support from senior management					
Clearly defined roles and responsibilities for asset information requirements					
Training in the development and management of asset information requirements (e.g., ISO 19650 Standard)					
Training in asset management standards (e.g., ISO 55000 standard)					

Training in the use of requirements management software					
Investment in requirements management software licenses					
Clear Government Agency/ Appointing Party standards and terms of contract covering the application of asset information requirements handling.					
Please list other resources that you think are important:					

The remainder of the survey focuses on the **challenges** of developing and managing **physical system requirements** and **asset information requirements**.

NB: **Asset information requirements (AIRs)** are the precise description of the information required to operate and maintain a specific built asset through its lifecycle. The information required in AIR focuses on the as-built state. It defines not only what information is required (content) but also how it should be delivered (form and accepted formats of deliverables). The **AIR** is a subset of the overall project brief. The processes of delivering the assets and the associated data and information are parallel and connected (see the figure below).

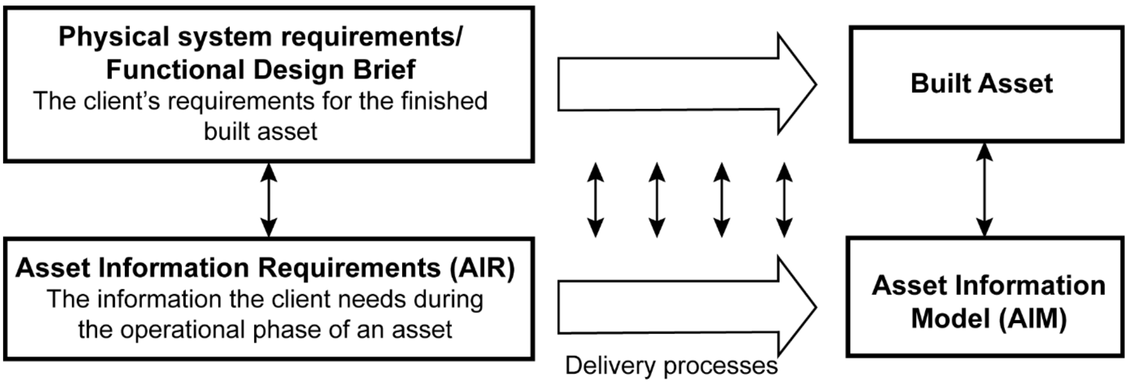


Figure: Parallel delivery of built asset and asset data

Source: https://bim.natspec.org/documents/abab-air-guide

PART 6: Prioritisation of Challenges

A) PROCESS

Please rank the **frequency** of the following **process challenges** to the development and management of physical system requirements and asset information requirements.

	Never	Rarely	Sometimes	Often	Always
Poor **physical system requirements** elicitation, specification and/ or documentation processes (e.g., Requirements written in different level of detail, in different formats, or from different perspectives)					
Poor **asset information requirements** elicitation, specification and/ or documentation processes (e.g., Requirements written in different level of detail, in different formats, or from different perspectives)					
Poor **physical system requirements** validation processes					
Poor **asset information requirements** validation processes					
Disconnects between **system architecture requirements** (including network requirements) and **physical system requirements**					
Disconnects between **system architecture requirements** (including network requirements) and **asset information requirements**					
Physical system requirements not adequately elicited, specified, or documented in Planning Phase					
Asset information requirements not adequately elicited, specified, or documented in Planning Phase					
Disconnects between **requirements management processes** and **design change management** processes					
Disconnects between **design change management** and **asset information requirements traceability**					
Poor **requirements verification and traceability** processes during Acquisition Phase					
Poor **asset information requirements change management**					
Lack of **practical guidelines** supporting development and management of different and interdependent requirements processes					
Poor **interface management** across requirement types					
Poor **management processes** supporting the handling of regulatory compliance documents during **requirements verification**					
Poor **utilisation of software** supporting the handling of regulatory compliance documents during **requirements verification**					

Other process related challenges please list below:

PART 6: Prioritisation of Challenges

B) TECHNOLOGY

Please rank the **frequency** of the following **technology challenges** to the development and management of physical system requirements and asset information requirements.

	Never	Rarely	Sometimes	Often	Always
Insufficient investment in requirements management software licenses					
Lack of **enterprise platforms** supporting integrated modelling and simulation, enabling digital continuity from concept to development to production					
Lack of **integrated** requirements management software tools and 3D modelling software					
Limited **interoperability** between requirements management software and 3D modelling software					
Lack of **interface management processes** supporting the handling of different requirement types throughout the Acquisition Phase					
Lack of **interface management software** supporting the handling of different requirement types throughout the Acquisition Phase					
Lack of common language supporting definition of **physical system requirements** and **asset information requirements**					
Limited use of requirements management software for **verification of physical system requirements**					
Limited use of requirements management software for **verification of asset information requirements**					
Limited use of requirements management software for **validation of physical system requirements**					
Limited use of requirements management software for **validation of asset information requirements**					
Limited use of software to support **configuration management**					

Other technology related challenges please list below

PART 6: Prioritisation of Challenges

C) ORGANISATION & PEOPLE

Please rank the **frequency** of the following **people and organisation related challenges** to the development and management of physical system requirements and asset information requirements.

- **Project Client** - meaning the organisation that procures the design and delivery of the asset as the main Appointing Party,
- **Project Delivery Team** - meaning the Appointed Parties in the delivery of the asset, e.g. design and engineering services, main contractor, sub-contractors, trades, manufacturers, fabricators, etc.,
- **FM Client** - meaning the organisation that procures facility services by means of a facility management (FM) agreement,
- **FM Customer** - meaning the organisational unit that specifies and orders the delivery of facility services within the conditions of a facility management (FM) agreement,
- **End user** - meaning the person receiving facility services.

	Never	**Rarely**	**Sometimes**	**Often**	**Always**
Absence of **Project-Client* participation** in Planning and/ or Acquisition Phases					
Absence of **key Project Delivery Team members** in Planning and/ or Acquisition Phases					
Absence of **FM-Client* participation** in Planning and/ or Acquisition Phases					
Absence of **FM-Customer* participation** in Planning and/ or Acquisition Phases					
Absence of **End-User* participation** in Planning and/ or Acquisition Phases					
Lack of collaborative **requirements engineering processes** during the **Planning Phase**					
Lack of collaborative **requirements engineering processes** during the **Acquisition Phase**					
Lack of a clear description of roles and responsibilities supporting **physical system requirements** development and management					
Lack of a clear description of roles and responsibilities supporting **asset information requirements** development and management					
Lack of experience in **physical system requirements development** (specification, documentation, allocation, validation etc.)					
Lack of experience in **asset information requirements development** (specification, documentation, allocation, validation etc.)					

Lack of experience in **physical system requirements management** (change management, verification and traceability, and validation)					
Lack of experience in **asset information requirements management** (change management, verification and traceability, and verification)					
Lack of training in **requirements engineering** methods					
Lack of training in **requirements engineering** software					
Lack of understanding and support from senior management in general requirements engineering methods					
Lack of understanding and support from senior management in handling **asset information requirements**					
Lack of experience in the creation of digital deliverables comprising 3D models and supporting databases					
Poor collaboration and lines of communication between Project Delivery Team members handling different requirement types					

Other organisation and people related challenges please list below:

Thank you for participating in this survey, if you would like to receive feedback on this study findings, please list your email address:

We thank you for your time spent taking this survey.

Your response has been recorded.

Appendix F: Capability Improvement Framework Overview

TfNSW Phases AS ISO 55001	TfNSW Asset Lifecycle Stages	Scores 3-Standardised 2-Normal 1-Discretionary 0-Never used	No.	Information Requirements Management (iRM) Activities	Project or Enterprise level (P/E)	Basic or Advanced Activity (B/A)	RM capability area	Reference
Demand /Need	**1 Need**		1.1	Prepare or review existing data and information asset management policy/strategy/standard, aligned to the asset management strategy	E	B	Requirements elicitation	PAS1192, TS 01515
			1.2	Establish or review existing/new organisational information requirements (OIRs) to ensure asset management activities are appropriately identified in the policy, strategy and plan	E	B	Requirements elicitation	PAS1192
			1.3	Identify asset/facilities managers as primary stakeholders and support the delivery team in understanding the operational service needs	E	B	Stakeholder involvement	BuildingSMART
			1.4	Understanding the asset managers' information requirements in the strategic and operational management of assets	E	B	Requirements elicitation	BuildingSMART
			1.5	Establish or review existing Concept of Operations (ConOps) or concept brief or service need	E	B	Requirements elicitation	TS 01498
			1.6	**Establish configuration management baselines and review gates for milestone delivery**	E	B	Configuration management	CMMI
			1.7	**Establish and maintain the plan for performing information requirements management process (linked to configuration management baselines)**	E	A	RM protocol and language	CMMI
Plan	**2 Concept**		**2.1**	**Develop/update Master Classification Library (MCL)/Common Data Dictionary based on identified system or asset and locations using common corporate asset classification coding standard (e.g., Uniclass)**	E	A	RM protocol and language	TS 01498 TfNSW DE P2

TfNSW Phases AS ISO 55001	TfNSW Asset Lifecycle Stages	Scores 3-Standardised 2-Normal 1-Discretionary 0-Never used	No.	Information Requirements Management (iRM) Activities	Project or Enterprise level (P/E)	Basic or Advanced Activity (B/A)	RM capability area	Reference
			2.2	When developing and completing Operations Concept Definition (OCD) and Maintenance Concept Definition (MCD), ensure that O&M requirements are allocated to the appropriate corporate asset classification (e.g., complex, facility, system and/or asset, and asset location)	P	B	Requirements allocation	Interview
			2.3	Establish the DE project strategy (approach to DE implementation)	P	A	Senior management support	TfNSW DE
			2.4	**Establish/review data classification and referencing (include asset classification, asset references, location classification, location references – confirming the "Common Data Model" for the client/asset owner based on the MCL.) Buildings = COBie/ Infrastructure Transport Data Building Blocks (Uniclass + Project / Contract Info + Legacy Asset classifications)**	E	A	RM protocol and language	Interview
			2.5	**Based on DE project strategy and setup, establish the project data dictionary (In Transport this equates to the Project Data Building Blocks (PDBB))**	P	A	RM protocol and language	TfNSW DE
			2.6	Aligning with the Project Management Plan (PMP), specify asset information required for O&M (based on DE Framework and PDBB or OIRs), AKA asset information requirements (AIRs)	P	B	Requirements elicitation	TS 01498 TfNSW DE P2
			2.7	**Generate Project Data Schemas (PDS) based on functional requirements and AIRs, following the Master Classification Library (data dictionary) established in Activity 2.4**	P	A	RM protocol and language	VDAS TfNSW DE
			2.8	**Establish the Client-side Common Data Environment (CDE) which includes Enterprise Content Management, Scheduling Schemas, Cost Estimating Systems, etc., Workflow definition and management processes linked to design coordination and information requirements management activities to be**	E + P	A	Integration/ Interoperability of tools	TfNSW DE

TfNSW Phases AS ISO 55001	TfNSW Asset Lifecycle Stages	Scores 3-Standardised 2-Normal 1-Discretionary 0-Never used	No.	Information Requirements Management (iRM) Activities	Project or Enterprise level (P/E)	Basic or Advanced Activity (B/A)	RM capability area	Reference
				established against the information requirements management plan (see "Need" Activity 1.6 and 1.7)				
			2.9	Embed Project Data Schemas/AIRs in the tender document (relative to other DE requirements including scope, draft DEXP, draft project data schema)	P	B	Integration of RM protocols with PM protocols	TfNSW DE
			2.10	Support the delivery team's tender response (Ensure alignment between information requirements/project data schemas, contract templates, technical disciplines and deliverables)	P	B	Integration of RM protocols with PM protocols	ISO 19650
			2.11	**When conducting tender evaluation, include the requirement for an information requirements management plan aligned to ISO 19650 (e.g., TIDP, MIDP, DEXP), project data schema alignment in assessment criteria, and CDE workflow specifications supporting asset information requirements management plan**	P	A	Integration of RM protocols with PM protocols	TfNSW DE, VDAP
			2.12	After awarding the contract, review and approve contractor's information requirements management plan which is included in DEXP against the tender document	P	A	Requirements change management	Interview
			2.13	After awarding the contract, review and approve contractor's final validation method to comply with project data schemas against the tender document	P	A	RM protocol and language	TfNSW DE
			2.14	**After awarding the contract, support the establishment of contractor's CDE which should include configuration of project data schemas (e.g., CAD, GIS, BIM, etc.) and specify the technology requirements to support information RM workflows (e.g., use of Solibri or Revizto for data validation), and integrate with the client CDE**	P	A	Integration/ Interoperability of tools	TfNSW DE

TfNSW Phases AS ISO 55001	TfNSW Asset Lifecycle Stages	Scores 3-Standardised 2-Normal 1-Discretionary 0-Never used	No.	Information Requirements Management (iRM) Activities	Project or Enterprise level (P/E)	Basic or Advanced Activity (B/A)	RM capability area	Reference
			2.15	**Update Project Data Schemas/AIRs to align with approved DEXP**	P	B	Requirements change management	TfNSW DE
			2.16	Validate the DE data (e.g., ECM data schema) in Strategic Business Case (SBC) (establish RVTM) submitted by Contractor against updated Project Data Schemas/AIRs in 2.15	P	B	Requirements verification and validation	TfNSW DE
			2.17	Validate the DE data (design model and data schema) in Options Design Model submitted by Contractor against updated Project Data Schemas/AIRs in 2.15	P	B	Requirements verification and validation	Survey
			2.18	**Model-based approaches are implemented to verify that Option Design deliverables are compliant with information requirements (AIRs, PIRs, EIRs) by contractor via CDE**	P	A	Requirements verification and validation	TfNSW CMF
	3 Specify		3.1	Elicit and analyse stakeholder information requirements with the support from asset and facilities management teams	P	B	Requirements elicitation Requirements analysis and prioritisation Stakeholder involvement	Interview
			3.2	Clarify existing or planned operating information management systems/software, and identify legacy asset and location classification, and hierarchy requirements	P	B	Requirements analysis and prioritisation	Interview
			3.3	**After the approval of SBC, review and update OIRs and Project Data Schemas/AIRs against the context of the project (e.g., key decision points when information is required, level of information need, LOD, asset classification, asset location reference, asset attributes and data schemas, asset register, etc.)**	P	B	Requirements change management	VDAS

TfNSW Phases AS ISO 55001	TfNSW Asset Lifecycle Stages	Scores 3-Standardised 2-Normal 1-Discretionary 0-Never used	No.	Information Requirements Management (iRM) Activities	Project or Enterprise level (P/E)	Basic or Advanced Activity (B/A)	RM capability area	Reference
			3.4	Embed information requirements of the OCD and MCD in the Business Requirements Specification (BRS)	P	B	Requirements elicitation	TfNSW DE P2
			3.5	When performing the feasibility study assessment on the preferred conceptual option, include the information requirements feasibility assessment	P	B	Requirements elicitation	Interview
			3.6	Develop the System architecture framework that draws together functional and performance requirements using SysML (make sure it aligns with the high-level DE assets classification hierarchy)	P	A	Systems architecture framework development	Interview
			3.7	**Review Project Data Schemas/AIRs based on outcomes of validation of business requirements using performance modelling simulations**	P	A	Requirements verification and validation	TS 01504
			3.8	**Update Project Data Schemas/AIRs which should be included in System requirements specification (SRS) (need to define interface between systems/technical requirements and information requirements)**	P	A	Requirements change management	TfNSW DE
			3.9	**Update client CDE (updates relative to revisions made to PDS and/or new contractor involvement)**	E + P	A	Integration/ Interoperability of tools	TfNSW DE
			3.10 - 3.15	// Repeat Activities 2.9 to 2.14				
			3.16	**Analyse and maintain project data schemas/AIRs in System Requirements Specification (update RVTM) for Final Business Case (FBC) (including review the integrity of AIR specifications, define the validation criteria for each AIR, allocate the AIRs to the relevant system or element, allocate the responsibility associated with each AIR, establish and maintain system level requirements traceability)**	P	B	Requirements analysis and prioritisation Requirements allocation Requirements traceability Requirements	TfNSW DE

TfNSW Phases AS ISO 55001	TfNSW Asset Lifecycle Stages	Scores 3-Standardised 2-Normal 1-Discretionary 0-Never used	No.	Information Requirements Management (iRM) Activities	Project or Enterprise level (P/E)	Basic or Advanced Activity (B/A)	RM capability area	Reference
							verification and validation	
			3.17	Validate the DE data (e.g., ECM data schema) in Final Business Case submitted by Contractor against updated Project Data Schemas/AIRs in Activity 3.16	P	B	Requirements verification and validation	TfNSW DE
			3.18	Validate the DE data (design model and data schema) in Feasibility Design Model submitted by Contractor against updated Project Data Schemas/AIRs in Activity 3.16	P	B	Requirements verification and validation	TfNSW DE
			3.19	**Model-based approaches are implemented to verify that feasibility design deliverables are compliant with information requirements (AIRs, PIRs, EIRs) by contractor via CDE**	P	A	Requirements verification and validation	TfNSW CMF
	4 Procure		4.1	After the approval of FBC, update Project Data Schemas/AIRs which should be included in partly developed sub-system requirements specification (SSRS)/Scope and performance requirements specification (update RVTM)	P	B	Requirements analysis and prioritisation Requirements change management	TfNSW DE
			4.2	**// Repeat Activity 3.9**	E + P	A	Integration/ Interoperability of tools	TfNSW DE
			4.3	**Establish the Asset Register/ Asset Breakdown Structure according to the updated Project Data Schemas/AIRs**	P	B	RM protocol and language	TfNSW DE
			4.4 - 4.9	// Repeat Activities 2.9 to 2.14				TfNSW DE
			4.10	Validate the DE data (design model and data schema) in Concept Design (also called Reference Design) Model submitted by Contractor against updated AIRs in 4.4	P	B	Requirements verification and validation	TfNSW DE

TfNSW Phases AS ISO 55001	TfNSW Asset Lifecycle Stages	Scores 3-Standardised 2-Normal 1-Discretionary 0-Never used	No.	Information Requirements Management (iRM) Activities	Project or Enterprise level (P/E)	Basic or Advanced Activity (B/A)	RM capability area	Reference
			4.11	**Model-based approaches are implemented to verify that concept design/reference design deliverables are compliant with information requirements (AIRs, PIRs, EIRs) by contractor via CDE**	P	A	Requirements verification and validation	TfNSW DE
			4.12	**After the approval of Concept design/Reference design, update Project Data Schemas specifying AIRs in partly developed sub-system requirements specification (SSRS)/Scope and performance requirements specification**	P	B	Requirements change management	TfNSW DE
			4.13	**// Repeat Activity 3.9**	P	A	Integration/ Interoperability of tools	TfNSW DE
			4.14 – 4.19	// Repeat Activities 2.9 to 2.14				
Acquire	5 Design		5.1	Update Project Data Schemas/AIRs in sub-system requirements specification (SSRS) / Scope and performance requirements specification at the unit level (update RVTM with design verification evidence)	P	B	Requirements analysis and prioritisation Requirements change management	TfNSW DE
			5.2	**Allocate updated Project Data Schemas/AIRs in Activity 5.1 into design/work packages in collaboration with development of the commercial and procurement strategy and update client and project CDEs and linked requirements management workflows**	E + P	B	Requirements allocation	TfNSW DE
			5.3	Document defined asset locations, sub-systems/assets, design/work packages and work zones in the data dictionary and data schemas	P	A	RM protocol and language	TfNSW DE

TfNSW Phases AS ISO 55001	TfNSW Asset Lifecycle Stages	Scores 3-Standardised 2-Normal 1-Discretionary 0-Never used	No.	Information Requirements Management (iRM) Activities	Project or Enterprise level (P/E)	Basic or Advanced Activity (B/A)	RM capability area	Reference
			5.4	Validate the DE data (design model and data schema) in Preliminary Design Model (LOD 200, 20%–30% completion) submitted by Contractor against updated project data schemas/AIRs	P	B	Requirements verification and validation	TfNSW DE
			5.5	**Model-based approaches are implemented to verify that Preliminary design deliverables are compliant with information requirements (AIRs, PIRs, EIRs) by contractor via CDE**	P	A	Requirements verification and validation	TfNSW DE
			5.6	Validate the DE data (design model and data schema) in Critical Design Model (LOD 300) submitted by Contractor against updated project data schemas/AIRs	P	B	Requirements verification and validation	TfNSW DE
			5.7	**Model-based approaches are implemented to verify that Critical design deliverables are compliant with information requirements (AIRs, PIRs, EIRs) by contractor via CDE**	P	A	Requirements verification and validation	TfNSW DE
			5.8	**Issue the Critical design review asset register to Enterprise Asset Management (EAM) platform, aligning with the updated project data schemas/AIRs**	E	A	Requirements verification and validation	TfNSW DE
			5.9	Document additional systems and/or sub-systems identified during the design process in the SSRS, data dictionary and data schema, update project data schemas/AIRs	P	B	Requirements change management	TfNSW DE
			5.10	Demonstrate traceability of design elements to business, system, and sub-system requirements using the agreed requirements schema and specification	P	B	Requirements traceability	TfNSW DE
	6 Build and Integrate		6.1	After the approval of Critical Design, validate the DE data (design model and data schema) in the Approved for Construction (AFC) model submitted by Contractor against the updated project data schemas/AIRs	P	B	Requirements verification and validation	TfNSW DE

TfNSW Phases AS ISO 55001	TfNSW Asset Lifecycle Stages	Scores 3-Standardised 2-Normal 1-Discretionary 0-Never used	No.	Information Requirements Management (iRM) Activities	Project or Enterprise level (P/E)	Basic or Advanced Activity (B/A)	RM capability area	Reference
			6.2	**Model-based approaches are implemented to verify that Approved for Construction (AFC) design deliverables are compliant with information requirements (AIRs, PIRs, EIRs) by contractor via CDE**	P	A	Requirements verification and validation	TfNSW DE
			6.3	Conduct system verification review, making sure the DE data meets the updated project data schemas/AIRs	P	B	Requirements verification and validation	TfNSW DE
			6.4	Before getting ready for testing, validate the Work as executed (WAE) asset register against the updated project data schemas/AIRs (update RVTM with material procurement, manufacturing and installation verification evidence)	P	B	Requirements verification and validation	TfNSW DE
			6.5	**Update project data schemas/AIRs in RVTM with testing and commissioning and V&V evidence, update the client and project CDEs with V&V evidence**	E + P	A	Requirements verification and validation	TS 01498
	7 Accept		7.1	Validate the DE data (design model and data schema) in the As-Built model submitted by contractor against the updated project data schemas/AIRs	P	B	Requirements verification and validation	TfNSW DE
			7.2	Validate the DE data when conducting physical configuration audit (PCA) against the updated project data schemas/AIRs	P	B	Requirements verification and validation	TfNSW DE
			7.3	**Review EAM and as-built asset register and evidence, making sure it meets the updated project data schemas/AIRs**	E + P	A	Requirements verification and validation	VDAP
			7.4	The asset/facilities manager/s performs final assurance of the AIM against the AIRs before assets are placed in service	P	B	Stakeholder involvement	Interview