Challenges to Asset Information Requirements Development Supporting Digital Twin Creation

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Abstract. The creation of a digital twin of rail infrastructure assets places greater emphasis on requirements engineering, model-based delivery methods, and digital information management to support the creation of both physical and virtual deliverables. However, requirements engineering capabilities are latent in comparison to complex discrete manufacturing. In this paper, we explore requirements engineering practices in Australian rail infrastructure projects creating digital twins for asset management and operations. An investigation of the challenges encountered by project teams during the development of asset information requirements for physical and digital deliverables was conducted using an in-depth literature review together with semi-structured interviews with rail project delivery teams. Challenges to the maturity of requirements engineering were categorised according to their main characteristics. The process, technology and supply chain issues identified provide empirical evidence of the pain points faced by delivery teams in developing asset information requirements in support of the creation of a digital twin. Findings serve as a starting point for further research into the development of requirements engineering methods distinguished by systems-based approaches.

Keywords: Requirements Engineering, Digital Twin, Asset Management, Systems Engineering, Rail Infrastructure.

1 Introduction

During the creation of a digital twin, informational requirements supporting the delivery and operations of physical systems, their virtual replicas, and real-time behaviours must be developed [1]. There are different types of information requirements related to the delivery and operational phase of rail infrastructure. The release of the International Standard ISO 19650, Parts 1 and 2 have provided rail projects with much needed consistency in the terminology, concepts, and principles of information requirements and related processes. The standard describes each information requirement type and process relative to the project delivery phases; it includes: i) organisation information requirements (OIR), ii) asset information requirements (AIR), iii) project information requirements (PIR), and iv) exchange (or employer) information requirements (EIR) [2, 3].

The information requirements defining rail assets follow a similar development process as in discrete manufacturing and software development projects; in what is a series of interconnected activities encompassing requirements elicitation and description, documentation and decomposition, analysis and allocation, and validation. However, recent research demonstrates that requirements development practices are relatively immature in the construction industry [4]. In complex construction projects generally, and in particular those creating digital twins to support rail infrastructure asset management and operations, lack mature methodologies and integrated tool ecologies to support information requirements development activities. Whilst ISO 19650 (Parts 1 & 2) [2, 3], provides much needed guidance to building and civil engineering projects in this area, there remains a lack of implementation-ready requirements development methods supported by software that can help automate, integrate, trace and record asset information requirements across temporary project-based supply chains.

Against this backcloth, the authors explore contemporary requirements engineering practices in rail infrastructure projects relative to the development of physical and virtual (digital twin) deliverables, and examine the challenges encountered by project stakeholders. The research aim is to identify and categorise challenges in order to understand the barriers to the development of asset information requirements that ultimately impact on the creation of a digital twin. The paper proceeds in Sections 2 and 3 with an overview of related literature. Section 4 describes the qualitative research methodology, and Section 5 presents the categories of challenges and discusses findings derived from interviews with rail infrastructure stakeholders. Section 6 concludes the paper with recommendations and discussion of open issues concerning systems approaches to requirements engineering and greater emphasis on co-engineering.

2 Digital Twin Creation and Requirements Development

The "Digital Twin" (DT) concept was first introduced by Grieves in 2003 [5]. Since then, definitions and explanations of the DT concept have been proposed and refined [5–8]. DT technologies were adopted in the spacecraft sector in 2010 and later in complex manufacturing sectors [9, 10]. NASA were pioneers of DT technologies for remote monitoring, controlling and running simulations of spacecraft from Earth [11]. DT applications in the aerospace, defence and nuclear sectors are often regarded as some of the most advanced due to higher demands for managing and optimising the performance of complex assets [1].

The development processes surrounding the physical asset and its virtual replica are described by Boeing using the classic V-model of the systems development lifecycle, mirroring the 'V' to create a "Diamond Model" [12]. With Model-based Engineering (MBE) as its foundations, the Diamond Model reflects the co-development processes of both the physical and virtual assets (see Fig. 1). The lower V reflects the classic systems engineering process of the physical system, while the mirror reflection of the V above represents the DTs modelling and simulation [12]. 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.

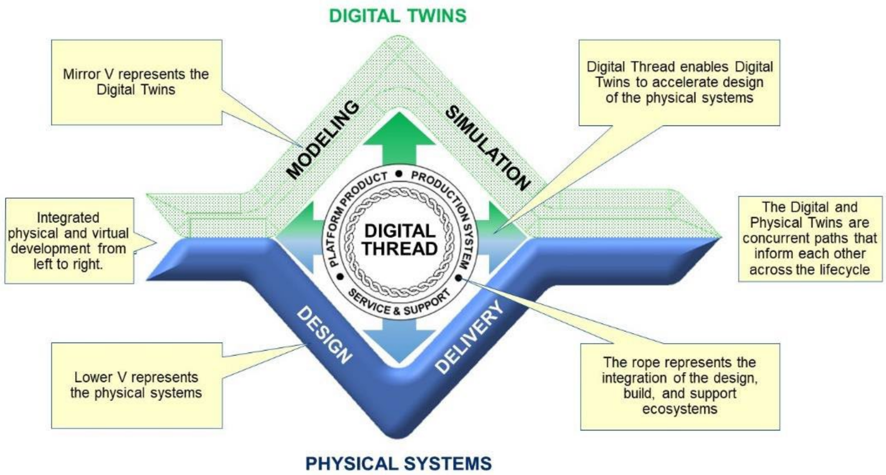

Fig. 1. MBE Diamond-Model [12]

The inverted V represents the design and realisation of the behavioural simulations [12]. 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, simulation phases, and as IoT devices are used, the physical informs the virtual. This interplay is simultaneous along the lifecycle and between the physical systems and their DTs [12]. The creation pathway of a DT is therefore predicated on a lifecycle approach to requirements engineering and information management, highlighting the critical role of software interoperability.

In the built environment, the development of DTs are in the early stages, with few fully-realised examples [13]. The effective creation of a DT arguably demands object-based approaches to structured data requiring BIM model use. In a white paper on DTs in the built environment, the Institution of Engineering and Technology propose an industry-agnostic DT maturity spectrum with five maturity levels (Table 1) [14].

Table 1. Digital twin maturity spectrum defining principles and outline usage [14]

Maturity[1]	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

[1] Logarithmic scale of complexity and connectedness

Systems requirements engineering in digital twin creation is emphasised due to inherent product, process, and stakeholder complexities. Product complexity exists relative to the asset itself, its virtual replica and real-time behaviours. Process complexity is present in the interdependent activities supporting the elicitation, description, documentation, decomposition, analysis and allocating of AIRs. Stakeholders complexity exists relative to the presence, power and influence of project team members involved (or not) in information requirements development activities.

The recent release of the ISO 19650 standard provides a step-change that can help address these complexities. ISO 19650 describes the processes supporting digital information management in the context of buildings and civil engineering works, including building information modelling (BIM) [2, 3]. Used in conjunction with the asset management standard ISO 55000, rail project teams are able to implement consistent and structured processes to support the identification of appropriate, relevant, and effective information requirements. The outcome of the information requirements elicitation and description activities starting with OIRs (the business case) is focused on the creation of AIRs, and ultimately the development of robust libraries of AIRs that can inform what data an organisation should be collecting and why it necessary throughout an asset's lifecycle. As a result, the EIRs supporting the creation of a DT can be identified.

In the built environment, to support requirements engineering processes, a range of software tools have seen steady increases in their application on AECO projects. A growing body of complex building and civil infrastructure projects are utilising tools to support requirements management, configuration and validation [4]. Adoption is largely driven by the need for AECO projects to identify and trace dependencies between requirements [15]. In other case studies on BIM-enabled building projects have investigated the effectiveness of requirements planning and management tools, including IBM Rational DOORS, dRofus, TRAM, ReqMan [16]. IBM Rational DOORS is a widely utilised tool in civil infrastructure projects, and in particular in rail infrastructure [20]. DOORS is an object-oriented requirement system supporting the capture, traceability, analysis, and management of requirements changes across the development lifecycle [17]. However, a drawback of the use of DOORS on rail infrastructure projects is its lack of support for automating the validation of requirements by linking to the 3D model. dRofus provides a centralised, data-driven platform supporting requirements traceability and change management, as well as client requirements capture and facility standards management [16]. Compared to IBM Rational DOORS, dRofus has limited requirements management capabilities that focus on the architectural and spatial elements of the building [4], however it does support validation by linking to the 3D model.

Yet, despite the use of requirements management software on AECO projects, the interactions between the myriad of interdependent requirements often go unchecked and as a result remain independent. Linking requirements management software with information contained in 3D models (or linked databases) to automate traceability and verification processes are therefore rare. Software companies and service providers from outside the built environment are introducing tools from aerospace and automotive sectors. Established requirements assurance and validation software supporting efficient requirements management and traceability processes have recently been introduced in rail infrastructure projects in Australia [18].

The use of software and validation services in rail infrastructure projects assumes that information requirements have been developed in accordance with an asset system hierarchy [19] and that the value of requirements assurance and validation processes extend beyond project delivery. Deficiencies in repeatable requirements development processes and availability of structured data also prohibit the value of systems approaches to requirements engineering in rail projects. Compounding these issues, is the lack of maturity in the co-engineering and collaborative information requirements development process supporting the physical and virtual assets.

3 Challenges to Information Requirements Development

Challenges to requirements development and related digital information management capabilities were investigated and categorised using three core areas of industry maturity, namely requirements development - i) Processes, ii) Technologies, iii) Supply Chain. By reviewing the AECO literature, the intention of the authors is to identify challenges specific to requirements engineering and related digital information management to understand their potential impact on the creation of DTs throughout project delivery.

In total, 36 papers from AECO domains were identified and 19 papers were reviewed after eliminating papers that did not meet the search criteria. The search criteria restricted papers to those using model-based approaches to project delivery with DT or BIM based facilities management (FM) deliverables. Due to the limited scope of this paper, a summary of the most relevant findings is reported in Table 2.

Table 2. RE and related Digital Information Management Challenges

Year	Challenge	Source	Maturity Classification
2010, 2016, 2019	Change of requirements/ evolution of client needs	[20–22]	Process
2012	Highly distributed requirements development with different levels of abstraction	[23]	
2013, 2015, 2021	Incomplete information requirements documentation, decomposition, analysis, and allocation	[24–26]	
2014	Lack of common language supporting information requirements development processes	[27]	
2015	Unstructured and late delivery of data and information to the FM phase of buildings.	[28]	
2015, 2017	Lack of application of standards or guidelines supporting information requirements processes	[28–30]	
2013, 2015, 2018, 2019	Lack of interoperability	[25, 28, 31, 32]	Technology
2014, 2017	Heterogeneous data inputs and outputs (e.g., different levels of detail, formats, units, etc.)	[29, 30, 33, 34]	
2016, 2017, 2019	Limited software support for managing conflicting requirements	[20, 30, 35]	
2017, 2020	Multiple disconnects in the flow of information due to technology-based deficiencies	[29, 36]	
2018	Limitations to systems requirements engineering software configuration	[37]	

2018	Ongoing investment in requirements engineering software	[37]	
2012	High level of diversity of stakeholders across distributed requirements development process with different levels of abstraction used by different stakeholders	[23]	Supply Chain
2013, 2015	Lack of clear roles and responsibilities, lack of contract and liability framework	[25, 28]	
2014	Missing links between requirements captured in the user requirements' document and their functional specification	[33]	
2015, 2017, 2019	Missing stakeholders and lack of collaborative work amongst the team during early design phase	[29, 32, 38]	
2017, 2019	Lack of awareness/ expertise of standards or guidelines supporting information requirements processes	[29, 30, 32]	
2018	Ongoing investment in training of requirements engineering software	[37]	

Table 2 summarises the three types of challenges, including those related to:

i. *Process maturity*: The continuous changes to AECO requirements and lack of adequate change management processes is one of the most well-documented challenges reported by researchers over the last decade [20–22, 34, 39]. Whilst this challenge is common to all project types - and is not unique to projects with DT or BIM based FM deliverables - the specification and allocation of OIRs combined with the consistent management of AIRs and EIRs throughout the project amplify traditional requirements change challenges. Other issues surround deficiencies in the requirements specification process resulting in unclear, incomplete [24] or conflicting requirements [20, 35], the lack of process standards [28–30], unstructured and late delivery of data and information to FM phases [28], and absence of a common language for AECO requirements [27].
ii. *Technology maturity*: Issues included errors or failures related to software interoperability [25, 28, 31, 32], deficiencies in common data input and output requirements [29, 30, 33, 34], limited software support for managing conflicting requirements [20, 30, 35], breaks in information flow due to a lack of platform enabled technologies [29, 36], and the lack of requirements engineering tool integrations and ongoing investment on requirements engineering software [37].
iii. *Supply chain maturity*: The spatial and organisational separation of stakeholders creates obvious challenges to collaboration and communication [23]. And there is a lack of clear roles and responsibilities, contract and liability framework for information requirements management [25, 28]. Missing links between high-level user requirements and their functional specification can as a result become amplified [33]. Further, early involvement of all stakeholders is essential for requirements elicitation, prioritisation, negotiation and communication. The absence of key stakeholders during the early design phase brings challenges to all activities in the requirements development process due to knock-on effects to downstream requirements-dependent tasks [29, 32, 38]. In terms of knowledge and expertise, there is a lack of awareness and expertise of standards and guidelines supporting information requirements processes [28–30]. The ongoing investment on requirements engineering software training is also regarded as a supply chain wide challenge [37].

4 Information Requirements Development Case Study

Following the literature review, the research collected primary data to investigate the challenges encountered by project teams when developing and managing complex and interdependent information requirements.

4.1 Research Design and Method

A case study [40] approach was adopted, and data collection involved semi-structured interviews with industry experts in the rail infrastructure domain who have participated in public rail project.

The semi-structured interviews ensured that multiple topics surrounding the research problem could be covered. Key interview questions therefore included the following areas: (1) experience in managing requirements of physical asset and digital deliverable, (2) Current challenges to developing and managing requirements (both functional and digital). Ten participants were interviewed across five companies (see Table 3). Interviews took place between February 2020 to May 2020. Each interview took approximately one hour, and recordings were subsequently transcribed and verified.

Table 3. Interviewees

Organisation	Role	# Interviewees
Developer	Digital Engineering Director	1
	Senior Project Manager	1
	Engineering Lead	1
	Systems Architecture Principal Engineer	1
Consultant	Systems Engineer	2
	Digital Engineering Lead	2
	Rail Systems Engineer	2
	Total Participants Interviewed	10

5 Case Study Findings

Interviews were transcribed and analysed using the same taxonomy as identified in literature review. Findings identified a variety of challenges relating to all three categories identified from the literature – that is: process, technology, and supply chain maturity challenges. Analysis also revealed insights related to the adoption of more integrated and systems-based approaches to requirements engineering. Due to the limited scope of this paper, a summary of findings is provided in each following sub-section.

5.1 Process Maturity

Process maturity refers specifically to requirements engineering related processes and the integration of those processes with traditional AECO project management processes. A number of significant challenges were identified by rail infrastructure interviewees, including i) lack of requirements change management processes, ii) lack of validation process supporting physical and virtual requirements, iii) delays in information requirements development process (elicitation and description and documentation and decomposition activities), iv) disconnection in the workflows that support system architecture and project level requirements, v) lack of process standards supporting AECO requirements development and management, and vi) lack of agreed and consistent requirement language.

Lack of requirements change management process. Change of requirements keeps happening during the development and delivery of rail infrastructure. To minimums delivery risk, it is important to inform those project level changes to network level. However, this process is lack at the moment as captured by the following responses from the Systems Architecture Principal Engineer.

> "…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…"
>
> --- Systems Architecture Principal Engineer

Lack of validation process supporting physical and virtual requirements. In 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 rail infrastructure was highlighted by all rail interviewees.

> "The behaviours that came from the Defence sector, where there is a lot of rigor in validating the mathematical information, is not being shared in construction industry."
>
> --- Systems Engineer

Delays in information requirements development process. The information requirements should be recognised during early planning phase and then fed into the design phase. However, the reality on many rail infrastructure projects is that this occurs during the detailed design and even construction phases.

> "…The rail systems are so fragile and sensitive… This industry is always at risk of making decisions that have side effects and unknown emergent properties and consequences that are picked up for too late…"
>
> --- Systems Engineer

> "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

Disconnection in the workflows that support system architecture and project level requirements. In rail infrastructure, network level requirements are performance based, and should guide the development of project level requirements. However, there is disconnect between the planning of the system architecture and the elicitation of project level requirements as captured by the following responses 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

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

"…different projects adopt a digital engineering approach in different levels of maturity… there is a lack of standards or structured guidance… and consistency across these approaches is really important…"

--- Senior Project Manager

"…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

In addition to the challenges identified above, it was noted by interviewees that the elicitation and documentation of information requirements underpinning the creation of DT in rail infrastructure is a complex and lengthy process which brings with it challenges related to the need to utilise an agreed and consistent requirements language which was seen as lacking in contemporary practice.

Lack of agreed and consistent requirements language. Consistent requirement language 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 infrastructure projects was lamented by those engineers with systems backgrounds.

"…there is no common set of requirements that go down…"

--- Rail Systems Engineer

5.2 Technology Maturity

Technology maturity challenges refer to technology artefacts and, including software tools, software integration, interoperability, and data exchange as well as hardware and network technologies. The technology maturity challenges identified by interviewees include: i) interoperability of requirements management software with digital modelling tool chain, ii) disconnected data and processes within the common data environment, and iii) lack of tools supporting automatic information requirements validation.

Interoperability of requirements management software and digital modelling tool chain. Requirements management tools like IBM DOORS were reported to be commonly used in rail infrastructure projects. However, the software was not commonly used to support requirements elicitation and configurations management, with these software functionalities being underutilised. Automation of requirements validation using a direct link with the 3D model was also absent. An integrated tool ecology was therefore noted by most participants as lacking.

"They use DOORS to baseline the requirements in 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

Disconnected data and processes within the Common Data Environment. The Common Data Environment (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 model information. According to the rail infrastructure experts interviewed, the design or purpose of CDEs is often not configured to support a through-life approach to digital information management as the scope of the CDE focuses on project delivery phases. The CDE therefore fails to take a lifecycle approach to requirements engineering and falls short in the management of information requirements beyond the handover and commission phase.

"The primary CDE was ProjectWise… However, ProjectWise does not support Revit well from the point 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

Lack of tools supporting automatic information requirements validation. As a physical-focused industry, the validation of physical deliverables and their functional requirements was seen as an important part of rail infrastructure projects. However, the lack of formal validation tools (and processes) of the information requirements describing the digital deliverables (i.e., models/ 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

5.3 Supply Chain Maturity

Issues relating to the maturity of the supply chain and participating project stakeholders relative to their knowledge and levels of collaboration/ participation. Supply chain maturity challenges therefore refer to project roles and responsibilities, culture and communication, and education and training. The three challenges noted by interviewees in this category surround the lack of a clear description of roles and responsibilities for information requirements development, lack of support from senior management, and lack of expertise in requirements development supporting DT creation.

Lack of a clear description of roles and responsibilities for information requirements development. It is essential to set up a clear roles and responsibilities for efficient and effective requirements management. However, so far in rail infrastructure, this role is not clearly set as captured by the following responses from multiple participants.

"…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

"…there is accountability from a company perspective which includes systems engineering. They've got their insurance and liabilities built in the contract. But when it comes to personal professional accountability, it's really lacking at the moment in a top-down driven way with transport to accredit the staff…"

--- Digital Engineering Lead

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

Lack of expertise in requirements development supporting DT creation. Having relevant expertise and a minimum a common understanding in rail infrastructure project teams was viewed as being critical to the successful implementation of information requirements processes, particularly those supporting the elicitation and documentation of AIRs and EIRs that underpin the creation of the DT. Moreover, the information requirements of a DT should be specified at the early stages of the project, ideally described as OIR and AIR, 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, DT 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

"…There is no consistency of requirements development approach. The SE consultant usually sits in a conflicting position by providing the service of stakeholder engagement and providing business requirements specifications, while at later stage, they are nominated to manage those requirements…"

--- Rail Systems Engineer

"…there is a misunderstanding with regards to this term digital engineering… they have completely different understanding of what the defence believe digital twin is…"

--- Systems Engineer

6 Discussion

Three key areas of maturity have been identified as key to information requirements development to support the creation of DTs in rail infrastructure projects, namely i) process maturity (including process-based standards and protocols), ii) technology maturity, and iii) supply chain maturity. Within these three areas of maturity, 12 challenges are identified from the case study.

6.1 Mapping Challenges

In comparing the identified challenges, a number of challenges identified in the existing research literature mirror the responses of case study interviewees. Eight challenges can be correlated between the case study and literature survey findings, including: i) lack of requirements change management processes, ii) delays in information requirements development process, iii) disconnection in the workflows that support system architecture and project level requirements, iv) lack of process standards supporting AECO requirements development and management, v) lack of agreed and consistent requirement language, vi) interoperability of requirements management software with digital modelling tool chains, vii) lack of a clear description of roles and responsibilities for information requirements development, and viii) lack of expertise in requirements development supporting DT creation.

The remaining four challenges are unique to the rail infrastructure case study, namely: i) lack of validation processes supporting physical and virtual requirements, ii) lack of tools supporting automatic information requirements validation, iii) disconnected data and processes within the CDE, and iv) lack of support from senior management. Three of these challenges are specific to the creation of DT deliverables. The validation process and technology for both physical and virtual requirements is a challenge that is not represented in the literature. Whilst data and process disconnects in the CDE are documented in the literature [29, 36], the impact of these deficiencies in information flow on requirements engineering processes, tool chains and outputs have not been reported. The lack of support from senior management was largely reference to with regard to the client. Whilst this challenge was not identified by the authors in the requirements engineering literature reviewed, similar challenges are often raised in research investigations on BIM adoption on AECO projects [41, 42]. Our case study highlights a common situation, where the public agency, acting as the client, lacks experience in SE and requirements engineering relative to supporting effective and efficient information requirements development in the creation of DTs.

Conversely, 7 out of the 18 challenges identified in the literature survey were not reflected in the interviewee responses. These challenges all related to either technology maturity or supply chain maturity categories. One explanation for this may be due to the nature of the roles and responsibilities of the interviewees – where most were from management or systems engineering roles that were not actively involved in the use of software to support SE or requirements engineering processes.

To locate the challenges identified in the case study in the asset lifecycle, each challenge was mapped to corresponding phases using the 'Diamond Model', see Fig. 2.

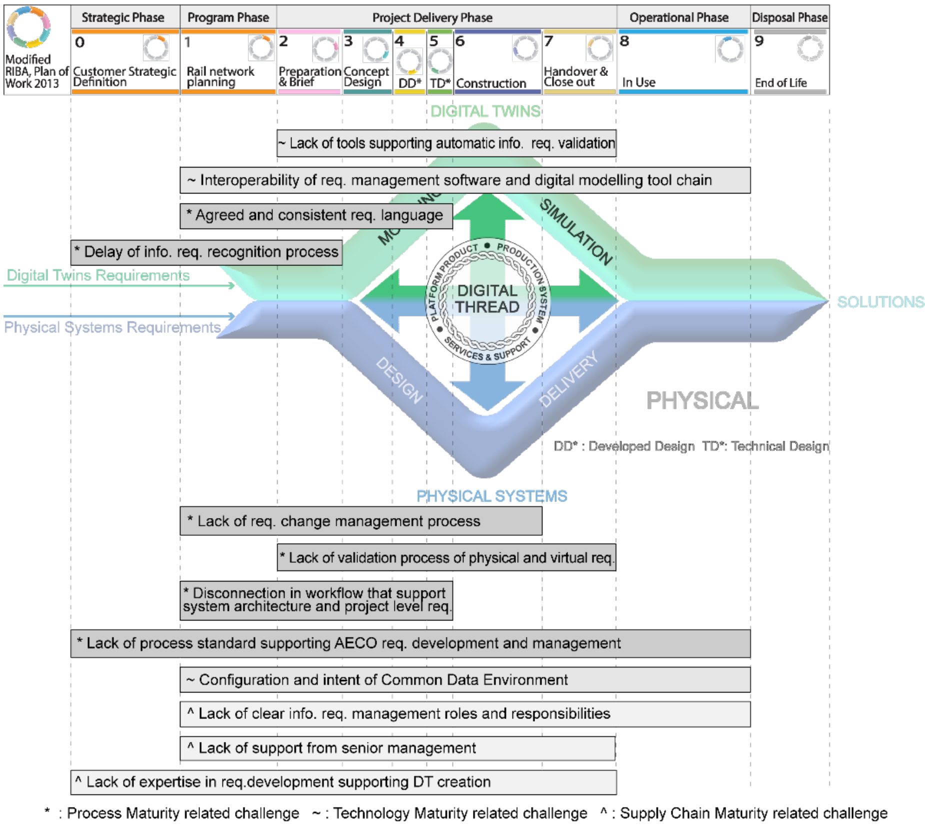

Fig. 2. Challenges to Information Requirements Development supporting DT Creation mapped to Diamond-Model Development Lifecycle [12]

The majority of challenges identified pertain to those commencing in the early phases of the project, including ‘Customer Strategic Definition’, ‘Rail Network Planning’, and ‘Project Preparation and Brief Development’. The effects of the issues identified continue across the ‘Concept Design’, ‘Developed Design’ and ‘Construction’ phases with most continuing to effect ‘Handover and Close Out’ or ‘Operational’ phases. Challenges that involved both physical and virtual requirements are represented below the ‘Diamond Model’, while challenges specifically related to digital requirements engineering activities are mapped onto the reflected ‘V’ of the ‘Diamond Model’. For validation related challenges, although this occurs during technical design phase, the setup of validation processes and supporting documents occur in the early planning phase.

In the creation of a DT, stakeholders are not only distributed, but also come from diverse disciplines, formalisms, and tools. Information requirements supporting both the physical and virtual deliverables must be shared and exchanged between multiple disciplines so as to build a common view of the targeted deliverables [43].

6.2 Recommendations and Supporting Research

Two deficiencies identified in both rail infrastructure case studies concern deficiencies in systems approaches and collaborative co-engineering practices. Firstly, our case study reflected a well-documented deficiency in the application of SE [44] and critically systems requirements engineering (SRE) methods [26]. Secondly, there exists a greater dependency on a co-engineering approach during the creation of complex and adaptive systems, where "co" requires the project team to work towards the DT deliverables as a common goal. Co-engineering therefore addresses both collaborative and concurrent engineering concepts. The impacts of the implementation of systems and co-engineering approaches can be identified at two levels; the organisation and project relative to the "mind-set" and sharing of the DT system objectives and vision. Thus, adopting systems and co-engineering approaches is identified as a key criterion for complex and adaptive systems when the lifetime of the asset extends over several decades. For rail infrastructure projects the co-engineering of information requirements is key to support the delivery of both physical and virtual assets with decades long lifespans. In adopting both systems and co-engineering approaches, SRE implementations are arguably better supported.

The key principles of SRE – including its holistic process-based approach, its focus on increasing interactivity across project teams, and validation of requirements against original system goals – are designed to overcome many of the challenges identified in the case study. The creation of DTs in rail infrastructure projects may therefore benefit from the application of SRE methods; from requirements elicitation and analysis to requirements prioritisation, and requirements communication and negotiation, and to requirements validation, change management and requirements traceability. Integrating SRE methods with model-based approaches using BIM during planning and early design stage presents a solution pathway for more effective support in DT creation.

Related research investigations have explored the role of SRE to support the specification of information requirements. Notably, [45] have used SRE to adapt and redefine the 'Level of Detail' concept, in order to provide more complete definitions of BIM model use in complex infrastructure projects. 'Level of Detail (or LOD), together with the Level of Information (or LOI) are widely used data definition standards that describe geometric (LOD) and non-geometrical (LOI) information. To extend these concepts, [45] introduce 'Level of Abstraction' (LOA) to describe relevant objects for different types of BIM model use. The application of SRE was successfully implemented by [46]to support specific areas of BIM-enabled infrastructure projects focused on the specification of exchange information requirements. A drawback of the LOA method proposed by [46] 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. In addition to the complexity of this approach, the LOA definitions themselves do not include all disciplines, with structural engineering notably missing. Moreover, the focus of the paper is on the EIR and neglects the AIR processes that are linked to the BIM and DT use domain. The applicable phase of this approach starts after the BIM Preparation and Brief phase which is too late in the asset lifecycle.

6.3 Concluding Remarks

The findings in this paper provide empirical evidence of a number of process, technology and supply chain 'pain points' that are currently facing NSW and Victorian rail infrastructure projects in the creation of DTs. The findings serve as a starting point for further research into the creation of rail DTs and the potential role of SRE. Future research will focus on the examination of how the introduction of SRE capabilities can positively affect the creation of DTs in rail infrastructure.

7 Acknowledgement

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