Requirements Engineering in Complex Infrastructure: Challenges to the Development and Management of Rail Transport Requirements

Yu Chen[1*] and Julie R. Jupp[2]

[1]*Faculty of Engineering and IT, University of Technology Sydney and yu.chen-4@student.uts.edu.au*
[2] *Faculty of Engineering and IT, University of Technology Sydney and Julie.Jupp@uts.edu.au*
**Corresponding author*

Abstract
This paper investigates information requirements development practices in Australian civil infrastructure projects characterised by the use of models, methods and tools to support a strategic approach to asset information lifecycle management. The research study focuses on rail transport infrastructure where the complexity of rail networks as a cyber-physical system-of-systems makes it increasingly difficult for current requirements engineering (RE) practices to handle the myriad of requirement types across temporary project supply chains. Consequently, the RE effort needs to continuously consider multiple disciplinary perspectives of the process throughout the asset life cycle. Using both literature and interview surveys, process-oriented challenges to RE are investigated. Findings identify a lack of implementation-ready requirements development and management methods supported by interoperable tool-chains that provide integration and automation in requirements traceability and change management workflows. The paper closes with a discussion on the correlation of our findings with previous studies and the direction of future research.

Keywords
Requirements Engineering, Asset Information Requirements, Asset Information Lifecycle Management, Rail Infrastructure, Challenges.

1 Introduction

Requirements engineering in rail transport projects is increasingly complex. As a part of a greater whole in a linear network, rail transport infrastructure assets are cyber-physical systems (CPS). Different types and levels of requirements about the physical and cyber systems must be developed and managed during the planning and delivery of rail transport projects. Requirement types include, amongst others, high-level capability requirements defining the system architecture capabilities, current and future operational requirements, definitions of system-, sub-system-, and unit- level requirements that span functional and performance requirements, physical requirements, and business case requirements. Government transport agency standards and terms of contract covering Systems Engineering (SE), Digital Engineering (DE), building information modelling (BIM), common classification systems, and supporting ISO standards (e.g., ISO 19650 and ISO 55000), play a key role in enabling more strategic approaches to asset information lifecycle management. Growing maturity in the application of these procedural methods and information schemas has resulted in new service-oriented offerings linking, for example, BIM to Facilities Management, and more recently to the development of spatial digital twins (DTs) in support of the operations and maintenance (O&M) of rail transport assets.

The recent application of the spatial DT to support O&M is largely driven by the need to manage the growing complexity of the rail CPS. There are a range of use cases for creating a DT of a rail transport assets, namely to: enable connected and autonomous transport capabilities, manage digital cadastral information, leverage the value of digital asset data created during project delivery (e.g., to locate and maintain assets), and to enable more strategic approaches to asset information lifecycle management. However, due to their scale, functional complexity, dynamic interactions, and emergent properties, rail transport projects are increasingly difficult for RE practices to handle.

Against this backcloth, the authors explore contemporary RE practices in rail transport projects relative to the development of the physical and cyber systems, as well as their virtual replicas and the digital deliverables required to support O&M. We examine the process-oriented challenges encountered by project stakeholders, with the aim of identifying the key barriers to the development and management of asset information requirements during the ‘plan’ and ‘aquire’ phases of the asset life cycle, which ultimately impact on the creation and verification of digital deliverables, and in particular those supporting the digital twin.

2 Background

In the built environment, integrated approaches to requirements engineering (RE) are relatively immature (Chen and Jupp, 2018; Johnson *et al.*, 2021). In rail transport projects, and in particular those implementing a strategic approach to asset information lifecycle management, the network of authorised engineering organisations (AEOs) including consultants and contractors must develop different types and levels of CPS requirements, and manage the complex of interfaces between them.

2.1 Rail Cyber-Physical Systems and Digital Twins

The phrase “Cyber-Physical Systems” (CPS) was coined by Gill in 2006 (Gill, 2006). It is used to describe systems that seamlessly integrate computational elements and physical components with mutual communication (Wiesner *et al.*, 2014; Deka *et al.*, 2018). The CPS approach has long been adopted in information systems in industry sectors like aerospace, automobile, shipbuilding, and healthcare (Akanmu *et al.*, 2013). Relative to a domain-specific level, where many sub-systems are working in parallel, term “Cyber-Physical s*ystem-of-systems*” (CPSoS) was coined to describe the multidimensional and complex network that integrates the cyber world and the dynamic physical world (Broy, 2013; Tao *et al.*, 2018). Complex rail transport projects can be categorised as a CPSoS. Rail CPSoS can be broadly classified into infrastructure-based CPS, vehicle–infrastructure coordinated CPS, and vehicle-based CPS (Deka *et al.*, 2018).

The “Digital Twin” (DT) concept was first introduced by Grieves in 2003 (Grieves, 2014) and differs from a CPS or CPSoS. Definitions and explanations of the DT concept have been proposed and refined by various researchers (Grieves, 2014; Negri *et al.*, 2017; Parott and Warshaw, 2017; Tao *et al.*, 2018). DT technologies were adopted in the spacecraft sector in 2010 and later in complex manufacturing sectors (Glaessgen and Stargel, 2012; Lee *et al.*, 2013). NASA were early pioneers of DT technologies for remote monitoring, controlling and running simulations of spacecraft from Earth (Shafto *et al.*, 2010). In the built environment, the application of DTs are in the early stages, with few fully-realised examples (Lamb, 2019). The creation and verification of a DT of a rail infrastructure and/ or vehicle CPSs is dependent on the timely definition of asset information requirements, asset information classification, and hierarchy management. 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.

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 *et al.*, 2019). Although emphasising different elements, it is necessary to understand DTs in light of CPSs as they share procedural similiarity and dependency relative to their creation, where the elicitation, specification, implementation, verification, and validation of asset information is essential to their successful delivery. The development and management of asset information requirements must span physical, cyber and virtual systems.

2.2 Strategic Asset Information Management

To support RE in rail transport projects, the International Standard ISO 55000 (2014), 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. Together, ISO 55000 and ISO 19650 are able to provide a regulated procedural method for the development of a strategic approach to asset information lifecycle management.

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.

The release of ISO 19650 describes the processes supporting digital information management in the context of buildings and civil engineering works, including building information modelling (ISO, 2018a, 2018b). Prior to the introduction of ISO 19650, projects implementing BIM and structured data approaches did not have a consistent information requirements management process across the industry. ISO 19650 provides a procedural method according to four requirements types, including client-side: i) organisation information requirements (OIR), ii) asset information requirements (AIR), and iii) project information requirements (PIR); as well as the: iv) exchange (or employer) information requirements (EIR) of the project team. Information requirements management activities commence with the client's OIR, which are established in a statement about the information needed by an organisation to inform decision-making about high-level strategic objectives (Simpson *et al.*, 2018). The OIR is therefore a critical 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. Australian government transport agencies widely utilise the AMAF to detail mandatory asset management requirements and provide guidance for managing assets.

Consequently, it is critical that the OIR accurately reflects *what* information is required so as it is able to inform the development of the AIR and PIR. The AIR and PIR will in turn inform production of the EIR, which represents the overall information requirements that span the managerial, commercial and technical aspects of the AIR and PIR, where the owner's requirements for asset registers to support spatial referencing, classification, hierarchical management and location referencing as per the nominated schema, e.g., Uniclass 2015. The EIR is then primarily concerned with the *who*, *how* and *when* of their delivery, and includes the information production processes and procedures, data standards, file formats, timetables for information exchange, and roles and responsibilities of the project team (Simpson *et al.*, 2018). The EIR is used to inform the development of the Digital or BIM Execution Plan (DXP/BXP). ISO 55000 and ISO 19650 procedural methods together play a central role in the development and management of asset information requirements, as well as the ongoing management of digital information and digital deliverables supporting asset management.

3 Literature Survey of Challenges to RE Processes

This section presents a literature-based survey of the challenges to requirements engineering and information requirements development. The research focuses on process-oriented issues. By reviewing the literature, the intention of the authors is to map the process based challenges to RE challenges and undertake an interpretive analysis. In total, 37 papers from the AECO domains were identified and 20 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 complex projects with digital deliverables supporting strategic approaches to asset information lifecycle management.

3.1 Challenges to Requirements Engineering Processes Identified in the Literature

The early involvement of all stakeholders is essential for requirements elicitation, prioritisation, negotiation and communication processes. 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 (Navendren *et al.*, 2015; Jupp and Awad, 2017; Heaton *et al.*, 2019). 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 (Yu *et al.*, 2010; Nekvi and Madhavji, 2014; Papinniemi *et al*, 2014; Patacas *et al.*, 2016; Koltun *et al.*, 2017; Junior *et al.*, 2019). These general challenges to RE processes are categorised and ordered in Table 1 according to author.

Table 1. Requirements Engineering Process Challenges

Code	Challenge	Source
LS-RE-PC01	Missing stakeholders and lack of collaborative work amongst the team during early design phase	(Navendren *et al.*, 2015; Jupp and Awad, 2017; Heaton *et al*., 2019)
LS-RE-PC02	Missing links between requirements captured in the user requirements' document and their functional specification	(Berkovich *et al.*, 2014)
LS-RE-PC03	Change of requirements/ evolution of client needs, Lack of change management processes	(Yu *et al.*, 2010; Nekvi and Madhavji, 2014; Patacas *et al.*, 2016; Koltun *et al.*, 2017; Junior *et al.*, 2019)
LS-RE-PC04	Highly distributed requirements development with different levels of abstraction	(Penzenstadler and Eckhardt, 2012)

3.2 Challenges to Information Requirements Development Processes

A series of challenges specifically related to information requirements development processes were then identified. These challenges are categorised and ordered in Table 2 according to author.

Table 2. Information Requirements Development Process Challenges

Code	Challenge	Source
LS-IRD-PC01	Incomplete information requirements documentation, decomposition, analysis, and allocation	(Kelly *et al.*, 2013; Aaramaa *et al.*, 2015; Johnson *et al.*, 2021)
LS-IRD-PC02	Lack of common language supporting information requirements development processes	(Jallow *et al.*, 2014)
LS-IRD-PC03	Unstructured and late delivery of data and information to the FM phase of buildings.	(Patacas *et al.*, 2015)
LS-IRD-PC04	Lack of application of standards or guidelines supporting information requirements processes	(Patacas *et al.*, 2015; Cavka et al., 2017; Jupp and Awad, 2017)

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 (Aaramaa *et al.*, 2015) or conflicting requirements (Scott *et al.*, 2016; Junior *et al.*, 2019), the lack of process standards (Patacas *et al.*, 2015; Cavka *et al.*, 2017; Jupp and Awad, 2017), unstructured and late delivery of data and information to facilities management (FM) phases (Patacas *et al.*, 2015), and absence of a common language for AECO requirements (Jallow *et al.*, 2014).

3.3 Key Challenges to Rail RE and Information Requirements Development

The complexity of rail transport RE processes is emphasised due to the number and type of system requirements, stakeholder requirements management interactions, and supporting requirements software tool-chains. RE challenges therefore increase in rail 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.

In projects with strategic approaches to asset information management, challenges to rail transport RE processes stem from the 'plan' phase of the asset life cycle and can be linked to a lack of owner-developed asset information requirements supporting current and future operational scenarios, as well as a deficiencies in the detail of required asset information to support asset management systems (Kasprzak, 2013). Whilst the asset management sector undergoes this digital transformation, it remains that few owners have defined their actual information needs and how asset information will map to asset management systems.

In the transition from the 'plan' phase to the 'acquire' phase of the asset life cycle, requirements specifications must make an important transition from system level to project level documentation formats. RE efforts may be compromised during this exchange process due to the lack of detail about sub-system and unit level asset information requirements, which affect the downstream information management capabilities of the project team. 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.

From a process standpoint, RE complexity remains a critical challenge due to the many interdependent activities enacted in the elicitation, description and documentation of organisational and asset requirements types, as well as the decomposition, analysis and allocation of requirements across collaborating AEOs. 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 RE tool-chains, lack of software interoperability, imperfect or incomplete information exchange, and poor stakeholder interface management across the asset life cycle. Complexity in RE processes is therefore also embedded in the social challenges surrounding the presence, power and influence of project team members involved in (or absent from) requirements development and management activities.

Requirements integration risks therefore persist in rail transport projects and evidence of bespoke RE tool-chain integration initiatives in rail transport projects exist (Roodt et al., 2020). However they are predicated on the key assumption that information requirements are consistently developed in accordance with industry agree data schemas providing a standard for asset system hierarchy (Chen and Jupp, 2019). Such approaches also demand that the value of requirements assurance, verification and validation processes extend beyond asset handover.

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

4 Interview Survey of Challenges to RE Processes in Industry

Following the literature review, the research collected primary data to investigate the process related challenges encountered by project teams when developing and managing complex and interdependent information requirements. An interview survey (Hox and Boeije, 2005) approach was adopted, and data collection involved semi-structured interviews with Australian 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.

4.1 Interview Questions and Participants

Key interview themes included the following question areas: (1) experience in developing and managing requirements of physical assets and digital deliverables, and (2) Current challenges to developing and managing different requirements types. 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/ Lead	2
	Senior Project Manager	1
	Systems Architecture Principal Engineer	1
Consultant	Systems Engineer/ Rail Systems Engineer	4
	Digital Engineering Lead	2
	Total Participants Interviewed	10

4.2 Interview Findings

Interviews were transcribed and analysed using the same taxonomy as identified in literature review. Findings identified a variety of challenges relating to process maturity issues. Analysis also revealed insights related to the adoption of more integrated and systems-based approaches to requirements engineering. A summary of findings is provided in Table 4 and discussed in the following sub-sections.

Table 4. Process Challenges to Requirements Engineering and Information Requirements

Code	Challenge	Phase
INT-RE-PC01	Disconnect in workflows and tool-chains linking requirements types and levels	Plan > Acquire
INT-RE-PC02	Lack of requirements change management process	Acquire
INT-RE-PC03	Lack of standard process for physical, cyber and info. requirements validation	Acquire
INT-IR-PC01	Delays in information requirements development process	Plan > Acquire
INT-IR-PC02	Lack of process standards supporting information requirements development	Plan > Acquire
INT-IR-PC03	Lack of agreed and consistent language describing information requirements	Plan > Acquire

4.2.1 Challenges to Requirements Engineering Processes

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, i) disconnection in the workflows that support system architecture and project level requirements, ii) lack of requirements change management processes, and iii) lack of validation process supporting physical and virtual requirements.

Disconnect in workflows and tool-chains linking requirements types and levels*:* In rail 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*

Lack of requirements change management processes: 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 standard process for physical, cyber and information requirements validation: 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*

4.2.2 Challenges to Information Requirements Development Processes

There are also some challenges specific to information requirements development processes identified, including i) delays in information requirements development process (elicitation and description and documentation and decomposition activities), ii) lack of process standards supporting AECO requirements development and management, and iii) lack of agreed and consistent requirement language

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 infrastruc-ture 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 often picked up far 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*

Lack of process standards supporting information requirements development: 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 maturi-ty… there is a lack of standards or structured guidance… and consistency across these ap-proaches 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*

Lack of agreed and consistent language describing information requirements: 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 Analysis and Discussion

To locate the procedural painpoints of RE identified in the literature and interview surveys, each challenge was mapped to corresponding phases using an adapted 'V-model' of the asset life cycle with the classic 'V' model reflected to represent the development phases of a CPS's digital twin, see Figure 1. The lower 'V' reflects the classic systems engineering process of the CPS, while the mirror reflection of the 'V' above represents the DTs modelling and simulation (Hatakeyama *et al.*, 2018).

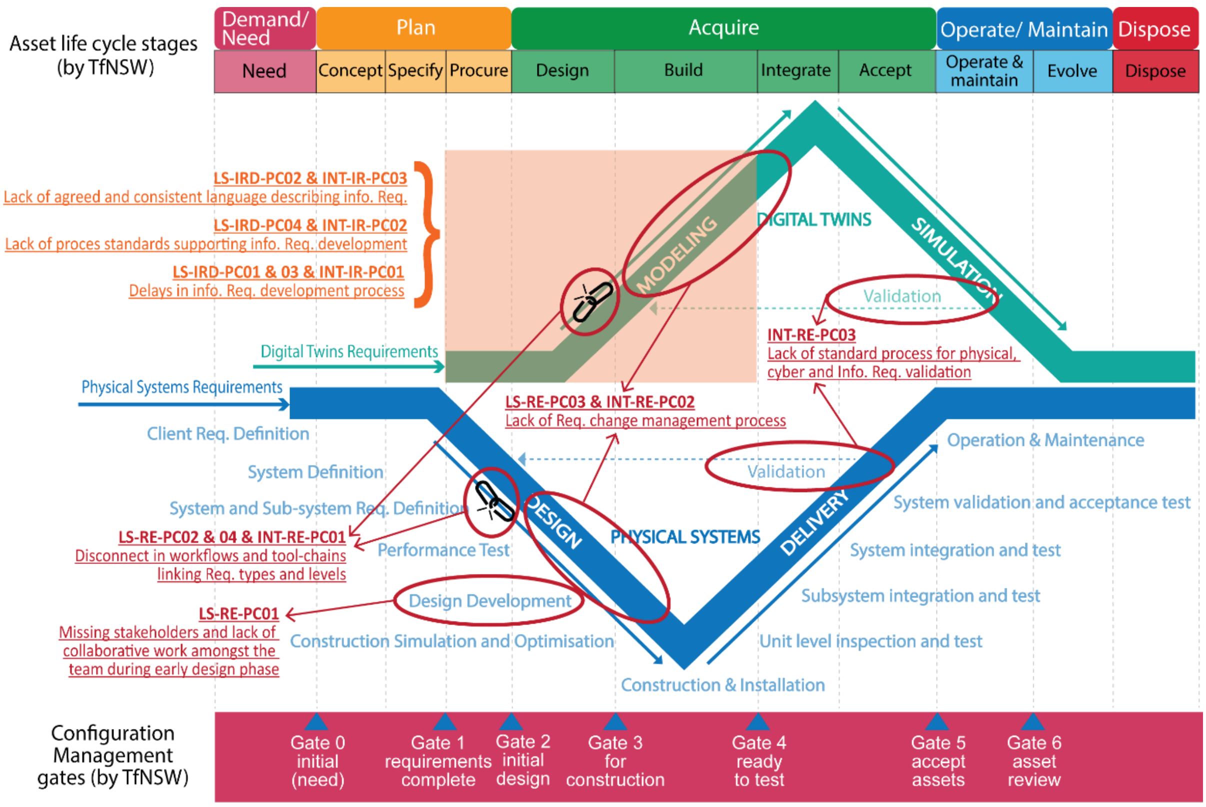

Figure 1. Challenges to RE and information requirements development

Challenges specifically related to information requirements development (and relating to ISO 19650 procedures) are mapped onto the reflected ‘V’. As shown in Figure 1, the development process of asset information requirements can be delayed and effectively shifts the reflect ‘V’ capturing the digital deliverables procedures to the latter stages of the classic ‘V’ development process of the CPS itself. Figure 1 also shows that the majority of challenges are located in the ‘specify’ and ‘design’ stages of the asset life cycle, with their knock-on effects causing impacts on downstream verification activities. Further, although verification issues identified are mapped to the ‘integrate’ stage, these process challenges can largely be addressed in the earlier ‘specify’ stage within the PIR and EIR specifications.

A comparison of the challenges reported in the literature with those identified in the interview survey reflects a number of overlapping issues. However, key differences can also be found. Process challenges relating to requirements validation processes have not been previously documented in the literature. Furthermore, the absence of key stakeholders and a lack of integrated workflows across the different AEO participants in the ‘design’ stage was not reported as a key challenge by interviewees. These differences will be explored in follow-up interviews to analyse their significance in rail transport projects.

Information requirements supporting the physical, cyber and digital assets must be shared and exchanged between multiple disciplines so as to create a common and integrated view of the targeted deliverables (Wiesner *et al.*, 2017). The implementation of strategic approaches to asset information lifecycle managment demands continuity in RE processes spanning the ‘plan’ and ‘acquire’ phases. However, our findings show that robust procedures and tool-chains linking RE phases across requirements elicitation and analysis, prioritisation, communication and negotiation, change management, traceability and validation activities are not well-supported by a continuous workflow shared by participating AEOs.

6 Conclusion and Future Work

The paper highlights a number of key challenges to RE in rail transport projects, where continuous workflows and integrated RE tool-chains spanning the asset life cycle impacts on the development and management of asset information requirements and the effectiveness of strategic approaches to information lifecycle management. Whilst regulated procedural methods are addressing the complexity of asset information requirements development and management, greater levels of maturity will provide greater capability in the verification of digital deliverables and ultimately supporting the efficacy of DT ceation. Existing studies of rail transport and complex building projects reported in the literature highlight the impediments to mature methodologies and integrated tool-chains to support RE. The interview findings presented demonstrate the need for greater levels of requirements interfaces and change management. Whilst together with ISO 55000 and ISO 19650 provide much needed guidance to building and civil engineering projects in this area, there remains a lack of implementation-ready OIR and AIR development and management methods supported by integrated tool-chains that provide continuity and automation in requirements traceability and change management workflows across collaborating project team members. Future research will focus on verifying the findings of this study and examining the prioritisation of challenges identified in both literature and interview surveys by using a more quantitative approach (e.g., survey questionnaires).

7 Acknowledgements

This research is supported by an Australian Government Research Training Program scholarship.

8 References

Aaramaa, S. *et al.* (2015) 'Design for excellence in the context of very large-scale requirements engineering', in *2015 10th Int.Joint Conf. on Software Technologies (ICSOFT)*. IEEE, pp. 1–12.

Akanmu, A., Anumba, C. and Messner, J. (2013) 'Scenarios for cyber-physical systems integration in construction', *J. of Information Technology in Construction (ITcon)*, 18(12), pp. 240–260.

Berkovich, M. *et al.* (2014) 'A requirements data model for product service systems', *Requirements Engineering*, 19(2), pp. 161–186.

Broy, M. (2013) 'Engineering Cyber-Physical Systems: Challenges and Foundations', in Aiguier, M. et al. (eds) *Complex Systems Design & Management*. Berlin, Heidelberg: Springer, pp. 1–13.

Cavka, H.B., Staub-French, S. and Poirier, E.A. (2017) 'Developing owner information requirements for BIM-enabled project delivery and asset management', *Automation in Construction*, 83, pp. 169–183.

Chen, Y. and Jupp, J. (2018) 'Model-Based Systems Engineering and Through-Life Information Management in Complex Construction', in *IFIP Int. Conf. on Product Lifecycle Management*. Springer, pp. 80–92.

Chen, Y. and Jupp, J. (2019) 'BIM and Through-Life Information Management: A Systems Engineering Perspective', in Mutis, I. and Hartmann, T. (eds) *Advances in Informatics and Computing in Civil and Construction Engineering*. Springer, Cham, pp. 137–146.

Deka, L. *et al.* (2018) '1 - Transportation Cyber-Physical System and its importance for future mobility', in Deka, L. and Chowdhury, M. (eds) *Transportation Cyber-Physical Systems*. Elsevier, pp. 1–20.

Gill, H. (2006) 'NSF perspective and status on cyber-physical systems. In National Workshop on Cyber-physical Systems', *Austin, TX* [Preprint].

Glaessgen, E. and Stargel, D. (2012) 'The digital twin paradigm for future NASA and US Air Force vehicles', in *53rd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference 20th AIAA/ASME/AHS adaptive structures conference 14th AIAA*, pp. 1818.

Grieves, M. (2014) 'Digital twin: manufacturing excellence through virtual factory replication', *White paper*, pp. 1–7.

Hatakeyama, J. *et al.* (2018) 'An Alternate View of the Systems Engineering "V" in a Model-Based Engineering Environment', in *2018 AIAA SPACE and Astronautics Forum and Exposition*, Orlando, FL: American Institute of Aeronautics and Astronautics.

Heaton, J., Parlikad, A.K. and Schooling, J. (2019) 'A Building Information Modelling approach to the alignment of organisational objectives to Asset Information Requirements', *Automation in Construction*, 104, pp. 14–26.

Hox, J.J. and Boeije, H.R. (2005) 'Data Collection, Primary vs. Secondary', in *Encyclopedia of Social Measurement*. Elsevier, pp. 593–599.

ISO 19650 (2018a) *Organization and digitization of information about buildings and civil engineering works, including building information modeling (BIM) - Information management using building information modeling - Part 1: Concepts and principles*.

ISO 19650 (2018b) *Organization and digitization of information about buildings and civil engineering works, including building information modeling (BIM) - Information management using building information modeling - Part 2: Delivery phase of the assets*.

ISO 55000 (2014) *Asset management — Overview, principles and terminology*.

Jallow, A.K. *et al.* (2014) 'An empirical study of the complexity of requirements management in construction projects', *Engineering, Construction and Architectural Management*, 21(5), pp. 505–531.

Johnson, A. *et al.* (2021) 'Informing the information requirements of a digital twin: a rail industry case study', *Proceedings of the Institution of Civil Engineers - Smart Infrastructure and Construction*, pp. 1–13.

Junior, J.S. *et al.* (2019) 'The Role of Building Information Modelling on Assessing Healthcare Design', in *CIB World Building Congress 2019: Constructing Smart Cities*. Int. Council for Research and Innovation in Building and Construction, pp. 1659–1672.

Jupp, J. and Awad, R. (2017) 'BIM-FM and information requirements management: missing links in the AEC and FM interface', in *IFIP Int. Conf. on Product Lifecycle Management*. Springer, pp. 311–323.

Kasprzak, C.M. (2013) *A Planning Procedure for the Identification and Development of Owner Information Exchange Requirements for Capital Facility Projects*.

Kelly, G. *et al.* (2013) 'BIM for facility management: a review and a case study investigating the value and challenges', in *Proceedings of the 13th Int. Conf. on Construction Applications of Virtual Reality*.

Koltun, G.D. *et al.* (2017) 'Model-document coupling in aPS engineering: Challenges and requirements engineering use case', in *2017 IEEE Int. Conf. on Industrial Technology (ICIT)*. IEEE, pp. 1177–1182.

Lamb, K. (2019) 'Principle-based digital twins: a scoping review'.

Lee, J. *et al.* (2013) 'Recent advances and trends in predictive manufacturing systems in big data environment', *Manufacturing Letters*, 1(1), pp. 38–41.

Navendren, D. *et al.* (2015) 'An examination of clients and project teams developing information requirements for the Asset Information Model (AIM)', *Building Information Modelling (BIM) in Design, Construction and Operations*, 149, pp. 169.

Negri, E., Fumagalli, L. and Macchi, M. (2017) ‘A Review of the Roles of Digital Twin in CPS-based Production Systems’, *Procedia Manufacturing*, 11, pp. 939–948.

Nekvi, M.R.I. and Madhavji, N.H. (2014) ‘Impediments to Regulatory Compliance of Requirements in Contractual Systems Engineering Projects: A Case Study’, *ACM Transactions on Mgmt Info. Systems*, 5(3), pp.1-35.

Papinniemi, J., Hannola, L. and Maletz, M. (2014) ‘Challenges in integrating requirements management with PLM’, *International Journal of Production Research*, 52(15), pp. 4412–4423.

Parott, A. and Warshaw, L. (2017) ‘Industry 4.0 and the digital twin: Manufacturing meets its match’, *Retrieved January*, 23, pp. 2019.

Patacas, J. *et al.* (2015) ‘BIM for facilities management: evaluating BIM standards in asset register creation and service life planning’, *Journal of Information Technology in Construction*, 20(10), pp. 313–318.

Patacas, J. *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’, *Journal of Information Technology in Construction*, 21, pp. 434–455.

Penzenstadler, B. and Eckhardt, J. (2012) ‘A requirements engineering content model for cyber-physical systems’, in *2012 Second IEEE Int. workshop on requirements engineering for systems, services, and systems-of-systems (ress)*. IEEE, pp. 20–29.

Roodt, D., Nadeem, M. and Vu, L.-T. (2020) ‘Model-Based Systems Engineering for complex rail transport systems–A case study’, in *INCOSE Int. Symposium*. Wiley Online Library, pp. 1581–1595.

Scott, W. *et al.* (2016) ‘Case Study: A Model Based Systems Engineering (MBSE) Framework for Characterising Transportation Systems Over the Full Life Cycle’, *INCOSE Int. Symposium*, 26(1), pp. 916–932.

Shafto, M. *et al.* (2010) *DRAFT Modeling, simulation, Information Technology & Processing Roadmap*.

Simpson, A. *et al.* (2018) ‘Asset Information Requirements Guide: Information required for the operation and maintenance of an asset’.

Tao, F. *et al.* (2018) ‘Digital twin-driven product design, manufacturing and service with big data’, *The International Journal of Advanced Manufacturing Technology*, 94(9–12), pp. 3563–3576.

Tao, F. *et al.* (2019) ‘Digital Twins and Cyber–Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison’, *Engineering*, 5(4), pp. 653–661.

Wiesner, S. *et al.* (2014) ‘Requirements Engineering for Cyber-Physical Systems Challenges in the Context of “Industrie 4.0”’, *IFIP WG 5.7 Int. Conf. on Advances in Production Management Systems*, pp. 281–288.

Wiesner, S., Hauge, J.B. and Thoben, K.-D. (2015) ‘Challenges for requirements engineering of cyber-physical systems in distributed environments’, in *IFIP Int. Conf. on Advances in Production Mgmt. Systems*. Springer, pp. 49–58.

Wiesner, S., Marilungo, E. and Thoben, K.-D. (2017) ‘Cyber-physical product-service systems–challenges for requirements engineering’, *Int. J. of Automation Technology*, 11(1), pp. 17–28.

Yu, A.T., Shen, G.Q. and Chan, E.H. (2010) ‘Managing employers’ requirements in construction industry: Experiences and challenges’, *Facilities*, 28(7–8), pp. 371–382.