Towards a Requirements Co-engineering Improvement Framework: Supporting Digital Delivery Methods in Complex Infrastructure Projects

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Abstract. To support the delivery of cyber-physical systems of complex infrastructure assets, different requirements (e.g., physical system requirements, asset information requirements) must be developed and managed properly during the lifecycle of the assets. However, there is a lack of integrated and continuous approach to support the co-development and co-management of physical systems requirements and asset information requirements. Adopting a design science research methodology, this paper develops the structure of Requirements Co-engineering Improvement Framework for complex infrastructure projects. This framework defines five maturity levels for requirements relevant process, protocol and supporting software tools. Further validation will be conducted using the Delphi Method in future research.

Keywords: Requirements co-engineering · Capability maturity · Process · Protocol · Technology

1 Introduction

As modern transport infrastructure projects have grown in size and complexity, there has been an increasing need to move away from traditional spreadsheets and find more efficient and reliable methods of managing large volume of requirements. For example, as a part of a linear network, rail transport assets can each be defined as a complex cyber-physical system. Requirements engineering (RE) in the context of the delivery of these projects is increasingly complex. This is particularly true when it comes to 'mega projects', where requirements can number in the hundreds of thousands. All of which must be managed and traced across multiple stakeholders, work packages and interfaces in a complex, high-pressure environment where errors, changes and delays can cost millions of dollars.

Different types of requirements about the cyber systems and physical systems of complex infrastructure assets must be developed and managed throughout the planning and delivery phases. Requirement types include, amongst others; high-level capability

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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 planning and acquisition of complex infrastructure projects, asset information requirements describing physical systems, their virtual replicas, and real-time behaviours must also be developed and managed.

Yet, often due to issues related to the scale, complexity, and emergent properties of the cyber-physical systems being developed, the different (and evolving) requirement types of cyber systems and physical systems and corresponding asset information requirements are increasingly difficult for current engineering practices to handle. The digital delivery of complex infrastructure projects increases the need to implement more integrated and continuous approaches to RE that recognised the importance of asset information requirements review processes and verification traceability methods.

Based on the Software Engineering Institute's (SEI's) Capability Maturity Model for Integration (CMMI), this paper develops a Requirements Co-engineering Improvement Framework for complex infrastructure projects. The proposed framework presents an approach for the organisation or project team to understand the current maturity level of requirements management capabilities and a potential pathway for improvement. The paper proceeds in Sects. 2 with an overview of current requirement engineering maturity models. Section 3 describes the design science research methodology, and Sect. 4 presents the development of the Improvement Framework. Section 5 concludes the paper with future research plan to further development and verification of the framework and the limitation of the research.

2 Requirements Engineering Maturity Models

The effectiveness level of an organisation to develop quality products or services is directly related to the maturity of their processes [1]. In the context of this research, measuring the maturity level of RE processes offers a solution to organisations who are seeking for RE process improvement. This section investigates the capability of existing capability maturity model, especially the relatively new and up to date RE process maturity models and discusses their applicability in supporting capability measurement of RE in rail infrastructure.

Several RE capability models have been proposed based on Software Process Improvement (SPI) standards and framework such as Software Engineering Institute's (SEI's) old Capability Maturity Model (CMM) and relatively new Capability Maturity Model for integration (CMMI). Existing models supporting RE process maturity assessment include Requirements Capability Maturity Model (RCMM) [2, 3], Market-Driven Requirements Engineering Process Model [4], Requirements Engineering Good Practice Guide [5] and Requirements Engineering Process Maturity Model [6]. However, all these four models arose in software industry and were built based on the retired and unsupported Software-CMM or CMM [7]. Some of them are not completely developed and validated while others are difficult to implement [8, 9].

In this research, Requirements Engineering Process Assessment and Improvement Model (REPAIM) and Capability Maturity Model improved (R-CMMi) are selected for further review as they are both cited as two of the most popular maturity models [8, 9]. However, REPAIM uses the continuous representation model to describe capability levels of processes, while R-CMMi adopts the staged representation model to define maturity levels, which characterise the organisation's behaviour. These two types of representation models are both defined in the CMMI standard (see Table 1) [10].

Table 1. REPAIM and R-CMMi levels in CMMi

	REPAIM	R-CMMi
Level	Capability levels Continuous/Process	Maturity levels Staged/Organisation
Level 0	Incomplete	–
Level 1	Performed	Initial
Level 2	Managed	Managed
Level 3	Defined	Defined
Level 4	–	Qualitatively managed
Level 5	–	Optimised

In REPAIM, four levels of maturity are defined as incomplete, performed, managed and defined. The REPAIM shows its capability to access RE processes and prioritise their improvement, adapt and complement existing maturity standards and assessment approaches, and adapt to the demands of different organisations [7]. However, there are two identified drawbacks of REPAIM. One of the main drawback is that training is still required by the practitioner in order to understand the model [7]. Another drawback is that it appears to need further examples, templates, and instructions to inform an effective implementation by potential users [7].

Five maturity levels are defined as initial, managed, defined, qualitatively managed and optimised in R-CMMi which shows a high consistency with CMMI standard [9]. The drawback of R-CMMi is similar with REPAIM in terms of validation, implementation issue, training, future work of instructions, examples and templates.

Furthermore, there are important interrelationships between maturity levels and capability levels. These organisational maturity levels are dependent on the capability levels of their processes. To research a certain maturity level, the organisation have to successfully achieve the objective of the targeted process areas to that level [1]. The maturity levels reflect the current status of RE in an organisation or a project, while capability levels provide with an improvement pathway to the higher maturity level. Thus, a combination of these two types of representation model would potentially resolve these issues and is adopted in this research.

3 Design Science Research Methodology

A design science research methodology (DSRM) was adopted as this whole research project seeks to extend the boundaries of human and organisational capabilities by creating new and innovative artefacts. Figure 1 adapts the design science research framework of Information System proposed by Hevner et al. [11] and overlays three inherent research cycles – relevance cycle, rigor cycle, and design cycle [12].

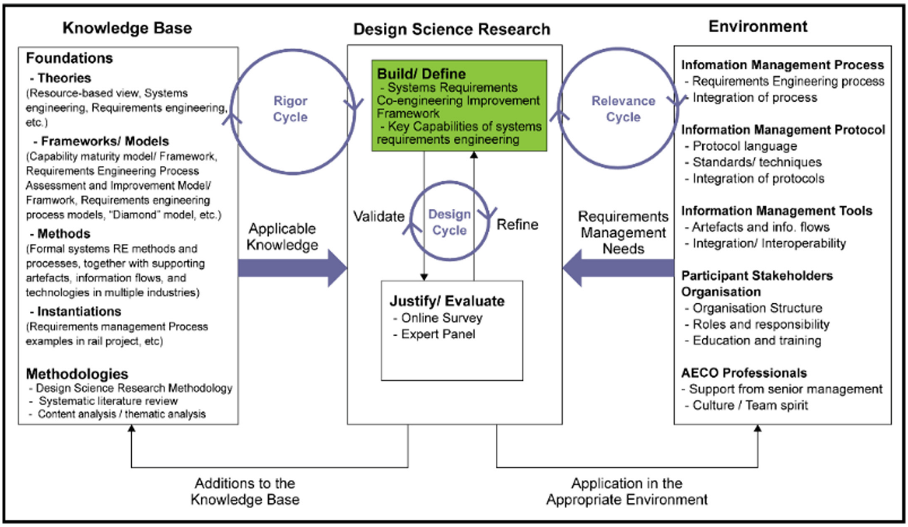

Fig. 1. Design science research conceptual framework [Adapted from 11]

Figure 1 reflects three main areas of the whole research project including the general knowledge base of the research area, the environment of research problem we are focusing on, and the core design science research activity. The content in each area has been adapted based on the research scope, nature of research problem, industrial context, as well as the availability of resource. The content of this paper focus on the Build and Define activity as highlighted in green in Fig. 1.

The central Design Cycle iterates between core activities of developing the Improvement Framework, its evaluation, and subsequent feedback to refine the framework [12]. Findings drawn from the systematic literature review form 'Knowledge Base' and semi-structured interviews form 'Environment' foundation of the design. Section 4 of this paper focuses on presenting the development of the structure of Requirements Co-engineering Improvement Framework. In the next stage of this research, survey among a group of experts will be implemented as evaluation methods to test and validate key elements of the framework and their significance with regards to supporting higher levels of integration and model-based approaches to requirements management in complex infrastructure.

4 Requirements Co-engineering Improvement Framework

4.1 System Requirements and Information Requirements

Different types of requirements about the cyber systems and physical systems in the built environment must be developed and managed throughout the Planning and Acquisition Phases of complex infrastructure projects. Requirement types include, 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.

Asset information requirements (AIR) is 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 Fig. 2 below).

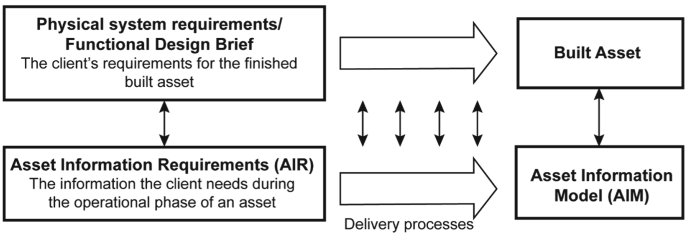

Fig. 2. Parallel delivery of built asset and asset data [28]

In complex infrastructure projects, especially in rail sector, the development and management of physical system requirements usually follow the process of the traditional systems engineering approach which also be described in the traditional "V" model. In order to understand the co-development and co-management of physical system requirements and AIR, a "Diamond" model (see Fig. 3) has been developed based on Boeing [29]and TfNSW [30]. The lower V reflects the classic systems engineering process of the physical system, while the mirror reflection of the V above represents the digital twins modelling and simulation [29, 30]. The inverted V represents the design and realisation of the behavioural simulations [29].

4.2 Contemporary Approaches to Requirements Engineering

Previous work of this research includes a systematic literature review which explored contemporary and state-of-the-art RE approaches to supporting the creation of complex software dependent systems (e.g., digital twins and cyber-physical systems) and semi-structured interviews with industry experts from transport infrastructure. Main capabilities supporting RE are identified and categorised into three main aspects including process and protocol, technology, organisation and people (as shown in Table 2). Based on this, the structure of Requirements Co-engineering Improvement Framework is developed and described in the following section.

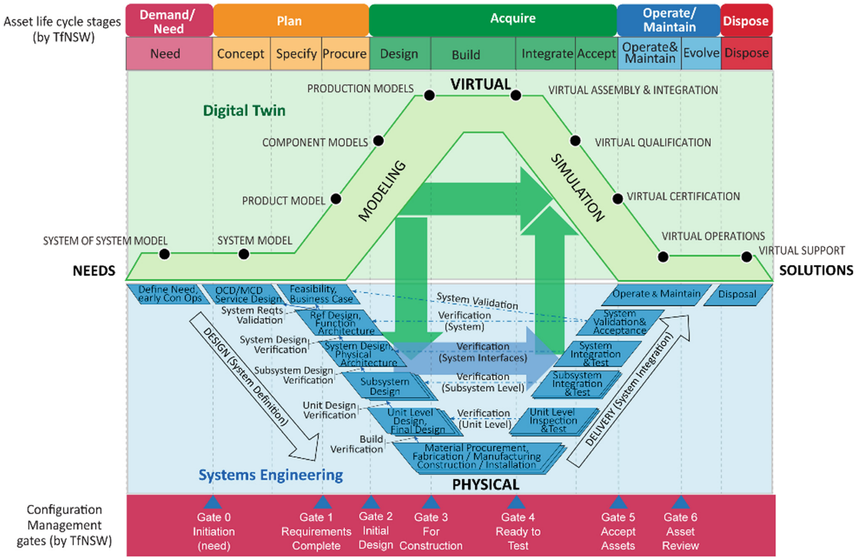

Fig. 3. "Diamond" model reflecting interaction of physical system requirements and AIR

4.3 Structure of Improvement Framework

Main capabilities identified in Table 2 have been developed into 14 requirements co-engineering sub-capabilities. Figure 4 presents the matrix displaying the score system for these sub-capabilities in different maturity levels. Once the maturity levels of capabilities are evaluated, a final sore of three categories (i.e., process and protocol, technology, organisation and people) will reflect the status of requirements co-engineering practices in a project or an organisation. 'Requirements' in Fig. 4 refer to physical systems requirements and asset information requirements.

Activities contained in each capability will be further developed and verified in the next stage of research which will then support identifying improvement pathway of requirement co-engineering capability in an organisation or a project. Moreover, the derivation of a sorting or rating system for all capabilities supports a modular and flexible approach assessment. A final weighting system is yet to be identified according to capabilities domains.

Table 2. Main capabilities supporting requirements engineering

Category	Main capabilities	Sources
Process & protocol	Requirements elicitation process	[13–15]
	Requirements analysis and prioritisation process	[14, 16, 17]
	Requirements allocation and verification process	[14, 16]
	Negotiation of conflicting requirements amongst stakeholders	[14, 15]
	Requirements change management process	[18–20]
	Requirements validation process	[18, 21]
	Use a recognised standard to support the definition and specification of requirements	[15]
Technology	Use a dedicated requirements management software supporting requirements documentation, verification, and validation	[16, 22, 23]
	Integration of requirements management software with 3D modelling software support the handling of Physical system requirements and Asset information requirements	[19, 24, 25]
Organisation & people	Involvement of stakeholders in eliciting and analysing requirements	[21, 26, 27]
	Formally defined roles and responsibilities for handling requirements in multiple phases of a project	[19, 21]
	Training in requirements software in support of requirements handling in multiple phases of a project	[18]

4.4 Development of Requirements Co-engineering Maturity Levels

In this research, a combination of REPAIM and R-CMMi maturity levels are adopted for the definition of processes and protocols maturity levels. While the definition of supporting technology maturity levels is concluded based on findings from semi-structured interviews with industry experts. Table 3 presents the description of maturity levels of process and protocol, as well as technology related capabilities supporting requirements co-engineering. Organisation and people related capabilities are relative intangible compared with process and technology. This requires a different way to describe its maturity. For example, the frequency of formally defined roles and responsivities, and the frequency of trainings. Because of the page limitation, organisation and people related maturity levels will not be included in this paper.

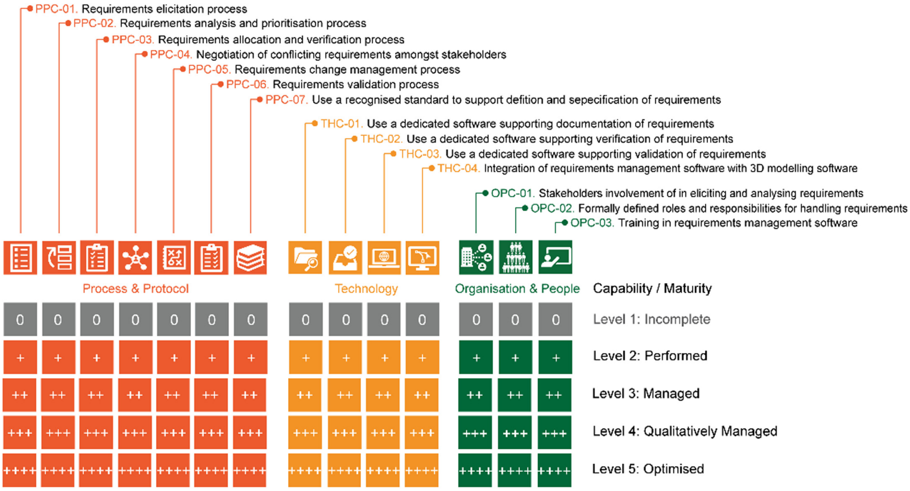

Fig. 4. Matrix displaying the scores for 14 capabilities in different maturity levels

Table 3. Description of requirements co-engineering maturity levels

Main capabilities	Maturity levels				
	Level 1: Incomplete	Level 2: Performed	Level 3: Managed	Level 4: Qualitatively managed	Level 5: Optimised
Process & protocol					
Process	There is no formal process defined or implemented	An ad hoc process is implemented during project delivery	An organisational standard that describes a generic process exists	Level 3 + Process is monitored, and performance is assessed	Level 4 + Continuous process improvement enabled by performance feedback loop
Protocol	There is no standard used to define and specify requirements	Standards supporting definition and specification of requirements based on individual delivery-side stakeholder approach	An industry sector-specific standard is used to define and specify requirements	A standard specified by the Government Agency/Client is used to define and specify requirements)	International standards are utilised (E.g., ISO Standard used to define and specify requirements)

(*continued*)

Table 3. (*continued*)

Main capabilities	Maturity levels				
	Level 1: Incomplete	Level 2: Performed	Level 3: Managed	Level 4: Qualitatively managed	Level 5: Optimised
Technology					
Software tools	There is no dedicated requirements software tool utilised by project delivery team organisations	Separate requirements software tools are utilised across the various project delivery team organisations	An integrated requirements software tool/platform is **used by a minority** of relevant project delivery team organisations	An integrated requirements software tool/ platform is **used by a majority** of relevant project delivery team organisations	Level 4 + Requirements managed by a dedicated project role, e.g., requirements engineer, systems engineer, digital engineer, BIM manager
Integration of requirements management software and 3D modelling software	Neither requirements management nor 3D modelling software is used	Only requirements management software is used but 3D modelling software is not	Separate and distinct requirements management and 3D modelling software is used, however there are no digital links between them	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	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

5 Discussion and Future Research

Adopting a design science research methodology, a preliminary requirements co-engineering capability improvement framework is developed. This framework includes two parts: i) capabilities supporting requirements co-engineering, and ii) maturity levels of capabilities. The main capabilities are developed based on findings from a systematic literature review and semi-structure interview survey with industry experts. They are then categorised into process and protocol, technology, organisation and people. Maturity levels of process and protocols in this research follow the structure of REPAIM and R-CMMi models while technology related maturity levels conclude from semi-structured interview survey.

During our semi-structured interview survey, we identified that there exists a great dependency on a co-engineering approach during the creation of complex and adaptive systems, where "co" requires the project team to work towards the virtual deliverables (e.g., digital twin, or cyber-physical systems) as a common goal [31]. 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 digital twin 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 [31]. For complex infrastructure projects the co-engineering of information requirements is key to support the delivery of both physical and virtual assets with decades long lifespans.

Thus, the development of this improvement framework is aimed at identifying main capabilities supporting requirements co-engineering and presenting an approach for the organisation or project team to understand the current maturity level of requirements management capabilities and a potential pathway for improvement. Further development and validation of this improvement framework will be conducted using the Delphi Method through an expert panel consisting of experienced practitioners and researchers in the area of complex infrastructure, systems engineering and requirements engineering.

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