Exploring the Nexus between Digital Engineering and Systems Engineering and the Role of Information Management Standards

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Abstract:
Information management standards provide much needed guidance to the implementation of processes supporting more integrated, digital, and model-based approaches to project delivery and through-life asset information management. These standards impact all stakeholders spanning the planning, acquisition and operational phases of buildings and infrastructure. In Australia, since the release of ISO 19650, a variety of state agency standards for digital engineering have been released in support of new model-based processes. A paucity of studies on the uptake of information management standards translates to a lack of understanding of their prevalence, impact, and perceived value on engineering design activities, and in particular systems engineering tasks surrounding requirements management. This paper provides the first step to providing insights into these standards via an online survey of digital engineering and systems engineering stakeholders. Findings reflect a number of differences in the experiences, interpretations, and applications of these standards between roles and sectors. Findings also reflect a greater perceived impact from government standards over international ones. The study highlights ongoing confusion in the roles and responsibilities of digital engineers and systems engineers, and the lack of interface management between information requirements and physical system requirements throughout design review activities.

Keywords:
Digital engineering, Industry survey, Information management, Standards, Systems engineering.

1 Introduction

The implementation of more integrated, digital, and model-based technologies to support strategic approaches to project delivery and whole-of-life asset information management has seen a growing number of international, national government and state-agency standards. Since the release of the ISO 19650 standards (Parts 1&2) in 2018, state government agencies have published supporting standards in digital engineering (DE) and building information modelling (BIM). These standards are aimed at providing greater consistency and maturity in information requirements management process across the diverse stakeholders engaged in the planning, acquisition and operations of buildings and infrastructure.

Transport for New South Wales (2019a, 2019b) first commenced the DE Framework Program – a fully funded program – running since 2017, with the aim of bringing together experts from around Australia to develop practical, cost effective DE solutions based on global best practices. The program resulted in the evolution and release of consecutive versions of Transport's DE Standards: Release 1 (in Sept 18), Release 2 (in Apr 19) and Release 3 (in Nov. 2019). The standards define the minimum requirements for implementing DE in project delivery phase and provide guidance in information management more generally. Similarly, Office of Projects Victoria (2020) released the Victorian Digital Asset Strategy (VDAS) in 2020, providing detailed guidance on planning, implementing, managing and maintaining an effective digital asset strategy throughout the lifecycle of an asset. As a pioneer in implementing BIM approach, in 2018 Queensland Government (2018) announced the policy to mandate BIM on all government construction projects costing over $50 million and expanding to all built assets by 2023. Other state like South Australian (2019) also published DE standard, intending to provide an overview of the minimum requirements for DE practices on road projects. From a nationwide perspective, National DE Policy Principles have been developed by governments in Australia in recognition of the potential benefits that DE and BIM can bring to the design, delivery, operation and management of land transport infrastructure assets.

The Australian experience is not unique. For the past two decades, growing maturity in the application of process and information requirements management standards supporting model-based approaches to asset planning and acquisition (Chen and Jupp, 2021). This has resulted in new service-oriented offerings linking, for example, BIM to Facilities Management (Matarneh et al., 2019), and more recently to the development of spatial digital twins (DTs) in support of the operations and maintenance (O&M) of building and infrastructure assets (Tchana et al., 2019; Johnson et al., 2021; Zhao et al., 2022). Whilst the ISO 19650 is widely acknowledged by organisations, there is a lack of studies on the uptake of ISO19650 and related DE and BIM standards. This then translates to a lack of understanding of the prevalence, impact, and perceived value of the standards. The paper provides a first step to providing insights about the effects of these standards. The objective of the paper is to explore two questions:

RQ 1: What is the prevalence of use of information management standards (e.g., ISO 19650 Standard (Parts 1&2) and other Digital Engineering standards?

RQ 2: What are the digital engineering and systems engineering roles and responsibilities, and levels of experience in information management standards?

2 Standards and Stakeholders of Information Requirements Management

In Australia, the release of the ISO 19650 standards in 2018 - together with other business and industry drivers - have accelerated recent efforts in government agencies to release DE and BIM standards for projects in support of more integrated digital approaches to the planning, acquisition and O&M of assets. In both building and infrastructure sectors, to support complex requirements management processes, a variety of formal systems engineering methods and processes play a critical role in the implementation of these standards – from the development and management of different requirement types to the verification and validation of physical system and digital deliverables. This results in a variety of interfaces between digital engineering and systems engineering standards and stakeholders.

2.1 Standards Supporting Information Requirements Management

The widespread acceptance of DE and BIM, and recognition of the growing digitalisation of the Australian construction industry has increased in both the building and infrastructure sectors (Hosseini *et al.*, 2020). However, the need to define and utilise standardised information requirements management methods as a key enabler of process consistency has received less wide-spread recognition (ABAB, 2018).

2.1.1 International Standards - ISO 19650 and ISO 55000

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

Prior to the introduction of ISO 19650, projects implementing BIM did not have a consistent information requirements management process across the industry (Chen and Jupp, 2021). Together *ISO 19650-1: 2018* and *ISO 19650-2: 2018* describe the processes supporting digital information management, with a focus on information requirements management in the context of buildings and civil engineering works, including BIM (ISO, 2018a, 2018b). ISO 19650 provides a procedural method according to four requirement types, including i) organisation information requirements (OIR), ii) asset information requirements (AIR), iii) project information requirements (PIR); and 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 on the information needed by an organisation to inform decision-making about high-level strategic objectives (Simpson et al., 2018).

The OIR therefore forms a critical first step in the procedural method[1] 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). This is also an integral component of ISO 55000:2014 implementation (Chen and Jupp, 2021). Australian transport agencies widely utilise the AMAF to detail mandatory asset management requirements and provide guidance for managing assets. The ISO 55000 series (2014) consists of three international standards that provide the terminology, requirements and guidance for implementing, maintaining and improving asset management systems. ISO 55000 is widely used by utilities, transport, mining, process and manufacturing industries worldwide, enabling the streamlining of expenditure, strengthening of credentials and future-proofing of facilities and assets (International Council on Systems Engineering, 2007; Transport for NSW, 2017).

The ISO 55000 and ISO 19650 standards and the procedural methods they define together play a central role in the development and management of AIR and asset information model (AIM), as well as the ongoing management of digital information and digital deliverables supporting asset management (Chen and Jupp, 2021).

2.1.2 Australian State Government Standards

Australia government commissioned a national BIM initiative in 2012 and recommended requiring full 3D collaborative BIM for all Australian Government building procurements by 1st July 2016 (BuildingSMART Australasia, 2012). However, due to the isolated and inconsistent work of different States, it was difficult to implement a national mandate (Jiang *et al.*, 2022). By contrast, the local states decided to move faster. In 2018, Queensland Government announced the policy to mandate BIM on all government construction projects costing over $50 million and expanding to all built assets by 2023 (Queensland Government, 2018). At the meanwhile, new DE standards have been developed and implemented by a

[1] 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 (Chen and Jupp, 2021). The AIR and PIR 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 (Chen and Jupp, 2021). 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 (DEXP/ BXP).

growing number of state infrastructure agencies, including *Digital Engineering Standard* (Transport for NSW, 2019a, 2019b), *Victoria Digital Asset Strategy* (Office of Projects Victoria, 2020), *Building Information Modelling Mandate Policy* (Queensland Government, 2018), and *Project Controls – Master Specification – PC-EDM5 Digital Engineering* (South Australian Department for Infrastructure and Transport, 2019).

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

Victorian Digital Asset Strategy, also known as VDAS, was released by the Office of Projects Victoria in March 2020. This guidance consists of three parts which provide strategic-level (Part A), organisational-level (Part B) and project-level (Part C) advice for the effective management of digital information and data throughout the life of an asset (Office of Projects Victoria, 2020). It provides detailed guidance on planning, implementing, managing and maintaining an effective digital asset strategy throughout the lifecycle of the organisation's asset base (Office of Projects Victoria, 2020). It has been developed in collaboration with industry and is aligned with international standard ISO 19650. Based on VDAS, the Digital Asset Policy (Office of Projects Victoria, 2022) describes three levels of capabilities of 14 requirements in organisational and project level throughout the asset lifecycle.

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

2.2 Information Management Roles and Responsibilities

To make the DE standards implementable in practice, the responsibilities and roles for information management throughout the lifecycle of the asset is defined. In ISO 19650-2 (2018b), a general information management process is presented from planning to close-out of a project. In state-based DE standards, key responsibilities and dedicated roles of information management are defined, providing a more detailed guidance for the project team (Office of Projects Victoria, 2020; Transport for NSW, 2019b).

2.2.1 Project Behaviour and Key Responsibilities

The information management processes of a project can be defined according to a series of five project behaviours including: 1) share, collaborate, deliver, 2) use common language, 3) auditable assurance pathway, 4) digital tools to support decision making, and 5) a platform to support innovation (Transport for NSW, 2019b). Key responsibility in the client-side tend to focus on the overall project DE strategy, and procurement and implementation. The client-side stakeholder is therefore responsible for the management and coordination of project execution and DE to meet the procurement strategy and cost containment (Transport for NSW, 2019b). As the accountable role for the successful implementation of DE on projects (International

Organization for Standardization, 2018b), the client-side's (also known as appointing party in ISO 19650) DE manager should manage the process of a delivery team virtually construction an asset in DE and oversee documenting it as per the EIR needs (Office of Projects Victoria, 2020). From an output documentation point of view, this include the development of OIR, AIR, and EIR and then reviewing the DEXP developed by the appointed party during the early planning and design phases (Office of Projects Victoria, 2020).

From the contractor's perspective, the responsibilities span a wide scope of tasks. Taking the TfNSW DE Standard (2019b) as an example, they include for example: 1) the development of the overall *project DE strategy* and its implementation by the Contract Project Team, 2) the setup and delivery of the project from a DE perspective, 3) the management of the overall production of the project's federated BIM Model and associated data sets, 4) initiation, agreement and implementation of information sub-plans, for control and governance of separate design packages (disciplines) and/or sub-contractor works, 5) the verification of compliance for information management in accordance with the Contract, legislation and relevant Safety, Environment & Regulation and Industry Standards, and lastly 6) the day-to-day implementation of document control processes and system support. The effectiveness and efficiency by which these responsibilities are met relies heavily on the experience of the contractor, supporting DE technical schemas and specifications, and delivery tools and templates that defined according to the client's OIR and AIR.

2.2.2 Dedicated Information Management Roles

Digital Engineering Roles: Typically, there would be three levels of DE roles that project stakeholders should perform at different stages of the project lifecycle, including: 1) DE manager – strategic level, 2) DE coordinator – management level, and 3) DE Modeller– production level (AbuEbeid and Nielsen, 2020). These roles are usually taken by different stakeholders. The DE modellers usually refer to the design team or subcontractors in various disciplines. The DE coordinator is the role sits in client side or main contractor side and responsible for coordinating the federated model among multiple disciplines. The DE manager is usually an organisational level role who is responsible for setting up DE process and workflow, standards, implementation and training (AbuEbeid and Nielsen, 2020). DE roles are the key executors to implement data and information asset management policies.

Systems Engineering Roles: Systems engineering (SE) in transport infrastructure plays a key part role in managing risk and safety during project delivery. In rail infrastructure it is essential to meeting the requirements of the Rail Safety National Law (RSNL), which emphasises the safety of the rail infrastructure projects. As described in SE standards of government transport agency, the SE roles should focus on 'defining stakeholder needs and functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and functional allocation to subsystems' (Transport for NSW, 2017, p. 12). Levels of responsibility and engagement of SE organisational roles can be mapped to SE management processes and activities across the system life cycle (Transport for NSW, 2017). SE roles include the: SE manager, Systems Engineer, Requirements Manager, Systems Integration Manager, Systems Architecture Manager, Systems Interface Manager, and Verification and Validation Manager. The setup of SE roles in a project is flexible depending on the complexity and scale of the project. In simple projects, SE roles could be carried out by the Design Manager, Engineering Manager, or Project Manager (Transport for NSW, 2017). In a project with digital deliverables, it is important to clarify the interface and interaction between DE and SE roles, as the coordination and consistency between AIR and physical system requirements is high.

3 Research Methodology

3.1 Research Design

An online survey was developed based on findings from literature review and semi-structured interviews conducted at previous stages of the research. The literature review focused on identifying the challenges of and existing methods supporting information requirements engineering practices in projects requiring digital delivery. As a result, a list of challenges has been identified (Chen and Jupp, 2021) which then form the main content of the online survey.

3.2 Survey Instrument

Engineering and Construction firms with high levels of organisational expertise in the civil infrastructure sectors were invited to participate in an online survey. The research survey specifically targeted organisations with high levels of expertise in and specifically those with expertise in DE, BIM, and Model-based Systems Engineering (MBSE) (Wymore, 2018) in order to identify the current state of implementation of different standards in in building and infrastructure projects. The respondents therefore listed a variety of DE/ BIM related roles (e.g., digital engineer, digital integration consultant, digital strategist, BIM managers and consultants, etc.), as well as systems engineers, and client-side DE and BIM management roles. In total, there were 32 valid responses recorded, providing a small, but high levels of expertise in the sound sample. The total number of respondents was relatively small because the use of DE in complex infrastructure projects is in its infancy. All survey responses were recorded from January to August 2022. Participants were asked to choose their roles, sectors of construction they involved in, and their level of experience in the application of different methods and standards supporting information management.

3.3 Data Analysis

Survey data are extracted from Qualtrics and analysed in multiple perspectives. First of all, an overview of the background of participants and the status of standard implementation in projects were presented. Based on that, further analysis was conducted to investigate the interrelationship between sectors and standards implementation, as well as relationship between ISO standards and state-based standards implementation.

4 Findings and Discussion

4.1 General Findings

As reflected in Figure 1, the respondents came from two main groups: DE roles (20) and SE roles (12). These two groups are the key stakeholders that are the executors of information management activities of a project, with their responsibilities intersecting during information requirements management tasks. DE roles are separated into three subcategories based on three roles in projects and year of experience in DE implementation. Digital Engineers are those who have 1 to 5 years' experience in DE implementation while DE managers more than 5 years' experience. DE developers / advisers are the strategic level roles who support the development of DE standards and guidelines in client-side or consultant organisations.

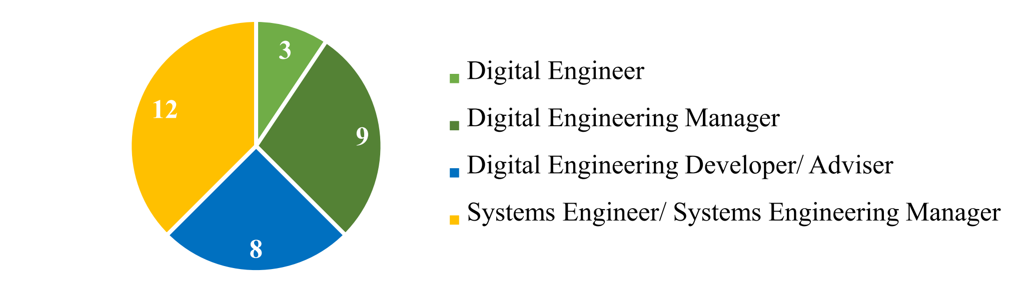

Figure 1. Breakdown of Digital Engineering and Systems Engineering Respondents' Roles

Figure 2 presents the industrial sectors that all the respondents have been involved in. More than half of respondents (R = 21) were involved in multiple sectors. The rail infrastructure sector is the main sector where most respondents accumulated their experience (R = 28), with Roads, Bridges and Highways (R = 17) and Commercial Office (R = 12) the next two sectors where respondents had most experience in the implementation of DE and SE standards.

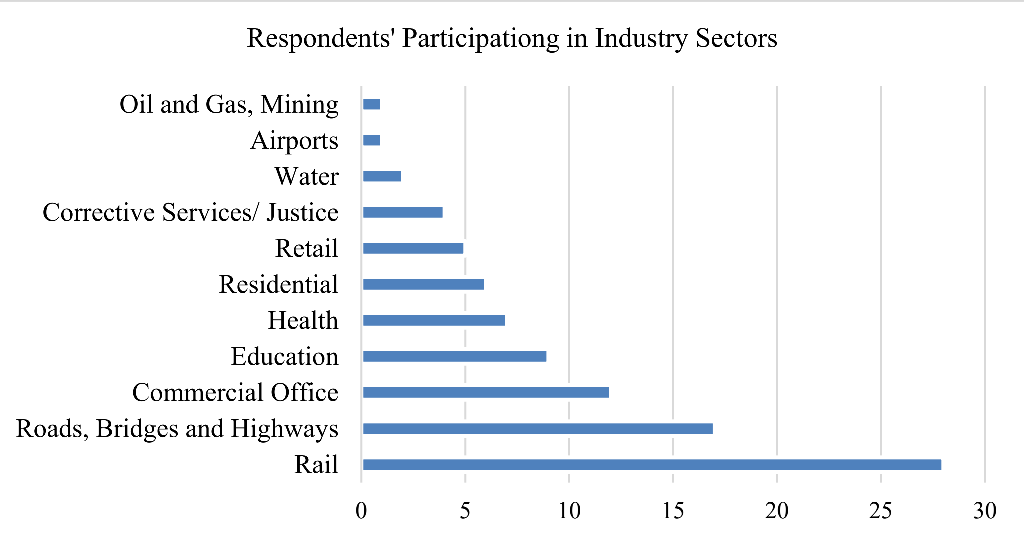

Figure 2. Respondents' Participation in Projects across Industry Sectors

4.2 Knowledge and Implementation of ISO and State-based Standards

Figure 3 presents an overview of respondents' level of experience in implementing ISO 19650 and state-based DE standards. Considering these standards have only been published for less than 5 years, four levels were defined based on their understanding of and involvement in the implementation of those standards (rather than based on the number of years of experience). These levels include: 1) No Knowledge, 2) Beginner, 3) Intermediate, and 4) Advanced.

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

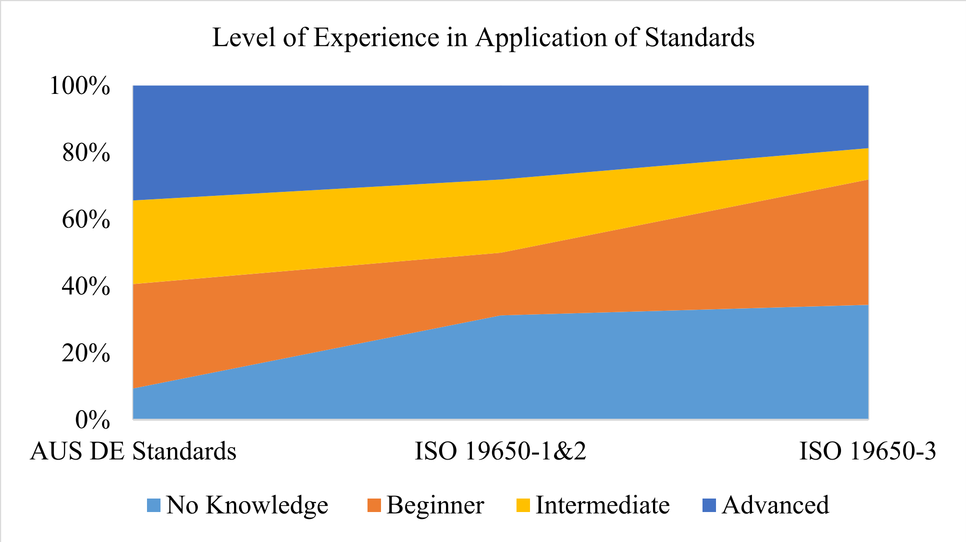

Figure 3 Overview of Implementing ISO 19650 and DE standards

An analysis of the survey findings in response of RQ1, which sought to identify the prevalence of use of ISO 19650 and related DE/ BIM standards in Australia - is presented in Figure 3. Intermediate and Advanced levels show that 60% of respondents have a working knowledge of the standards and been directly involved or responsible for the implementation of Australian (state-based) DE standards on projects, and only 50% having integrated ISO 19650-1&2 and 30% ISO 19650-3 methods in their working practices.

RQ2 attempts to build a greater understanding of the related DE and SE roles relative to their responsibilities (also ref. to Section 2.2), and their respective levels of experience in information requirements management standards. Further analysis of the survey findings in response to RQ2 is presented in Figure 4, shows that state-based standards are more commonly recognised and used on projects than the ISO 19650 standard. The respondents who have no to little knowledge of Australian DE standards were those who identified as systems engineers, who responded that they also do not have any or limited experience in DE related projects. ISO 19650 Part 3 also has a lower rate (30%) of implementation than Part 1&2 (50%), as the current emphasis of DE implementation is still in project delivery phases indicating a lower level of maturity in implementation of DE in O&M phase.

During the early implementation of DE processes, those in systems engineering roles have had limited to no understanding of international standards such as ISO 19650. Due to dependencies between 'traditional' requirements management practices (led by SE roles) and new, evolving information requirements management practices (led by DE roles) a significant knowledge gap arises which presents substantial risk to requirements traceability. An awareness of Australian DE Standards was reported by the majority of SE roles in transport infrastructure sectors (refer to 'Beginner' in Figure 4), indicating a low level of knowledge. There are potential opportunities for systems engineers to play a greater role in information requirements management processes. It also reveals opportunities for further transformation of SE roles in the use of model-based data during design review activities for requirements verification. The evolution of traditional SE competencies to MBSE competencies would assist in managing the interface between physical system, functional and performance and information requirements.

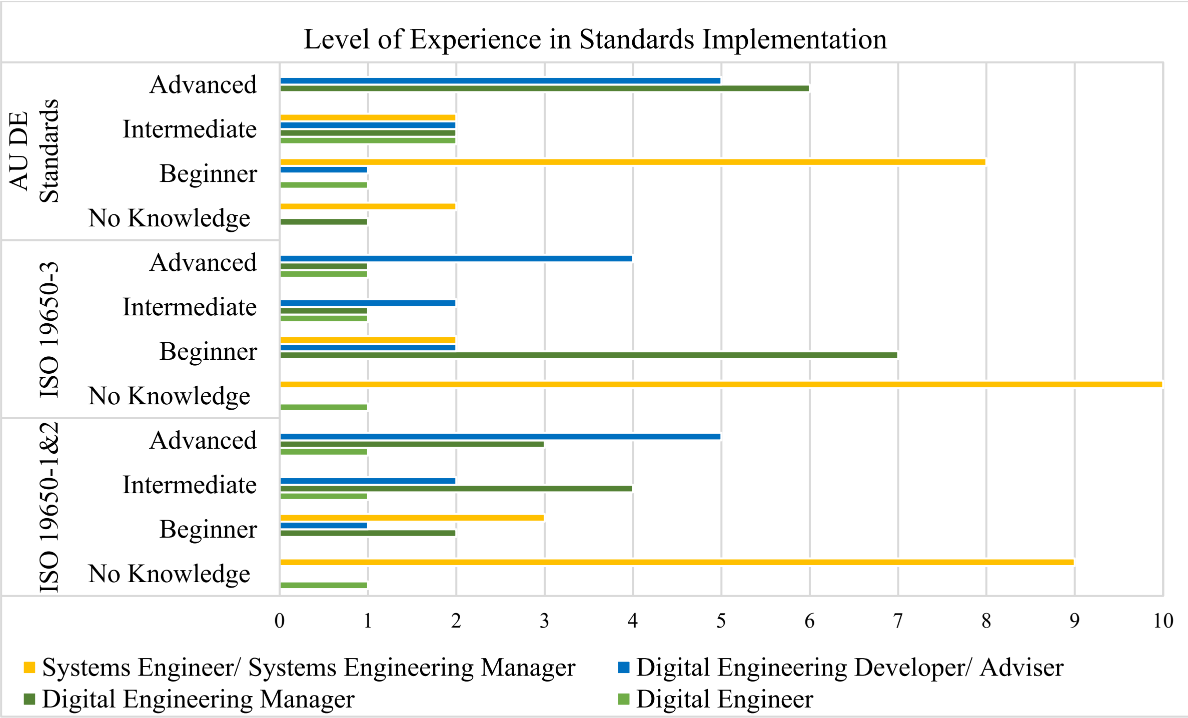

Figure 4. Respondents' Level of Experience in Implementing Different Standards

4.3 Discussion

With the adoption of new digital ways of working and information management processes come new forms of contract and a shift roles and responsibilities. Many of the individuals currently working as systems engineers or digital engineers have previously held positions as civil or mechanical engineers, architects, and construction managers. They now find themselves, through choice or circumstance, in new and rapidly evolving roles. In addition, other roles such as 'design manager' and 'design coordinator' have also evolved and become more commonplace (Emmitt and Ruikar, 2013). Beyond Australian state government transport agencies mandating DE and SE requirements and responsibilities, there is otherwise a paucity of DE and SE roles and interfaces defined in organisational standards. Thus, their exact nature is not always well-defined or understood.

Part of the confusion appears to stem from the wide interpretation and application of DE and SE standards and thereby roles and responsibilities. The impact of this confusion can be evidenced throughout design coordination and systems design review activities, where the interfaces between 3D model-based design coordination activities (undertaken by DE roles) and requirements verification activities (undertaken by SE roles) are largely ignored in the EIR and related planning documentation (e.g., DEXP and BXP). Consequently, current interfaces between SE and DE activities are managed in an ad-hoc manner throughout system functional review (scoping), preliminary design review (concept design), and critical design review (detailed design) activities.

A range of issues impact the industry's ability to address these issues. There is a lack of education and training programmes for aspiring SE and DE managers. There is also little recognition of the need for – and opportunities arising from – the creation of greater alignment between DE and SE disciplines. This has already happened in complex discrete manufacturing with increasing maturity in MBSE (Wymore, 2018). Compounding these educational issues is the lack of accreditation and benchmarking of competencies from industry bodies, particularly with regards to DE. Given that DE is an emerging discipline, and that SE is still relatively immature in transport infrastructure sectors – and often unrecognised in the building sectors – a lack of clarity is to be expected as the construction industry refines both DE and SE roles.

5 Conclusion and Limitation of Research

To support a consistent and structured information requirements management process across multiple stakeholders throughout the lifecycle of an asset, ISO 19650 standards and government state-based standards are being implemented in Australian building and infrastructure sectors. This paper investigates the application of and participation in ISO19650 and other Australian government standards supporting DE in building and infrastructure projects. Findings reflect a variety in understanding and implementation of ISO 19650 as well as other related standards across different types of organisations. Government state-based standards are more commonly used and recognised than international standards. The study also reflects a knowledge gap of ISO 19650 in SE roles who however have a basic understanding of state-based DE standards. This indicates a lack of well-defined DE and SE roles and responsibilities to support the interface management of DE information requirements with physical system requirement. The study's findings provide important insights on the challenges to applying ISO and government standards in support of digital project deliver and through-life asset information management. The limitation of this research is that because of the use of DE in complex transport infrastructure projects is in its infancy, the total number of respondents was relatively small. Future research will focus on identifying key enablers supporting interface management between SE and DE roles in transport infrastructure projects.

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