Digital Engineering 1 (2406) 100003

Contents lists available at ScienceDirect

Digital Engineering

journal homepage: www.sciencedirect.com/journal/digital-engineering

Digital transformation maturity assessment framework for large infrastructure asset owners

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ARTICLE INFO

Keywords:
Digital transformation
Asset lifecycle management
Analytic hierarchy process
Building information modelling
Maturity assessment framework

ABSTRACT

This research project developed a framework for assessing digital transformation (DT) maturity in large government-owned corporations (GOCs), focusing on integrating building information modelling (BIM), digital engineering (DE) practices, value of information, data integration aspects, and critical information management competencies, relating to asset management, asset delivery, and asset performance. Recognising DT's strategic importance in asset lifecycle management, researchers created a practical DT maturity assessment tool applied to an Australian GOC. The framework and Excel assessment tool outline DT maturity across seven categories and 56 indicators, using the analytical hierarchy process (AHP) to rank indicators based on expert input. The tool enables straightforward data input and DT maturity evaluation, helping organisations understand their current DT status and set improvement targets. Workshops with DT professionals validated the tool's effectiveness through a case study, offering insights into DT maturity levels and a roadmap for technological integration and data-driven decision-making. The research highlights DT's role in enhancing efficiency, innovation, and safety, emphasising the need for strategic alignment with organisational objectives.

1. Introduction

The building and infrastructure industries are gradually transitioning towards building information modelling (BIM) as an object-based digital representation of an asset's physical and functional characteristics [1,2] and digital engineering (DE) practices to enable more productive methods of planning, designing, constructing, operating, and maintaining assets, using digital processes [3]. As detailed later in the paper, "digital" encompasses approaches, tools and technologies such as BIM and DE together with data science, the Internet of Things (IoT), and AI solutions integrated to digitise assets throughout the lifecycle. Asset owners recognise the importance of digital transformation (DT) in delivering and managing assets [4], as it offers many benefits throughout the asset lifecycle and can enhance efficiency, value for money, productivity, innovation, and safety.

1.1. DT of large infrastructure asset owners

Governments and government-owned corporations (GOCs) are typically owners and operators of large assets, such as buildings, infrastructure, and other asset holdings across the spectrum of services. Governments and industries must transition from 'digital by exception' towards 'digital by default' [5,6]. The infrastructure sector should adopt an evidence-based approach to infrastructure planning, delivery, and operations, including BIM, DE, embedded sensors, and digital asset management [7]. DT offers significant potential value and benefits to government agencies that manage assets across the whole-of-asset lifecycle. DT can assist in strategic investing and partnering with local governments and industry to deliver more benefits, including [8]:

- Planning and developing new and existing infrastructure,
- Supporting multiscale and multistakeholder decision-making environments,
- Decreasing the cost of ownership,
- Increasing asset utility through the understanding of capacity,
- Improving impact assessment, planning, and consultation processes,
- Optimising transport network planning and use through sharing integrated data,
- Enabling resilient infrastructure, and
- Benchmarking and reducing procurement and insurance costs.

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https://doi.org/10.1016/j.dte.2024.100003
Received 5 April 2024; Received in revised form 27 April 2024; Accepted 5 May 2024
Available online 13 May 2024

1.2. Phases of DT in the whole-of-life asset management domain

Organisations can initiate changes in their business models through leveraging digital capabilities and technologies [9]. DT in infrastructure and built environments refers to the adoption of technologies and the ability to digitise assets [10]. Digital approaches, tools and technologies include BIM, augmented and virtual reality (AR/VR), laser scanning, robotics, 3D printing, prefabrication, big data analytics, digital twins, IoT, and machine learning solutions integrated throughout the asset lifecycle [11]. DT aims to utilise digital concepts and technologies on different levels, such as information management, workforce, governance, strategy, culture, and leadership. DT comprises three phases: digitisation, digitalisation, and DT.

(1) *Digitisation* is the conversion of analogue information into digital information that a computer can process.
(2) *Digitalisation* is the broader use of digital technologies to optimise existing business processes and functions through enhanced integration and coordinated collaboration to create more business opportunities [12].
(3) *Digital transformation* leads to better-informed decisions regarding business objectives and strategy with the use of digital technology. DT applies to every aspect of the infrastructure and built environment, including the operation, maintenance, and use of existing assets and the delivery of new infrastructure.

The current industry's *growth mindset* is focused on capital expenditures (CapEx) and needs to move towards a maturity mindset with an emphasis on whole-life costs and the management of the operating expenditure (OpEx) of existing assets [8]. By adopting collaborative data models and recognising the value of information in relation to operational strategies, government and GOC infrastructure asset owners can improve consistency and efficiency in operations, maintenance, monitoring, control, and optimisation.

1.3. Unlocking value from information and data integration

The main component of industrial DT is data governance and management, with the focus being on integrating various datasets from different sources accompanied by sense-making data science for better-informed decision-making. Real-time data can improve infrastructure operation, enable informed decision-making, and improve responses to disruptions, failures, and environmental concerns. Enabling an integrated approach with the use of high-quality data that allows sharing, visualisation, and analysis is critical to improving every nation's infrastructure and management. It is crucial to enable consistent, informed decision-making that relies on high-quality, robust data for efficient management of building and infrastructure assets (Fig. 1).

An organisation's insights are only as good as its data, both static and dynamic. At the base of the integrated information value framework lies data inputs and repositories, while critical decisions are made at its apex. Core asset information and performance data are sourced from BIM and GIS models and other information-rich models, along with real-time information from sensors. Standardising data formats and protocols and fostering training around data management are pivotal steps. By increasing connectivity and minimising data loss at interfaces, asset owners create valuable information that supports timely and effective decisions underpinned by an asset management information strategy. Physical assets enhanced with digital technology provide improved information to enable better information management. In order to unlock the full potential of DT in the building and infrastructure sector, consistent, informed decision-making must rely on access to robust data that are structured and secure. Maximising value from physical assets necessitates a parallel focus on maximising the value derived from asset data. The high value-added opportunity lies in making sense of data using data mining, big data analysis, modelling and simulation and leveraging the data to enhance the performance of both physical and digital assets. Decision support systems and optimisation algorithms assist in improving reliability and reduce asset whole-life costs. Organisations should actively learn from their data and refine their decision-making processes. By embracing continuous learning, asset owners can stay agile and responsive in an ever-evolving data governance and management landscape.

1.4. Research objectives and scope

It is essential for government agencies and asset owners to measure DT maturity, as it aids organisations in identifying BIM/digital twin implementation challenges and developing improvement strategies. However, there is currently a lack of practical tools for assessing DT maturity and benchmarking at an organisational level. Therefore, there is a need to develop a practical approach that can efficiently guide the industry in evaluating digital maturity by extending beyond readiness and capability. This research project focuses on the following:

(1) Investigating the gaps in the assessment of DT maturity to fulfil the requirements and expectations of the asset management industry along with government agencies.
(2) Addressing the industry challenge of assessing DT and benchmarking at an organisational level to guide DT strategically.
(3) Developing a multilevel framework for practical DT maturity assessment to ensure a common approach.

This research project responds to the industry's need for a practical approach to assess DT maturity and benchmarking at an organisational level. The specific objectives are as follows:

(1) To conduct a review of various DT/BIM/digital twin/smart city capability/maturity assessment tools and methods.
(2) To identify the requirements for a comprehensive framework and tool for whole-of-life owners of large assets (e.g., major government transport agencies).
(3) To develop a DT maturity assessment tool for whole-of-life asset owners; and
(4) To conduct a case study with the use of the developed tool to comprehensively review the DT maturity level of an Australian GOC.

This paper comprises six sections. The introduction is followed by the section presenting the research design and methods. The existing DT maturity assessment approaches that were reviewed are explained in the following section, followed by the description of the proposed DT maturity assessment framework development, and the application of this framework in a GOC case study evaluation. The conclusion and recommendations for future studies are presented in the final section of the paper.

2. Research design and method

2.1. Overview

The stages to achieving the research objectives are illustrated in Fig. 2. Stage 1 is a comprehensive review that investigated existing maturity assessment methods and tools and evaluated their aims and focus. Moreover, the assessment areas and defined maturity levels of these tools were analysed to determine the leading assessment categories and indicators. Common strengths and weaknesses across the existing tools and methods were also analysed to justify the need for a new DT maturity assessment tool for whole-of-life government infrastructure asset owners. A facilitated workshop with government and GOC managers enabled the research team to refine and validate the critical assessment categories and indicators, and strategies to transition to the next DT maturity level.

Stage 2 was dedicated to the development of the DT maturity assessment tool. In order to calculate the relevant importance of the

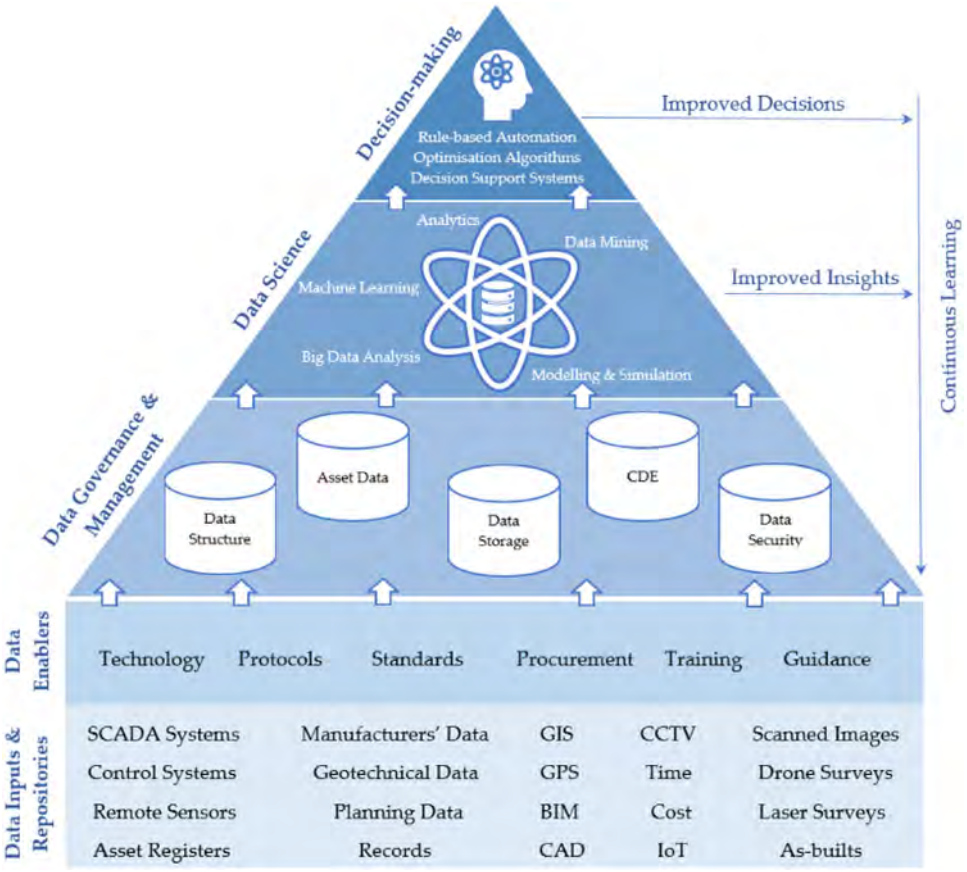

Fig. 1. An integrated information value framework.
Source: Adapted from [13,14].

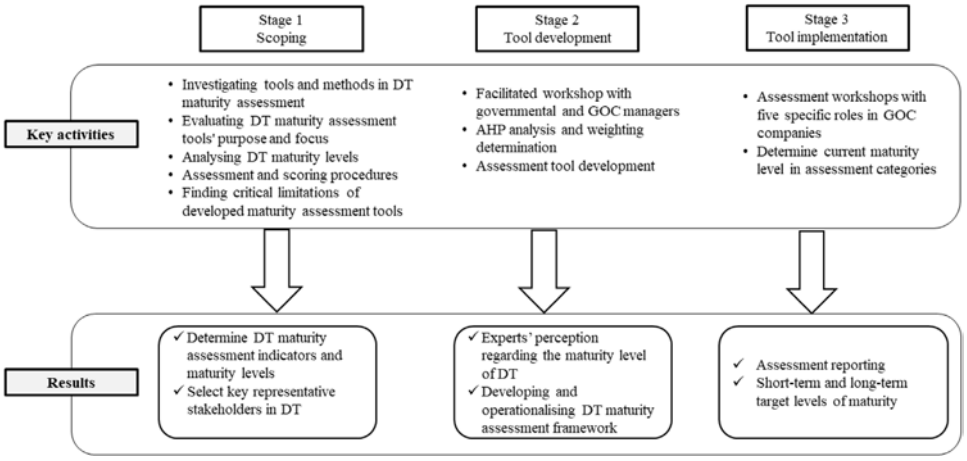

Fig. 2. The project stages.

indicators of the assessment framework (Fig. 2), a stakeholder survey was designed to collect and analyse judgments from representatives of asset owner organisations and experts in the industry DT field. The approach used the Analytic Hierarchy Process (AHP) method. Ultimately, the stakeholder workshop facilitated the comparison/ranking process. After the DT maturity assessment framework was developed and validated, the tool was implemented in a GOC to evaluate their current DT maturity level and propose short- and long-term recommendations based on the current and target levels gap to facilitate progress in DT (Stage 3).

2.2. Stage 1: scoping

The assessment of DT maturity frameworks was the foundation for the development of a comprehensive new tool. Recent advancements in DT have led to an increase in the number of tools and methods for assessing BIM maturity to aid implementation and enhance organisational outcomes [15]. Despite this growth, there is still a significant gap in understanding the practical application, particularly in the construction and asset management sectors [16]. Comprehensive desk research was conducted to assess this gap, with the focus being on identifying and

evaluating DT maturity frameworks. As this stage aimed to review the maturity tools and methods best suited to assessing an asset-owning organisation, only tools that evaluate maturity at the organisational level were considered. The assessment areas and maturity levels of the developed tools were analysed, and the scoring procedure in each DT maturity assessment was analysed along with common strengths and weaknesses across the existing tools and methods.

Of 14 tools developed for evaluating organisational DT maturity, seven focused on assessing organisational BIM maturity, three focused on determining organisational digital twin maturity, two focused on evaluating organisational industry DT maturity, and two focused on assessing organisational maturity in relation to smart cities. This thorough review enabled the identification of key DT assessment indicators and the selection of representative stakeholders in target organisations to establish the groundwork for the development of a comprehensive new DT maturity assessment tool. The review of assessment areas resulted in the list of assessment areas to be adapted as a restructured set of categories and indicators suitable for the DT maturity assessment of whole-of-life government infrastructure asset owners. In order to strengthen the construct validity of assessment areas, a stakeholder workshop was organised with government and GOC managers. The participants discussed critical DT maturity assessment areas, the benefits and value of getting to each maturity level across the organisation, strategies to transition to the next DT maturity level and robust starting/entering points of the DT journey. The workshop aimed to refine and validate the proposed assessment framework in terms of both assessment categories and contextual content for each maturity level.

2.3. Stage 2: tool development

2.3.1. Step 1: participatory workshop for category and indicator pairwise comparisons

A stakeholder survey was designed to collect and analyse judgments of owners of asset-owning organisations and experts in the DT field with the aim of prioritising the indicators of the assessment framework. During the workshop, stakeholders were asked to complete seven comparison matrices in a spreadsheet. Each comparison matrix included a pairwise comparison of indicators relevant to one of the main DT maturity categories, namely (i) strategic intent, (ii) data, (iii) digitally enabled workforce, (iv) organisational processes and systems, (v) technology, (vi) asset delivery, and (vii) asset management.

2.3.2. Step 2: AHP analysis and weighting determination

AHP was selected to analyse the survey responses as a well-established, multi-criteria decision-making method. AHP uses a pairwise comparison method to generate weightings (ratio scales) for criteria instead of simply listing and ranking the levels of importance [17], and it has been implemented in numerous studies and applications in planning and management [18,19]. The steps taken to conduct AHP analysis are explained in Part B of Supplementary Data.

2.3.3. Step 3: assessment tool development

After the expert survey to gather insights into DT maturity indicators had been conducted and the responses had been analysed with the AHP, the normalised weighting for each DT maturity indicator was calculated. The calculated weightings reflect the relative importance of each indicator as perceived by the experts. This approach ensures that the assessment tool captures the nuanced perspectives of those with practical expertise in the field. These weightings provided a robust, data-driven foundation for the evaluation of DT maturity that accounts for the multifaceted nature of DT in organisations. The assessment tool was developed in Excel with the use of the calculated weightings. This tool was designed to be user-friendly and accessible to enable organisations to easily input data to evaluate their DT maturity level. The Excel-based tool leverages the power of spreadsheet software for data analysis, which makes it a practical choice for a wide range of users. It includes features such as automated calculations, graphical representations of maturity levels, and customisable fields to cater to the specific needs of different organisations.

2.4. Stage 3: tool implementation

The developed tool was implemented in a GOC in Queensland, Australia, to evaluate their DT maturity level. This implementation aimed to assess the organisation's current standing as well as the aspirational target state of DT in the organisation. A workshop, which included participants in five key roles in the GOC, was organised to achieve a comprehensive assessment. These participants were carefully selected to ensure a diverse and inclusive representation of the organisation's operational spectrum.

2.4.1. Assessment workshop

A 2-hour in-person workshop was held in April 2023 to assess the DT maturity level of the targeted organisation using the self-assessment Excel tool. The assessment consisted of two steps. First, five workshop participants were requested to collectively choose the target level of maturity for seven assessment categories to be achieved within 5 and 10 years. Thereafter, they were required to individually select the current level of maturity for the seven assessment categories.

2.4.2. Assessment reporting

Once all five participants had completed the assessment, current maturity levels for all seven categories were automatically calculated based on the scoring approach. The maturity level of each DT assessment indicator was calculated as the weighted mean based on the assessment performed by all five assessors. Thereafter, the maturity level of each of the seven categories was calculated as the sum of the normalised and weighted values of each indicator in its relevant category; together, it represented the overall current maturity level. Moreover, for a visual understanding of the maturity level within categories and indicators, the software tool utilised the weighted assessment scores to create spider diagrams. Finally, short-term and long-term performance improvement recommendations were provided based on the current and target levels gap.

3. Stage 1 results: review of DT maturity assessment approaches

3.1. Step 1: investigating tools and methods

A selection of 14 assessment tools and methods derived from prior research were curated to evaluate the DT maturity level. These can be methodologically categorised into four broader groups: BIM maturity tools, digital twin maturity tools, industry-specific maturity tools, and smart city maturity tools. A complete explanation of the DT maturity assessment tools is presented in Part A in Supplementary Data.

3.2. Step 2: evaluating DT maturity assessment tools' purpose and focus

The tools employ various evaluation methods, ranging from online surveys to detailed MS Excel and PDF workbooks and even interview-driven questionnaires. The level of assessment detail, which indicates the depth of an assessment, is low or moderate for most tools. The *BIM Excellence Online Platform* [20] offers the most comprehensive online assessment, workshops, and on-site interviews. Maturity models and assessment tools capture gradual and continual improvements in quality, depth, repeatability, and predictability within available capabilities. This progression in digital outputs and services is represented as performance enhancement markers, termed maturity levels.

The majority of the tools are intended to be used by informed individuals from organisations undergoing DT with the aim of improving their digital maturity. While some tools are designed to be used by various organisations, including design firms, contractors, and facility management firms, others target asset owners and operators (e.g., [21] and [22]), infrastructure owners, operators, and supply chain organisations [23]. A summary of the assessment purposes of DT

maturity tools and methods for organisations is presented in Table A.1 in Supplementary Data.

Many maturity tools and methods focus on evaluating the specific technical requirements and technological characteristics of DT while neglecting the assessment of organisational processes, people, and behaviours that promote collaboration. Only a few tools assess topics associated with the use of data and digital solutions related to asset management, asset delivery, and asset performance [22–26]. A list of topics addressed by organisation maturity assessment tools and methods is displayed in Table A.2 in Supplementary Data.

3.3. Step 3: analysing DT maturity levels

A summary of various maturity levels that DT maturity tools and methods assess for organisations is presented in Table A.2. The majority of the tools/methods divide organisational digital maturity into four to six levels that reflect the extent of an organisation's capabilities.

The maturity levels typically increase from the initial/ad hoc/traditional level represented by an early stage of an organisation's 'DT journey' to an optimised level enabled by the value unlocked by DT and continuous improvement through incremental and innovative processes and technological advancements linked to overall organisational performance.

3.4. Step 4: assessment and scoring procedures

Different assessment and scoring procedures have been implemented in DT maturity tools. Some tools adopt a single evaluation approach, such as scales that represent maturity levels (e.g., [27]), multiple-choice questionnaires (e.g., [28]), or binary (yes/no) inputs from users (e.g., [23]); others combine multiple approaches and integrate qualitative methods such as open-ended questions (e.g., [20]).

Weighted summation is the most common approach to calculating the aggregate digital maturity scores. Each question and indicator is assigned a particular weight to obtain the final score. The scores from the questions are then multiplied with the corresponding weights to produce the scores of divisions pertaining to the questions. The overall score is calculated by adding the scores of the categories multiplied by the corresponding category weights. Nevertheless, the algorithm that transforms users' answers to numeric scores is not always transparent. Moreover, most of the tools assign an equal weighting to all responses when calculating organisational and sectoral maturity, which undermines the accuracy of the assessment approach as organisations could score high, even if some critical criteria are not met and could hinder the organisation's DT.

While most assessment tools generate various reports upon completion, detailed roadmaps intended to aid organisations in progressing to a more mature DT level are only offered by certified consultants who perform a thorough assessment after the initial self-assessment (e.g., [23,28]).

Some tools are only suitable for internal evaluations, as the aim is to achieve a certain level of BIM maturity to provide certifications while disregarding benchmarking to compare an organisation's performance and promote mutual learning among users. For example, the *NBIMS Capability Maturity Model* focuses on achieving a basic level of BIM instead of encouraging users to improve organisational performance by implementing BIM [29].

The *BIM Excellence Online Platform* [20], *BIM Compass* [28], and *Smart Infrastructure Index* [23] tools initiate extensive and practical benchmarking data collection to obtain benchmarking across various industries. Nevertheless, the DT maturity benchmarking system is not recognised worldwide. The *Smart Infrastructure Index* [23] assessment tool is the only tool used to measure digital maturity in the UK built environment. It is used for benchmarking by the ICG, the Buildings Client Group (BCG), and various individual organisations representing asset owners and operators.

3.5. Finding critical limitations of developed maturity assessment tools

The limitations of current digital maturity assessment tools for government infrastructure asset owners represent a gap in evaluating DT capabilities, particularly in the context of whole-of-life asset management. The summary of strengths and weaknesses of the reviewed assessment tools and methods for organisations is presented in Table A.3 in Supplementary Data. The common weaknesses identified in existing tools and methods highlight the need for a new approach that addresses the following limitations:

(1) Existing tools lack a connection between maturity capabilities and the roles of asset owners in information management, data integration, decision-making, and the leading of DT. Providing such a relationship will improve the usability of the maturity assessment from an asset owner's perspective due to the connection with their actual roles and responsibilities. A new tool should encompass these aspects to ensure that digital maturity assessment is aligned with the core functions of asset owners.
(2) Many tools do not provide a comprehensive perspective on leveraging data and digital solutions across asset management life cycles in organisations. A more holistic tool should assess digital practices related to asset creation, management, and performance.
(3) The effectiveness of current tools is limited by the focus on technical specifications without adequate consideration of organisational processes and the human element. Such tools make it challenging to capture varying organisational objectives and consider broad DT aligned with business strategies. A balanced assessment tool should evaluate technical capabilities, organisational processes, and the behaviours that encourage collaboration equally.
(4) The value of information and data integration aspects do not receive sufficient attention in most reviewed assessment tools and methods, especially in relation to asset delivery and asset management.
(5) The majority of existing tools assign an equal weighting to all responses when calculating organisational and sectoral maturity, which undermines the accuracy of the assessment approach, as organisations could have high scores even if some critical criteria are not met. Applying an evidence-based scoring approach and assigning weight to the assessment indicators based on their importance will ensure the accuracy of the assessment.
(6) Most tools do not provide actionable guidance or a roadmap to organisations regarding improving their DT maturity. It is also important to allow comparison against a business contextualised 'desirable' target to facilitate performance improvement. This way, recommendations could be based on the current and target levels gap while realising the benefits and value of getting to each maturity level.
(7) Some tools only apply binary (yes/no) assessments, mainly focused on capabilities for compliance purposes. At the same time, other tools are too detailed, time-consuming, and require significant support from the tool developer. A new tool would aim to balance both assessment accuracy and completion efficiency.
(8) Most tools do not offer a multiperspective assessment. As a result, subjective single answers may not represent the actual situation in the organisation and undermine the accuracy of the assessment. Setting up a requirement for people in specific roles in the organisation to complete the survey would result in assessing the DT maturity of specific departments, followed by an organisation-wide analysis.

Therefore, the research project aims to address the identified limitations and fill the gap by developing a new fit-for-purpose assessment tool. The new DT maturity assessment tool for infrastructure asset owners should balance assessment accuracy and completion efficiency,

be integrated with asset owner operational roles, balance technical and organisational factors, and employ a weighted scoring system to reflect digital maturity accurately. This tool would be aligned with the overall digital strategy of the asset owner organisation and provide a more accurate measure of DT maturity.

3.6. Proposed DT maturity assessment framework

The leading question for government agencies and GOCs regarding DT is where and how singular asset owners and operators can leverage data and achieve digital capabilities and technologies in such a way that improves their business models. The goal of DT is to utilise digital concepts, data and technologies on different levels, such as information management, workforce, strategy, culture, and leadership.

Following the review of the existing industry digital maturity assessment tools and methods and a stakeholder validation workshop, the proposed DT maturity assessment framework (Fig. 3) and assessment tool for singular whole-of-life government infrastructure asset owners provide a holistic view of how effectively organisations use data and digital solutions that goes beyond BIM and digital twin applications to consider broader DT aligned with the asset owner's business strategies. The framework and the assessment tool focus on the value of information, data integration aspects, and critical information management competencies, especially relating to asset management, asset delivery, and asset performance. Moreover, the proposed framework and the assessment tool are useful for evaluating the digitisation of large asset infrastructure, IoT components, smart sensors in the network, and connectivity with digital models. The maturity assessment of the digitisation of integrated city assets is out of scope.

Seven categories and associated assessment indicators are as follows:

(1) ***Strategic intent:*** Activities related to establishing organisational vision, leadership, long-term objectives, and approach to DT.
(2) ***Data:*** Generation and flow of information and data between stakeholders across the asset lifecycle, data integration, and data management capability.
(3) ***Digitally enabled workforce:*** Achieving and maintaining the desired competency level in organisations through training, education, and mentoring. The assignment of individuals and teams for a specific purpose.
(4) ***Organisational processes and systems:*** Processes and systems at an organisational level to provide consistent DT to deliver value throughout the asset life.
(5) ***Technology:*** Preparing, developing, and maintaining information, data, and communication technology systems to support the attainment of organisational objectives.
(6) ***Asset delivery:*** Use of data and information to deliver new assets efficiently.
(7) ***Asset management:*** Use of data and information to manage assets efficiently throughout the asset's lifecycle.

A summary of the DT maturity categories and associated indicators and five maturity levels assessed by the proposed DT maturity tool is presented in Tables A.4 and A.5 (Supplementary Data), respectively.

4. Stage 2 results – DT maturity assessment tool development

This section describes the data collection process for the development of a DT maturity assessment tool. A workshop was conducted with experts in relevant fields, and their insights regarding the importance of DT indicators were collected. The AHP method was applied to calculate the relative weightings of these indicators. This method facilitated a structured comparison, which allowed for the transformation of qualitative expert opinions into quantifiable data. Ultimately, the Excel-based self-assessment tool was developed, featuring automated calculations and graphical representations of maturity levels.

Table 1
Respondents' demographic profiles.

Demographic	n	%
Area of expertise		
Digital transformation		
BIM/DE/digital twin lead	5	31.25
Digital asset technical lead	1	6.25
Change management specialist	1	6.25
Asset/Facility management		
Asset management specialist	5	31.25
Capital delivery and planning		
Principal engineer	2	12.50
Project officer	2	12.50
Sector		
Water	4	25.00
Transport	4	25.00
Civil infrastructure	3	18.75
Built environment	5	31.25
Region		
New South Wales	3	18.75
Victoria	5	31.25
Queensland	6	37.50
Western Australia	2	12.50

4.1. Step 1: facilitated workshop with governmental and GOC managers

The purpose of the survey was to prioritise the indicators of the assessment framework through gathering and analysing expert judgments. The respondents were carefully selected to represent a diverse range of expertise to obtain nuanced insights into different aspects of DT and ensure a comprehensive understanding of the practical application and impact of DT in various operational contexts. Table 1 presents the detailed demographic profiles of the respondents. These diverse participants ensured that the survey results would encapsulate a wide range of perspectives and experiences, which are vital to a holistic AHP analysis.

4.2. Step 2: AHP analysis and weighting determination

The survey respondents expressed their viewpoints regarding DT indicators (Part B in Supplementary Data). The relative weighting of DT indicators was calculated using the AHP method, as shown in Part C in Supplementary Data. Below, a comparison is made among different expert groups (i.e., digital transformation experts [DTs], asset management experts [AMs] and capital delivery and planning experts [CDPs]). The consistency ratio for all the expert responses varied between 0.012 to 0.081. As Saaty [17] states that a CR of less than 0.10 suggests acceptable evaluations within the matrix, the experts' responses were deemed consistent.

In the *Strategic planning* category, the respondents from the different areas of expertise mainly had similar opinions. Across all three groups, the highest percentages were attributed to 'Customer experience', 'Customer engagement', and 'Value of data and information'. Specifically, 'Customer engagement' was most valued by the DTs (16.73%), while 'Customer experience' was a top priority for both AMs (16.10%) and CDPs (16.44%). 'Vision' and 'Strategy' received lower percentages, especially from the DTs.

The weightings of different indicators in the *Data* category were relatively balanced. 'Standards' received the highest percentage from the CDPs (21.65%), which suggests a strong focus on implementing organisation-wide data standards. The DTs and AMs view 'Fit-for-purpose requirements' as highly important (17.87% and 17.65%, respectively), as they prioritise ensuring that digital tools and processes are tailored to specific organisational needs. Although 'Security and compliance' were moderately rated, the lowest rating this criterion received was from the CDPs (7.55%).

'Culture' was highly emphasised in the *Digitally enforced workforce* category, especially by the CDPs (28.32%). Deployment of multidisciplinary teams across the organisation/projects/assets to support

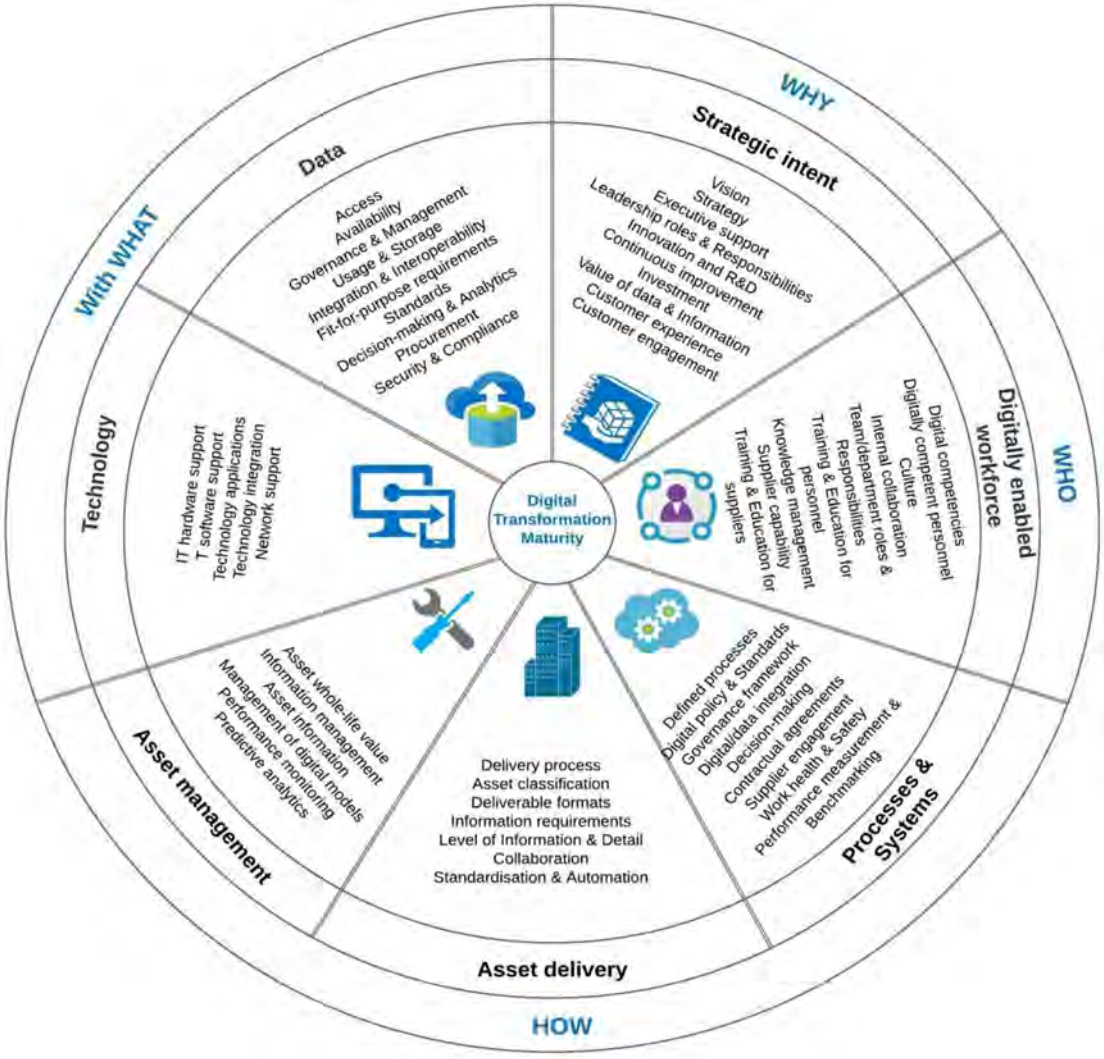

Fig. 3. DT maturity assessment framework for whole-of-life for government infrastructure asset owners.

organisational objectives (i.e. 'Internal collaboration') was highlighted by the DTs (18.19%). 'Training and education for personnel' and 'Team/department roles and responsibilities' were of moderate importance, with the AMs placing slightly more emphasis on training and education (14.17%) than the other indicators. (13.27%).

The experts' opinions on *Organisational processes and systems* were less consistent than in the previous categories. On the one hand, 'Work health and safety' received the highest weighting share in the CDPs (26.02%). On the other hand, the 'Governance framework', which reflects the importance of a defined governance framework that effectively manages the digital/data-driven business, was particularly emphasised by the DTs (16.62%). 'Contractual agreements' were highly prioritised across all expert groups with nearly equal importance (approximately 17%), suggesting a universal recognition of its significance in DT.

Under *Technology*, 'IT software support' was accorded high importance across all groups, particularly in CDPs (25.91%). On the one hand, 'Network support' was notably emphasised by AMs (29.17%) and DTs (24.84%), which highlights the importance of the ability of an organisation's IT network to support the use of digital processes and activities, including collaboration and the sharing of data. On the other hand, 'IT hardware support' was less emphasised across the groups (less than 9%).

Among *Asset delivery* indicators, 'Information requirements' had the highest rating from CDPs (24.77%), which strongly emphasises the importance of detailed and specific information in organisational, asset, and other requirements for new projects. 'Level of information and detail' was particularly emphasised by the DTs (19.51%); this highlights the value accorded to the level of information and detail required for digital models across the different asset lifecycle stages.

On the one hand, among the *Asset Management* indicators, 'Asset whole-life value' received the highest rating from CPDs (36.65%), emphasising the crucial need for the optimisation of investment decisions in the lifecycle of a project. The AMs also accorded significant importance to this criterion (23.69%). On the other hand, 'Information management' was rated highest by the DTs (25.28%).

The overall weighting for all DT maturity indicators is presented in Table 2. These values are used to develop the multilevel framework for practical DT maturity assessment.

4.3. Step 3: excel assessment tool development

The DT maturity assessment framework and assessment tool for whole-of-life for government infrastructure asset owners provide a holistic view of how effectively organisations use data and digital solutions to consider broader DT aligned with the asset owner's business strategies. The framework and assessment tool focuses on the value of information, data integration aspects, and critical information management competencies, especially relating to asset management, delivery, and performance.

Table 2
The weightings of DT maturity indicators.

Strategic intent	%	Data	%	Digitally enabled workforce	%	Organisational processes and systems	%	Technology	%	Asset delivery	%	Asset management	%
Vision	4.6	Access	5.5	Digital competencies	5.1	Defined processes	9.5	IT hardware support	7.7	Delivery process	8.4	Asset whole-life value	25.4
Strategy	7.0	Availability	7.2	Digitally competent personnel	8.5	Digital policy & Standards	10.0	IT software support	24.5	Asset classification	14.3	Information management	23.2
Executive support	14.9	Governance & management	12.1	Culture	25.3	Governance framework	12.7	Technology applications	19.4	Deliverable formats	11.9	Asset information	17.2
Leadership roles & responsibilities	8.5	Usage & storage	4.6	Internal collaboration	17.2	Digital/data integration	10.2	Technology integration	24.5	Information requirements	19.4	management of digital models	16.9
Innovation and R&D	4.7	Integration & interoperability	11.9	Team/department roles & responsibilities	11.5	Decision-making	7.9	Network support	23.9	Level of information & detail	15.5	Performance monitoring	10.2
Continuous improvement	4.4	Fit-for-purpose requirements	16.0	Training & education for personnel	12.6	Contractual agreements	17.8			Collaboration	15.9	Predictive analytics	7.1
Investment	8.6	Standards	18.2	Knowledge management	10.2	Supplier engagement	7.6			Standardisation & automation	14.5		
Value of data & information	16.1	Decision-making & analytics	8.5	Supplier capability	5.5	Work health & Safety	16.2						
Customer experience	16.1	Procurement	6.1	Training & education for suppliers	4.2	Performance measurement & Benchmarking	8.1						
Customer engagement	15.0	Security & compliance	10.0										

The self-assessment tool developed in Excel covers the seven key categories of DT described in the section *'Proposed DT maturity assessment framework'*. The purpose of the assessment tool is to evaluate the DT maturity indicators individually and provide sufficient guidelines for increasing DT maturity within GOCs. The DT maturity assessment should be performed by five representatives whose roles in the organisation meet the following descriptions:

(1) Executive leader.
(2) Digital transformation strategy leader.
(3) Asset/facility manager.
(4) Capital delivery and planning manager.
(5) Information technology and systems/data manager.

The assessment's first step is setting the short- and long-term target maturity levels for each of the seven assessment categories. Each assessment category is characterised by four target levels for maturity (Levels 2–5). The five selected representatives are required to discuss and collectively choose the target level of maturity for the assessment categories to be achieved in 5 and 10 years in their respective organisations.

After the target levels have been identified, the representatives are required to assess the DT maturity of the seven categories individually, depending on their roles in the organisation. Each assessment category comprises 5–10 indicators (Table A.4 in part A of the Supplementary Data). An example of the assessment for the *Technology* category is shown in Fig. 4, which indicates that the evaluation is completed by an executive leader, who is tasked with selecting the level of maturity for each of the indicators in the *Technology* category.

Once all five representatives have completed the assessment, the current maturity levels for all seven categories are automatically calculated. The maturity level of each assessment indicator is calculated as the weighted mean based on the assessment of the five selected GOC representatives. The maturity level of each of the seven DT maturity categories is then calculated as the sum of each indicator's normalised and weighted values in its relevant category, which comprises the overall current maturity level.

The calculated scores and graphical illustrations of the GOC's short- and long-term target values for the DT maturity level assist organisations in evaluating and enhancing their use of digital technologies, ensuring that implemented DT efforts effectively support their strategic goals.

5. Stage 3 results – DT maturity assessment framework implementation

This section presents the results of the DT maturity analysis in an Australian GOC. The results of the DT maturity assessment are divided into seven main DT categories: strategic intent, data, digitally enabled workforce, organisational processes and systems, technology, asset delivery, and asset management.

5.1. Strategic intent

Fig. 5 illustrates the assessment of strategic intent maturity in the case study GOC. The organisation actively researches and identifies leading digital practices of progressive entities, market leaders, and technology providers, indicating a commitment to remain at the forefront of digital advancements.

Investment in DT has been recognised as essential, and pilot projects to assess the financial opportunities and risks associated with DT initiatives have been launched. The selected GOC has developed digital plans for various organisational functions, demonstrating a structured approach to integrating digital strategies. However, there are still challenges in the implementation of the DT processes. While there is a high-level digital roadmap, the implementation lacks a documented, overarching strategy with specific, actionable details. Despite the absence of detailed documentation, senior leaders and managers in the GOC share a vision for DT, and in-house champions advocate for digital initiatives across multiple functions. The leadership for DT has been formalised, with distinct roles in the implementation process being clearly defined. However, most of the DT-related tasks are assigned in addition to employees' regular activities, which could impact the efficiency and focus of these initiatives.

Innovation and R&D in the GOC are primarily directed towards technological innovations. The organisation acknowledges DT as a series of technological, process, and policy changes, and business opportunities arising from DT are recognised and utilised for business improvement. Although the value of data and information in driving

Technology Maturity

Processes and systems at an organisational level for providing consistent digital transformation to delivering value throughout the asset life.

Instructions for completion: Each assessment indicator is characterised by five levels of maturity (Columns E-I). Please choose the level of maturity for each of the indicators by populating the cells in **column K (Maturity level)**. This will automatically calculate the maturity level for the "**Technology**" category based on the scoring approach.

	Assessment criteria	Question	1 Initial	2 Managed	3 Defined	4 Measured	5 Optimizing	Maturity level
Digital Transformation - Technology								Executive leadership
	IT hardware support	**Does your organisation have a defined process in place to provide relevant computer hardware to support digital/data management activities?**	Inadequate support. Equipment replacement or upgrades are treated as cost items and performed only when unavoidable. Specifications are too low or inconsistent across the organisation.	Computer specifications are suitable for the delivery of digital products and services. The budget is standardised across the organisation. Hardware replacements and upgrades are well-defined cost items.	A strategy is in place to transparently document, manage and maintain computers to support digital activities and data analytics. Investment in hardware is well-targeted to enhance staff mobility (where needed) and extend DT productivity.	Computer hardware deployments are treated as DT enablers. Investment in equipment is tightly integrated with financial plans, business strategies and performance objectives.	Existing computer equipment and innovative solutions are continuously tested, upgraded and deployed.	1
	IT software support	**Does your organisation have a defined process in place to provide relevant software applications to support digital, data management and data analytics activities?**	Usage of software applications is unmonitored and unregulated. Procurement of current technology is led by in-house ICT.	Software usage/introduction is unified within the organisation or specific teams/departments. Engaging with software vendors to understand new digital/data capabilities.	Software selection and usage is controlled and managed according to defined deliverables.	Software selection and deployment follow performance objectives, not just operational requirements. Investments are tightly integrated with financial plans and business strategies.	Selection/use of software tools is continuously revisited to enhance productivity and align with strategic objectives.	2
	Technology applications	**Where is your organisation's primary focus with regard to technology?**	Ad-hoc technologies within the organisation: 3D CAD, Online quotes, Estimating & scheduling software, Document management software, Software to view 3D/BIM models.	Rapid trials with new technologies: BIM (store, manage, re-use), LiDAR scanning and photogrammetry, Point cloud, Basic IoT devices, VR, GIS integration.	Conducting agile pilot projects: Integration of BIM models and other datasets, including GIS, Scan-to-BIM, Multi party collaboration tools, Fully integrated Common Data Environment (CDE), On-site/mobile technology usage, Big data analytics, AI, Simple robotics, 3D printing.	Working to establish best practice digital technologies as the norm: Automated scan-to-BIM, Advanced visualisation tools, Benchmarking/dynamic performance metrics, Intelligent BIM, Advanced IoT integration, Blockchain & Smart Contracts, Machine learning, Advanced manufacturing.	Automated flow of data between stakeholders across the asset lifecycle: Predictive asset modelling & management, Advanced cyber-physical systems, Sentient digital twins, Integrated IoT and blockchain tools, Extensive use of robotics & automation, and Fully-integrated digital and data analytics tools.	3
	Technology integration	**How well are the organisation's engineering, operational and information technologies integrated?**	Complete lack of integration. New assets are generally specified as either purely physical or digital. Engineering technology is usually provided first, with operational and information technologies 'bolted on' afterwards as a digital overlay.	Limited integration. Physical assets are specified, with digital technologies' tagged on' afterwards. Delivered by different suppliers with limited interface and coordination.	Leading investments are delivered as integrated physical-digital systems. Digital upgrades enhance the value of existing assets.	Integrating technologies to support the management and exchange of structured data. Investments maximise value from integrated physical-digital systems. Delivery of new information assets is considered as necessary as corresponding physical assets.	Investments maximise shared value across multiple organisations/government departments and sectors through integrated physical-digital systems.	2
	Network support	**Does the organisation's IT network support digital processes and activities, including collaboration and data sharing?**	Network solutions are non-existent or ad-hoc. Personnel (single location/dispersed) and project/asset/other teams use whatever tools are available to communicate and share data. Stakeholders lack the network infrastructure necessary to collaborate and share information.	Network solutions for sharing data and controlling access are identified within and between the organisation and suppliers. Project and asset teams identify their requirements for sharing data/information. Dispersed project/asset teams are connected through relatively low-bandwidth connections.	Network solutions for collecting, storing and sharing knowledge within and between the organisation and suppliers are well managed through shared platforms. Content and asset management tools are deployed to regulate structured and unstructured data transmitted across high-bandwidth connections.	Network solutions enable multiple facets of the DT process to be integrated through seamless real-time sharing of data, information and knowledge. Solutions include project-specific networks/portals which enable data-intensive interchange (interoperable exchange) between stakeholders.	Network solutions are continuously assessed and replaced by the latest tested innovations. Networks facilitate knowledge collection, storing and sharing between all stakeholders. Continuous optimisation of integrated data, process and communication channels exists.	2

Fig. 4. Screenshot from the Excel self-assessment tool.

Fig. 5. Assessment of strategic intent maturity.

Fig. 6. Assessment of data maturity.

better decision-making is recognised, neither is fully integrated or linked to the organisation's objectives. There is a strong emphasis on improving customer service and fostering a customer-first culture.

5.2. Data

The research team assessed indicators associated with the generation and flow of information and data between stakeholders across the asset lifecycle data integration and data management capability (Fig. 6). Several strengths and areas for improvement are highlighted in the *Data* category of DT maturity for the targeted GOC. The organisation has established some standards for tagging and storing information related to projects, assets, operations, and performance. These standards facilitate searchability, although there are data redundancy issues and some difficulties locating specific data. Data are widely available across projects and assets, but this is marred by some duplication and inconsistencies. Notably, performance and condition data are available for high-value or high-risk assets, which indicates that the organisation prioritises data management for critical assets.

However, the use of third-party or open data is limited, and the organisation is in the process of assessing its current data management capabilities. Data management tends to be decentralised and handled at the project or asset level without centralised requirements, which leads to a lack of uniformity across the organisation. Metrics for evaluating information quality, quantity, and usability have been developed. However, specific, organisation-wide systems for consolidating data into a common platform are absent, leading to a fragmented data landscape where separate systems exist in different departments. This situation results in challenges in data exchanges and interoperability in the organisation.

5.3. Digitally enabled workforce

Indicators associated with preparing and maintaining the desired competency levels in organisations through training, education, mentoring, and assignment of individuals and teams were assessed (Fig. 7). Most departments in the organisation clearly understand their digital competencies and can identify capability gaps and priorities that

Fig. 7. Assessment of digitally enabled workforce maturity.

Fig. 8. Assessment of organisational processes and systems maturity.

need addressing. The existence of centralised digital teams that create critical-mass capability suggests a strategic approach to consolidating digital skills and knowledge.

Transferable digital skills alongside sector-specific experience are valued in the recruitment process. However, digital initiatives are primarily managed by specialist teams, limiting the impact on most functions and focusing predominantly on technology. This approach may restrict the broader integration of digital strategies. The organisation has designated in-house digital champions, which highlights its internal commitment to promoting digital literacy. While some teams specifically pursue digital skills, this approach is not yet a centralised HR strategy, which indicates a need for a more cohesive approach to skill development. Digital and data training requirements are defined and provided on an as-needed basis, with training channels delivering varied content to allow for flexibility.

5.4. Organisational processes and systems

We assessed indicators associated with processes and systems at an organisational level for a consistent DT to deliver value throughout the asset lifecycle (Fig. 8). Digital and data management roles in the organisation are informally defined, with teams formed based on these loosely structured roles. Digital/data competencies have been clearly identified and targeted, indicating an awareness of the importance of these skills. The organisation provides basic digital and data guidelines in the form of training manuals and digital model delivery standards, which are crucial for standard operations. The standards for modelling and documentation are well-defined and align with industry-accepted standards and quality plans. However, the implementation of digital frameworks varies across different departments and teams, and there is a lack of a standardised approach across the organisation and assets. Governance primarily focuses on controlling access to data and information, which is critical to data security but may not encompass broader data management strategies.

Collaboration tools are used to manage 2D/3D content and provide a CDE, although there is limited connectivity between the environments across the organisation and with suppliers. High-value or high-risk decisions are supported by tools and systems that generally require manual analysis, assessment, and input, which emphasises a need for automated and integrated decision-support systems.

5.5. Technology

The indicators associated with preparing, developing, and maintaining information, data, and communication technology systems to support the delivery of organisational objectives were evaluated (Fig. 9). The specifications of the computers used in the organisation are sufficient to deliver these digital products and services and ensure that the basic technological needs of DT are met. In addition, the hardware replacement and upgrade process is well-defined and indicates a clear understanding of the costs associated with maintaining up-to-date technology. The use and introduction of software appear to be unified in the organisation or specific teams and departments, suggesting a level of consistency in software practices across different areas of the organisation. The GOC also actively engages with software vendors to remain informed regarding new digital and data capabilities, which is crucial for keeping pace with technological advancements.

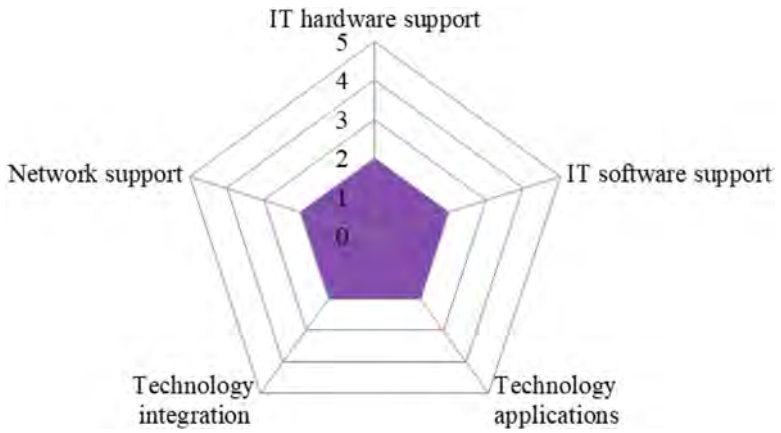

Fig. 9. Assessment of technology maturity.

Fig. 10. Assessment of asset delivery maturity.

Regarding technology, the organisation primarily focuses on rapidly experimenting with new technologies. This includes BIM for storing, managing, and re-using data and exploring emerging technologies such as LiDAR scanning, photogrammetry, point cloud, basic IoT devices, virtual reality (VR), and geographic information system (GIS) integration. Such explorations indicate a forward-thinking approach and a willingness to innovate. However, there are some limitations to the organisation's technological approach. The integration of engineering, operational, and information technologies is limited, which may hinder seamless interplay and the optimisation of these systems.

5.6. Asset delivery

We assessed indicators associated with the use of data and information to deliver new assets efficiently (Fig. 10). A key issue in the *Asset delivery* category is the limited visibility of the most recent capital projects or large-scale asset improvements. This lack of transparency can hinder effective project management and decision-making. A pattern was noted regarding the specification of physical assets first, with digital technologies being added or 'tagged on' afterwards. This approach may result in less-than-optimal integration of digital solutions into the asset lifecycle.

Furthermore, capital projects and updates often experience costly changes, budget overruns, and delivery delays, indicating improved project management and forecasting needs. On a positive note, all suppliers have agreed on organisational classification schemas and guidelines, which suggests a level of standardisation in project requirements and expectations. Similarly, organisation-specific delivery requirements have been uniformly agreed upon by all suppliers. This consensus is crucial to maintain consistency and quality in project delivery. The organisation has taken proactive steps to define and document complete information requirements, including those concerning the organisation and its assets, and to exchange information. Early involvement of asset/facility managers in the design phase of projects is another strategic move that will ensure that operational considerations are integrated into the design from the outset.

5.7. Asset management

The research team assessed indicators associated with data use and information to manage assets efficiently throughout the asset lifecycle (Fig. 11). Investment decisions in the GOC are primarily driven by the goal of achieving the minimum whole-life cost for set performance levels. This indicates a focus on cost-effectiveness and long-term value in asset management. However, the application of whole-life cost principles is inconsistent across various organisational functions, leading to variations in cost allocation and the economic valuation of benefits. This inconsistency can impact the overall efficiency and effectiveness of investment strategies. The organisation uses reality capture technologies such as LiDAR scanning and scan-to-BIM models to manage critical and high-value assets/interfaces. These technologies provide valuable once-off data snapshots that aid in maintaining and managing essential assets. Basic sensors have been installed to monitor the condition of high-risk assets, which represents an initial step towards more comprehensive, technology-driven asset monitoring. Asset information, while searchable, is not centrally located and can be difficult to verify. This decentralised approach to data management may pose challenges in terms of data accessibility and verification. Although digital models are

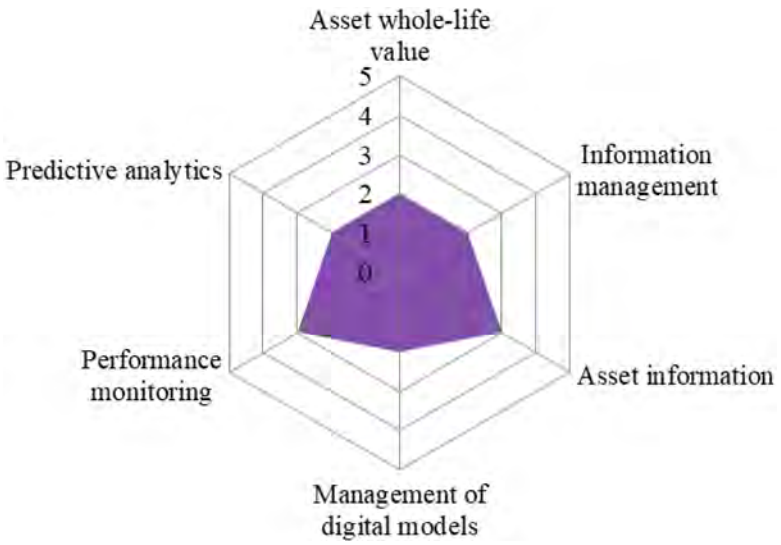

Fig. 11. Assessment of asset management maturity.

received and stored in different locations, they are widely available to project stakeholders, which is beneficial for project collaboration and transparency.

5.8. Target state and gap analysis

The target levels reveal the ambition of the assessed GOC regarding DT. Both short- and long-term target levels and the current DT maturity level are illustrated in Fig. 12. Based on the current and target levels gap, recommendations to facilitate maturity improvement were provided to the GOC.

Currently, *Strategic intent* is at level 2, and there is a GOC executive who is exploring opportunities for DT. Steps for successful organisational change are being considered, along with research into leading digital practices. The aim is to reach level 4 over the next 5 years with a comprehensive DT strategy closely aligned with corporate strategy, supported by executives, and measured against clear digital targets. The intention is to solidify these strategies by the 10-year mark to maintain level 4 with established foundations for digital twins and smart cities.

The GOC's *Data* strategies are currently at level 2, which means that the value of data is acknowledged but there is not yet full business outcome integration. Interoperable data exchanges have been defined and prioritised. The GOC aspires to reach level 3 within 5 years, when data-driven decision-making will be common, and there will be board-level ownership for data security. The goal is to standardise data requirements and enhance data-driven processes to achieve level 4 maturity with a robust information security culture by the 10-year mark.

At level 2, the GOC's *Digitally enabled workforce* has defined champions and recruits with digital skills in mind, but currently digitalisation is mainly handled by specialist teams. The 5-year plan is to advance to level 4, with dedicated teams creating data-centric business processes and new training programs. The ambition is to foster a digital culture attractive to leading talent, normalise data literacy, and align HR practices to meet intellectual capital needs and thus achieve maturity level 5 within a decade.

The category *Organisational processes and systems* explores best practices and learning from digital project deliverables and is currently at level 2. The 5-year goal is to move to level 3, with more advanced specifications and calibrated digital project requirements.

As a DT maturity category, *Technology* is at level 2, and the GOC is investigating new technologies and engaging with vendors. Technology selection and deployment are expected to follow strategic objectives over the next 5 years, with the GOC working to establish best practices as the norm and moving to level 4. The 10-year vision includes a continuous review of technology use, aiming for level 5 maturity with an automated information flow across the asset lifecycle.

The GOC's approach to *Asset delivery* is currently at level 3, indicating that there are well-defined information requirements and a plan for digital delivery. The organisation is on the path to refining and further developing this area, with the aim of achieving level 4 within the next 5 years. The goal is to integrate a digital asset lifecycle throughout the organisation and implement significant automation to optimise routine processes across all functions. As for the 10-year target, the GOC aims to achieve level 5 maturity, where asset delivery is seamlessly integrated with asset management. The vision is that all as-designed, as-built, as-maintained, and as-operating information should be interconnected and readily available to all relevant stakeholders. This goal signifies a holistic and interconnected approach to asset delivery, with every stage of the asset's life digitally captured and leveraged for better asset management practices.

In the *Asset management* category, the GOC is at level 2, which means that while reality capture technologies such as scan-to-BIM are utilised to provide snapshots to manage critical and high-value assets, this is often done on a once-off basis and limited to specific assets or interfaces. Furthermore, there are defined requirements across the asset and information lifecycle, but asset registers are not entirely centralised, leading to duplication and inconsistencies. The GOC intends to progress to level 3 over the next 5 years so that analytics teams will able to rely on data for decision-making, and assets will be regularly monitored through reality capture and sensors to enhance the lifecycle management of assets. The aim is to achieve level 4 by the 10-year mark, when the organisation will have established digital asset lifecycles across all operations. Decision-making processes will be informed by actual performance and foresight, with real-time analytics available when necessary. There will also be widespread use of machine learning to unlock the value of current and legacy data for a sophisticated and predictive approach to managing assets. This forward-thinking strategy reflects a commitment to a data-driven and technologically advanced asset management system. The extended recommendations for the case study GOC to improve their DT maturity levels are presented in Part D of Supplementary Data.

6. Conclusion

The dynamic evolution of the building and infrastructure sectors towards digitalised practices underscores the growing importance of asset owners engaging in comprehensive DT. This research project has

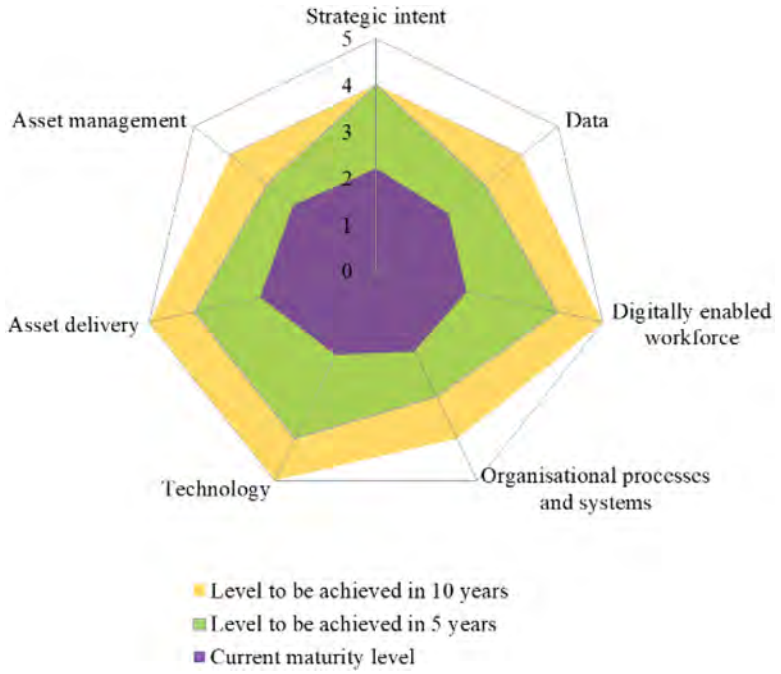

Fig. 12. DT maturity assessment outcomes.

developed a multifaceted framework for assessing DT maturity tailored to the needs of large GOCs.

The existing assessment tools and methods have been reviewed for suitability in assessing the DT in whole-of-life asset owner organisations. The reviewed tools offer varying assessment scopes, including a capability assessment, maturity assessment, and benchmarking. The need and potential benefit of a new maturity assessment tool that would balance assessment accuracy and completion efficiency were established based on the shortcomings and limitations of existing DT maturity tools and methods. The key contributions of the new DT maturity assessment framework and tool developed by the research team include (i) a holistic view on the assessment of how well organisations use data and digital solutions, focusing on BIM capabilities, the value of information, data integration aspects, components of the smart city concept and critical information management competencies; (ii) an evidence-based scoring approach including assigning weight to various assessment indicators based on their importance to ensure the accuracy of the assessment; (iii) a multiperspective assessment allowing for more accurate organisation-wide analysis; (iv) short-term and long-term recommendations based on the current and target levels gap to facilitate performance improvement while realising the benefits and value of getting to each maturity level.

The foundational maturity categories and indicators for DT were determined through an exhaustive review of existing maturity assessment models and tools, followed by a series of stakeholder workshops that included participants with roles such as BIM/DE/digital twin leads, digital asset technical leads, and change management specialists. The workshop aimed to refine and validate the proposed assessment framework regarding assessment indicators (including their weightings and importance in each assessment category) and contextual content for each maturity level, along with strategies to transition to the next maturity level of the DT journey. The framework distilled DT maturity into seven key categories, encompassing 56 indicators, with maturity levels scaled from 1 (initial) to 5 (optimal). Ultimately, an Excel-based assessment tool enabling organisations to input data effortlessly and gauge their DT maturity was developed. The tool capitalises on the analytical capabilities of spreadsheet software, making it accessible and functional for various users.

The application of this tool in the GOC context has confirmed its utility in capturing the nuanced realities of DT across various organisational disciplines. It has enabled a detailed analysis of the current maturity levels and facilitated the setting of ambitious yet attainable targets for DT advancement over the next 5 and 10 years. The research findings emphasise the multifaceted benefits of DT, including enhanced efficiency, value, productivity, innovation, and safety, which are critical to sustaining a competitive advantage in a rapidly transforming digital landscape.

The case study underscores the necessity for GOCs to develop a coherent technology integration roadmap that aligns with strategic imperatives in the short term, with a pronounced emphasis on data-driven decision-making to underpin digital investments. In the long term, such a roadmap will be instrumental in fostering a culture of continuous improvement and innovation.

This research project's limitation regarding the number of case studies points to the need for broader research incorporating various sectors and geographical contexts to strengthen the general applicability of the findings. A follow-up study is recommended to evaluate the progress of DT maturity in the GOC and to benchmark the progress against the targets established through this initial assessment. Such longitudinal studies would be invaluable to refine the DT maturity framework and ensure its relevance and efficacy in guiding organisations through their DT journeys.

Even though the tool offers a multiperspective assessment where assessors are required to answer questions depending on their position in the organisation and the responsibilities associated with DT, it is recommended to set up a requirement for the minimum number of people in each role to complete the assessment of the DT maturity within the organisation. Including more assessors for each role and applying the Delphi technique to ensure consistency will improve the representativeness and accuracy of the assessment.

The developed tool provides recommendations from which asset owners can benefit by anticipating DT maturity improvement. However, this analysis was not able to prioritise short-term and long-term actions within the framework. Apart from the assessment tool being able to compare against a business contextualised target to facilitate performance improvement, it is crucial to compare the organisation's maturity against the best practices from other organisations and other

sectors. Future research is needed to create a comprehensive and user-friendly web-hosted DT maturity assessment tool and database that can be used for benchmarking that enables the comparison of processes, activities, and performance between sectors (e.g., transport, water utilities, electricity utilities), government levels (e.g., local governments, state governments), or within a single asset owner organisation over time.

While the developed assessment tool helps evaluate the digitisation of large singular asset infrastructure, further research is needed to allow the maturity assessment of the digitisation of integrated city assets while shifting the focus to integrating data science and digital asset management practices with smart city concepts.

CRediT authorship contribution statement

Emiliya Suprun: Writing – original draft, Visualization, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Soheil Roumi:** Writing – original draft, Resources, Formal analysis, Data curation. **Sherif Mohamed:** Writing – review & editing, Validation, Funding acquisition. **Rodney A. Stewart:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

There is no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

Authors would like to acknowledge the support and contributions that made this research possible. We extend our thanks to the Australian Research Council (ARC) for their Linkage Project Grant Funding (LP180100222) and the Sustainable Built Environment National Research Centre (SBEnrc) for convening the project steering group. Industry partners to the ARC Linkage Project Grant, and other industry and government professionals involved in the development of the framework are acknowledged.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.dte.2024.100003.

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