FINAL PROJECT REPORT

A Decision Support Tool for Assessing Digital Twin Maturity and Supporting Digital Transformation in Construction Projects

Prepared by

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Executive Summary

Digital twin has rapidly emerged as one of the most influential components of digital transformation within the construction industry. By enabling the dynamic integration of digital models, real-time data, and physical asset behaviour, digital twins have the potential to significantly improve how construction projects are delivered and operated. They offer opportunities to enhance efficiency, reduce uncertainty, improve sustainability, and support more informed and proactive decision-making across the lifecycle of built assets.

Despite this strong potential, the successful implementation of digital twin technologies remains inconsistent across the industry. Many organisations invest in advanced systems but fail to realise the expected benefits. A key reason for this gap between expectation and outcome lies not in the lack of technology itself, but in the difficulty of determining what level of digital twin maturity is actually appropriate for a given project. Without a structured way to make this decision, organisations are often faced with uncertainty, leading to either overinvestment in unnecessarily complex systems or underinvestment in capabilities that could provide value.

This report presents the outcomes of research supported by the Chartered Institute of Building (CIOB) and published by the American Society of Civil Engineers[1], which directly addresses this challenge. The core contribution of the research is the development of a Decision Support Tool (DST)[2] designed to assist construction professionals in determining the most suitable level of digital twin maturity based on their project's objectives, constraints, and organisational readiness. A tutorial demonstrating how to use the DST is also available online[3].

A central insight of this research is that higher levels of digital twin maturity do not inherently lead to better outcomes. Instead, success depends on achieving alignment between the capabilities of the digital twin system and the specific needs of the project. In some cases, relatively simple systems may deliver significant value if they are well aligned with project objectives. In other cases, more advanced capabilities such as predictive analytics or automation may be necessary. The key is not to maximise sophistication, but to optimise alignment. To support this decision-making process, the research introduces a four-dimensional maturity model that goes beyond traditional technology-focused approaches. This model captures the interaction between data, organisational processes, decision-making capabilities,

[1] https://ascelibrary.org/doi/10.1061/JCEMD4.COENG-17977
[2] https://digital-twin-maturity-assessment.vercel.app/
[3] https://www.youtube.com/watch?v=K_blHMFtvO0

and physical assets. By integrating this model with identified drivers of digital twin adoption, the research provides a comprehensive framework that is both theoretically grounded and practically applicable.

The developed Decision Support Tool operationalises this framework, enabling users to evaluate their project context, assess current capabilities, and identify an appropriate range of digital twin maturity levels. The tool also facilitates scenario analysis, allowing stakeholders to explore how changes in priorities or conditions affect outcomes. The findings demonstrate that the use of such a tool can significantly improve clarity in decision-making, reduce the risk of misaligned investment, and support communication among stakeholders. Ultimately, this research contributes to improving the effectiveness of digital twin adoption in the construction industry by shifting the focus from technological ambition to informed and purpose-driven decision-making.

1 Introduction

The construction industry is currently experiencing a period of significant transition as digital technologies become increasingly embedded within project delivery and asset management practices. Over the past decade, advancements such as Building Information Modeling (BIM), cloud-based collaboration platforms, and data-driven analytics have begun to reshape how construction projects are conceptualized, executed, and operated. Among these developments, digital twin technology has emerged as one of the most promising yet complex innovations.

A digital twin can be broadly defined as a dynamic digital representation of a physical asset, system, or process that is continuously updated through real-time or near real-time data. Unlike traditional digital models, which often serve as static representations, digital twins create a bidirectional connection between the virtual and physical worlds. This capability allows stakeholders to monitor performance, simulate future conditions, and make more informed decisions at various stages of the asset lifecycle.

The potential value of digital twins in construction is substantial. During the design and construction phases, they can enhance coordination between disciplines, reduce errors, and improve planning accuracy. During operation, they can support predictive maintenance, optimize resource use, and improve asset longevity. These capabilities have positioned digital twins as a central component of digital transformation strategies across the construction sector.

However, despite this strong potential, the adoption of digital twin has been far from straightforward. Many organizations that attempt to implement digital twins encounter significant challenges, and in some cases, fail to achieve the intended outcomes. These challenges are not purely technical; rather, they stem from a deeper issue related to decision-making, strategy, and alignment.

One of the most critical yet underexplored challenges in this context is determining the appropriate level of digital twin maturity for a given project. Digital twins exist across a wide spectrum of capability, ranging from simple data-enabled models to highly integrated systems capable of predictive analytics and autonomous decision-making. This diversity introduces considerable uncertainty for project stakeholders. When faced with the decision to adopt digital twin for their projects, they must answer not only whether to adopt it, but also how advanced the system should be.

In practice, these decisions are rarely straightforward. Stakeholders may lack clear guidance on how to evaluate different maturity levels or how to align them with project objectives. As a result, decisions are often influenced by external trends, perceived best practices, or the capabilities of available technologies rather than a structured assessment of actual needs. This can lead to outcomes where systems are either overly complex or insufficiently capable.

The implications of such misalignment can be significant. Overly advanced systems may require substantial investment in infrastructure, data integration, and workforce training, without delivering proportional benefits. Conversely, systems that lack sufficient capability may fail to support key project objectives, limiting the value of digital transformation efforts.

This research is motivated by the need to address this gap in decision-making. It proposes a structured framework, supported by a Decision Support Tool, to help stakeholders determine the most suitable level of digital twin maturity for their projects. By shifting the focus from technology-driven adoption to purpose-driven decision-making, the research aims to improve the effectiveness and success rate of digital twin implementation in the construction industry.

2 The Challenge of Digital Twin Adoption

The growing interest in digital twin technology reflects a broader transformation within the construction industry toward data-driven and digitally enabled processes. However, while awareness and enthusiasm for digital twins have increased significantly, the ability to implement them effectively remains inconsistent. Many organizations find themselves navigating a complex landscape of technologies, expectations, and uncertainties.

A key issue underlying these challenges is the tendency to equate technological advancement with project success. In many cases, digital transformation initiatives are driven by the assumption that more advanced technologies inherently lead to better performance. This assumption, while intuitive, does not always hold true in practice. The effectiveness of a digital twin depends not only on its technical capabilities but also on how well those capabilities align with the specific needs and context of the project.

One of the most common manifestations of this misalignment is over-specification. In such cases, organizations adopt highly sophisticated digital twin systems that exceed the requirements of the project. These systems may include advanced analytics, complex simulation capabilities, or automated control functions. While these features can be valuable in certain contexts, they also introduce additional complexity, requiring significant investment in data infrastructure, system integration, and skilled personnel. When these capabilities are not fully utilized, the result is inefficiency rather than improvement.

On the other end of the spectrum, under-specification presents a different but equally problematic challenge. In this case, the digital twin system lacks the capabilities needed to achieve the intended project objectives. For example, a project that requires dynamic performance monitoring or predictive insights may be limited by a system designed primarily for static visualization. In such situations, the digital twin fails to deliver meaningful value, leading to missed opportunities for improvement.

A further complication arises from the issue of organizational readiness. Even when the chosen level of digital twin maturity is appropriate in principle, the success of its implementation depends on the organization's ability to utilize it effectively. This includes having the necessary skills, processes, and cultural readiness to integrate digital twin capabilities into decision-making workflows. Without this alignment, even well-designed systems can become underutilized or disconnected from operational practices.

Another important challenge is the difficulty of assessing the value proposition of digital twins. Unlike traditional investments, the benefits of digital twin technology are often indirect and realized over an extended period. For instance, improvements in decision-making, risk reduction, or long-term asset performance may not be immediately quantifiable. This makes it challenging for stakeholders to justify investments and select the most appropriate level of implementation.

In addition, the construction industry is characterized by its fragmented nature, involving multiple stakeholders with different roles, priorities, and levels of expertise. This fragmentation further complicates decision-making, as different stakeholders may have differing views on what constitutes an appropriate level of digital twin maturity. Without a structured framework, reaching consensus can be difficult.

These challenges highlight the need for a more systematic approach to digital twin adoption. Rather than relying on assumptions or generalized best practices, stakeholders require tools and frameworks that allow them to evaluate their specific needs, assess their capabilities, and make informed decisions.

This research addresses these challenges by proposing a decision support framework that explicitly accounts for the complexity and variability of construction projects. By providing a structured method for aligning digital twin maturity with project drivers and organizational readiness, it aims to reduce uncertainty and improve the effectiveness of digital transformation efforts.

3 Methodology

This research employs a mixed-methods approach designed to address the challenges of adopting multifunctional digital twins in the construction industry. The methodology is structured into four primary stages to ensure theoretical robustness and practical utility for industry stakeholders:

Stage 1: Identification and Refinement of Adoption Drivers: A comprehensive literature review was conducted to identify key drivers for digital twin adoption. These were then refined using a novel, multimodal large language model (LLM)–based multi-criteria decision-making (MCDM) framework, which incorporated insights from industry experts.

Stage 2: Development of a Maturity Model: A four-dimensional maturity model (encompassing Data and Technology, Business Integration, Decision-Making Support, and the Relationship between the twin and its physical counterpart) was developed using the Design Science Research (DSR) approach.

Stage 3: Database Construction: Using expert elicitation, the research established a consensus-based reference database that defines the minimum and maximum suitable maturity levels for identified drivers across all four dimensions.

Stage 4: Decision Support Tool (DST) Development and Validation: A DST was created to enable stakeholders to input project-specific drivers and current maturity states, receiving tailored recommendations and sensitivity analyses to guide informed decision-making.

The tool was validated through rigorous comparative analysis, expert feedback, and real-life case studies, ensuring its reliability for use during the front-end planning stage and throughout the project lifecycle. A detailed description of the research methodology, including the development of the digital twin maturity model, identification of adoption drivers, and validation process, is available in the peer-reviewed article published in the *Journal of Construction Engineering and Management*. Readers are referred to this publication for further methodological details (Mahdiyar et al., 2026)[4].

4 A Multidimensional Understanding of Digital Twin Maturity

To effectively address the challenges associated with digital twin adoption, it is essential to develop a clear and comprehensive understanding of what digital twin maturity entails. Traditional approaches to defining maturity have often focused primarily on technological factors, such as the level of data integration or the sophistication of analytical capabilities. While these aspects are important, they do not fully capture the broader context in which digital twins operate within construction projects.

This research introduces a multidimensional model of digital twin maturity (Figure 1) that reflects the complexity of real-world implementation. Rather than viewing maturity as a single linear progression of technological capability, the model conceptualizes it as a combination of multiple interrelated dimensions. This perspective allows for a more nuanced understanding of how digital twins function and how they can be effectively aligned with project needs.

The first dimension of the model is data and technology. This dimension encompasses the methods used to collect, manage, and analyze data within the digital twin. At lower levels of maturity, systems may rely on static or manually updated datasets with limited integration. As maturity increases, data becomes more dynamic, often involving real-time or near real-time

[4] https://ascelibrary.org/doi/10.1061/JCEMD4.COENG-17977

integration from sensors and external systems. Higher levels of maturity may also incorporate advanced analytics, including machine learning and simulation capabilities.

The second dimension is business integration, which reflects how well the digital twin is embedded within organizational processes and aligned with strategic objectives. A digital twin that operates in isolation, without integration into workflows or decision-making processes, is unlikely to deliver significant value. Higher levels of maturity in this dimension involve the seamless incorporation of digital twin outputs into operational and strategic decisions.

The third dimension relates to decision-making support. This dimension captures the extent to which the digital twin enables better decisions at different levels of the organization. At lower levels, the digital twin may provide descriptive information, such as visualizations or historical data. As maturity increases, it can offer predictive insights, enabling stakeholders to anticipate future conditions. At the highest levels, it may support prescriptive or even automated decision-making.

The fourth dimension is the relationship between the digital twin and the physical asset. This dimension focuses on the degree of interaction between the virtual and physical systems. At lower levels, this relationship may be unidirectional, with updates occurring periodically. At higher levels, the interaction becomes more dynamic, involving continuous feedback loops and, in some cases, automated control mechanisms.

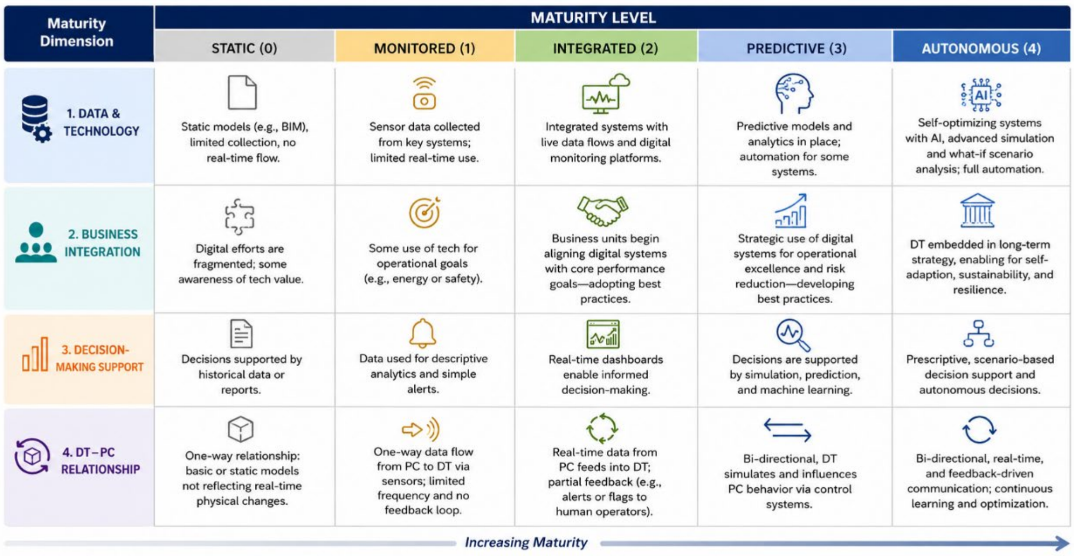

Figure 1. Four-Dimensional Digital Twin Maturity Model

By combining these four dimensions, the model provides a comprehensive framework for understanding digital twin maturity. It highlights that maturity is not defined solely by technological sophistication, but by the interaction between technology, organizational processes, and decision-making capabilities.

Importantly, this multidimensional perspective enables stakeholders to identify trade-offs and make more informed decisions. For example, a project may require high levels of decision-making support but only moderate levels of automation. Alternatively, it may prioritize integration across stakeholders over advanced analytics. The model allows these distinctions to be explicitly considered, rather than forcing projects into predefined categories.

5 Drivers of Digital Twin Adoption

Understanding the drivers of digital twin adoption is a critical step in determining the appropriate level of maturity for a given project. These drivers represent the underlying motivations that lead organizations to consider the use of digital twin technologies, and they play a central role in shaping the requirements that such technologies must meet.

One of the most prominent drivers identified in this research is the need to improve operational efficiency. Construction projects often involve complex interactions between multiple activities, stakeholders, and resources. Inefficiencies can arise from poor coordination, limited visibility into project status, or delays in decision-making. Digital twins can address these issues by providing a centralized platform for monitoring and analysis, enabling stakeholders to respond more effectively to changing conditions. However, the level of maturity required to achieve these benefits depends on the complexity of the project. For relatively simple projects, basic monitoring and visualization capabilities may be sufficient, whereas more complex projects may require integrated systems with advanced analytical capabilities.

Another important driver is sustainability and environmental performance. Increasing regulatory requirements and societal expectations are placing greater emphasis on the environmental impact of construction projects. Digital twins can support sustainability objectives by enabling the monitoring of energy consumption, material use, and carbon emissions. They also allow for scenario analysis, helping stakeholders evaluate the environmental implications of different design or operational decisions. Projects that prioritize sustainability often require higher levels of maturity, particularly in terms of data integration and predictive analysis.

The need for effective data integration and information management is also a significant driver. Construction projects generate large volumes of data from various sources, including design models, sensors, and operational systems. Integrating this data into a unified system is essential for enabling informed decision-making. Digital twins can serve as a platform for such integration, but achieving this requires a sufficient level of maturity in both technological and organizational dimensions.

Collaboration and stakeholder coordination represent another key driver. The construction industry is known for its fragmented structure, with multiple organizations involved in different aspects of a project. Digital twins can facilitate collaboration by providing a shared digital environment in which stakeholders can access consistent and up-to-date information. This can improve communication, reduce misunderstandings, and enhance overall project coordination.

A particularly notable finding of this research is the importance of workforce-related drivers. Issues such as skills shortages, the need for training, and the expectations of a digitally skilled workforce are increasingly influencing technology adoption. Digital twins are often seen as tools for enabling new ways of working and supporting workforce development. However, these drivers also highlight the importance of aligning the level of maturity with the capabilities of the workforce. Adopting highly advanced systems without the necessary skills can lead to underutilization and inefficiency.

Finally, risk management and safety are critical drivers in many construction projects. Digital twins can enhance safety by providing real-time insights into site conditions and enabling proactive risk management. In high-risk projects, such as large infrastructure developments, these capabilities may justify the adoption of more advanced levels of maturity.

Overall, these drivers demonstrate that digital twin adoption is influenced by a complex set of factors. Understanding these factors is essential for making informed decisions about the appropriate level of maturity. The Decision Support Tool developed in this research incorporates these drivers into a structured framework, enabling stakeholders to systematically evaluate their importance and align them with suitable digital twin capabilities.

6 Development and Function of the Decision Support Tool

The Decision Support Tool (DST)[5] developed in this research represents the central practical contribution of the study. While the earlier sections establish the conceptual foundation through the maturity model and adoption drivers, the DST translates these elements into a structured, operational framework that can be directly applied by construction professionals. Its purpose

[5] https://digital-twin-maturity-assessment.vercel.app/

is to assist stakeholders in navigating the inherent complexity of digital twin adoption and to provide a clear, evidence-based method for determining the most appropriate level of digital twin maturity.

At its core, the DST is designed to address a fundamental gap in current practice: the absence of a systematic approach for aligning digital twin capabilities with project-specific needs. In many real-world scenarios, decisions regarding digital twin implementation are made based on intuition, precedent, or available technology rather than a structured evaluation of requirements. The DST replaces this ad hoc process with a transparent and repeatable methodology.

The first stage of the DST involves the selection of relevant drivers (Figure 2). As established in the previous section, digital twin adoption is motivated by a range of drivers, including operational efficiency, sustainability, data integration, collaboration, workforce considerations, and risk management. The tool provides a comprehensive set of such drivers and allows users to select those that are most applicable to their project. This step is essential because it ensures that the analysis is grounded in the specific objectives of the project rather than generic assumptions.

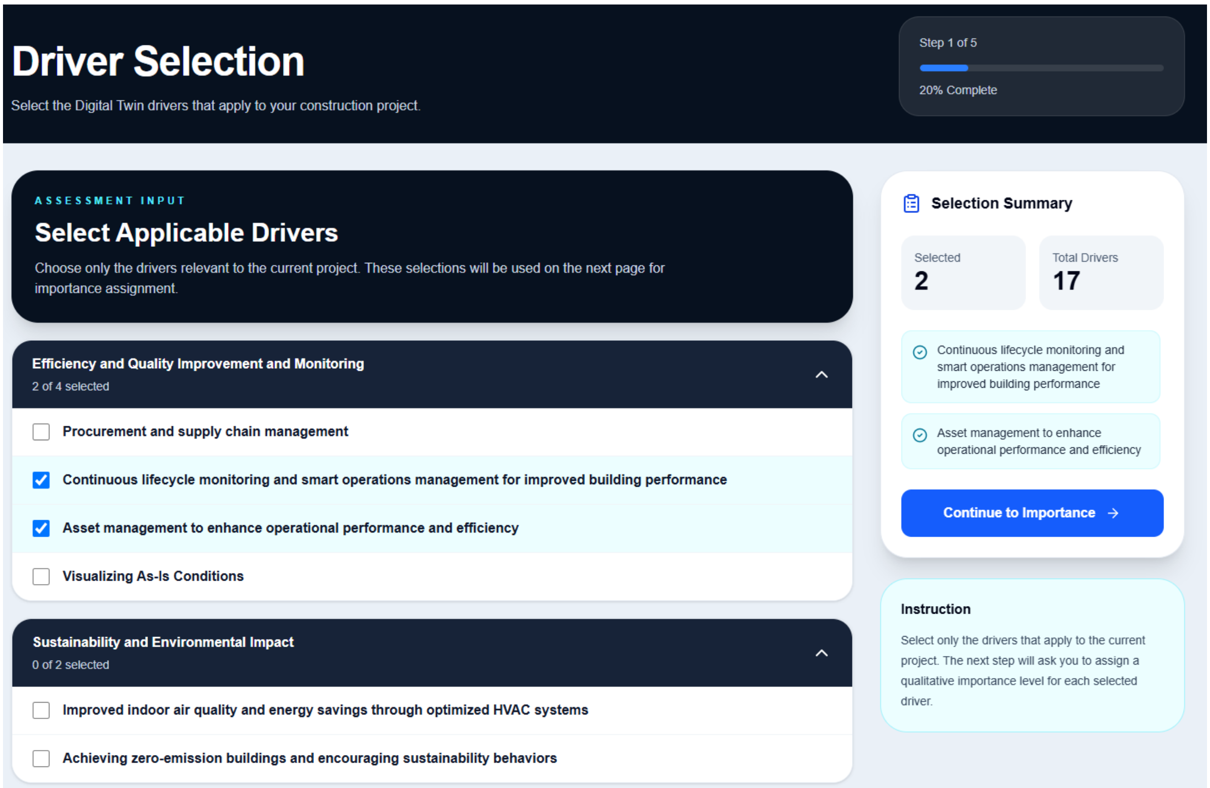

Figure 2. Driver selection page. This figure shows only two driver categories, with two drivers selected in the first category.

Following the selection stage, the DST requires users to rank the importance of the selected drivers (Figure 3). This ranking process captures the relative priority of different objectives, acknowledging that not all drivers carry equal weight. For instance, in a project where safety is the primary concern, risk-related drivers may be ranked more highly than efficiency-related ones. Conversely, in a cost-sensitive project, efficiency and resource optimization may take precedence. By incorporating this prioritization, the DST ensures that the final output reflects the strategic priorities of the stakeholders.

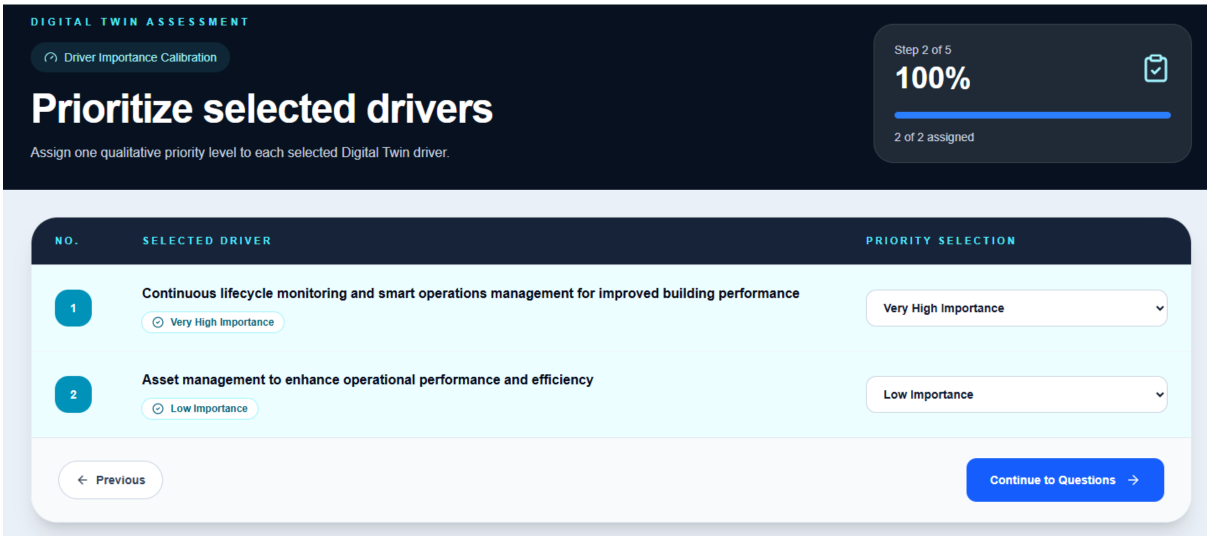

Figure 3. Prioritization page. Example of the prioritization process, in which the project-relevant drivers are evaluated using a 9-point scale. For illustrative purposes, only the two drivers selected in Figure 2 are displayed.

The next critical step involves assessing the current maturity level of the organisation across the four dimensions introduced earlier: data and technology, business integration, decision-making support, and the relationship between digital and physical systems (Figure 4). This assessment requires users to evaluate their existing capabilities in a structured manner. For example, they may consider whether their current systems support real-time data integration, whether digital tools are embedded in decision-making processes, and whether there is any level of interaction between digital models and physical assets.

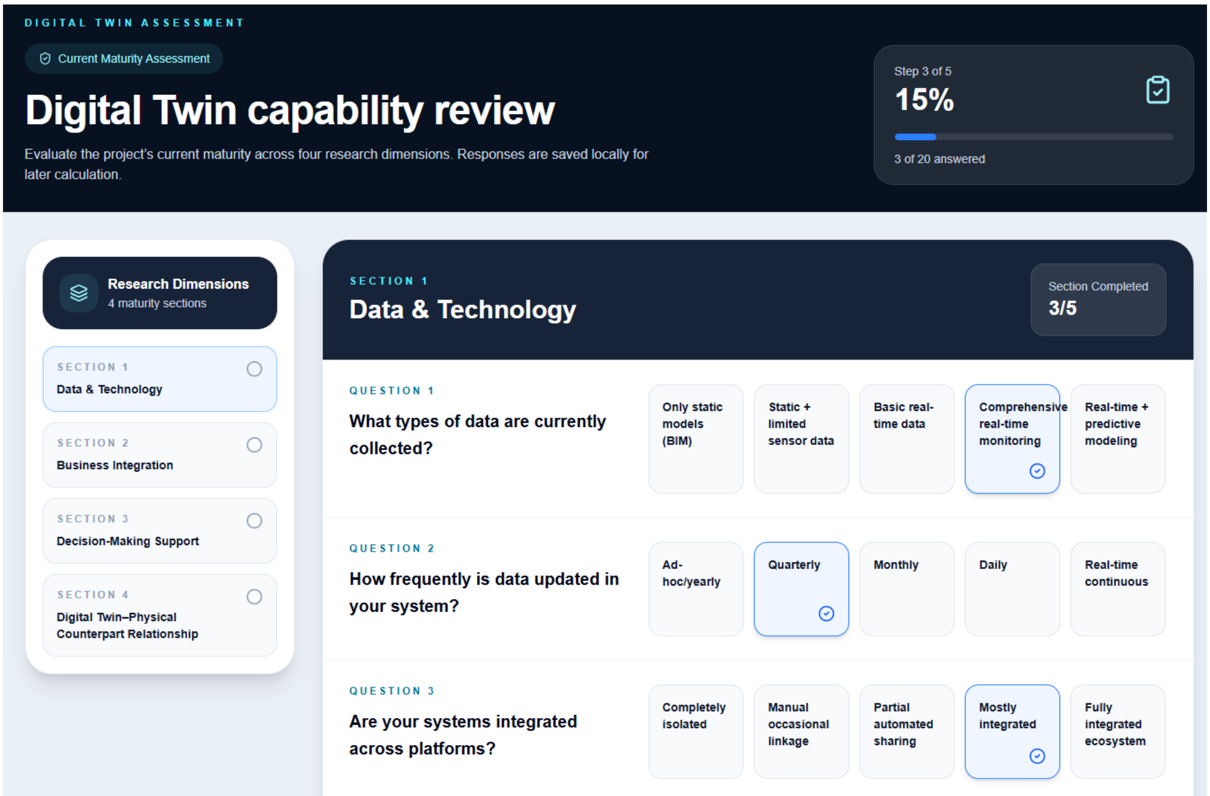

Figure 4Current state of Digital Twin maturity. Example assessment showing three questions and hypothetical responses for the Data and Technology dimension, provided for illustrative purposes.

This stage is particularly important because it captures the concept of organisational readiness, which is often overlooked in technology adoption decisions. Even if a project requires a high level of digital twin maturity, it may not be feasible to achieve this level immediately if the organisation lacks the necessary infrastructure or expertise. By explicitly assessing the current state, the DST provides a realistic basis for decision-making.

Once the inputs from the previous stages have been collected, the DST uses an analytical framework to calculate the suitability of different maturity levels (Figure 5). Rather than producing a single deterministic output, the tool generates a range of recommended maturity levels. This is a deliberate design decision that reflects the complexity and uncertainty inherent in construction projects. In practice, multiple levels of maturity may be acceptable depending on how trade-offs are managed.

For example, a project may have a recommended maturity range between integrated and predictive (as shown in Figure 1) levels. Within this range, stakeholders can consider factors such as budget constraints, available expertise, and implementation timeline to select the most appropriate option. This flexibility allows the DST to support nuanced decision-making rather than forcing a single outcome.

One of the most valuable features of the DST is its ability to perform a gap analysis between the current state and the recommended maturity range. This analysis highlights discrepancies between where the organisation is and where it needs to be. Such information is critical for planning the next steps. If a significant gap exists, stakeholders may consider options such as investing in training programs, upgrading infrastructure, or adopting a phased implementation strategy.

The DST also supports sensitivity analysis, enabling users to explore how changes in priorities or conditions affect the recommended maturity levels. For instance, if sustainability becomes a higher priority, the tool can show how this change influences the outcome. This capability is particularly useful in dynamic project environments, where objectives and constraints may evolve over time.

Figure 5. Results page. This figure illustrates the results of a hypothetical case for the Data and Technology maturity dimension. Although the tool assesses all maturity dimensions, only the Data and Technology dimension is presented as an example. The left side shows the current maturity level based on the project's current state and the required maturity range to achieve project objectives successfully. The right side presents the contribution of selected digital twin adoption drivers to the assessment results.

To illustrate the practical application of the DST, consider a scenario involving a large construction project in an urban environment. The project team identifies key drivers such as sustainability, stakeholder coordination, and long-term asset performance. After ranking these drivers and assessing their current capabilities, the DST indicates that a relatively high level of maturity is desirable, particularly in terms of data integration and decision-making support. However, the tool also reveals that the organisation's current capabilities in these areas are limited. This insight prompts the team to adopt a phased approach, beginning with improvements in data integration before moving toward predictive analytics.

In contrast, consider a smaller-scale project with limited resources and a primary focus on efficient delivery. In this case, the DST may recommend a lower level of maturity, indicating that basic monitoring and coordination capabilities are sufficient. This helps avoid unnecessary investment in complex systems and ensures that resources are used effectively. Through these examples, it becomes clear that the DST does not simply provide answers; it facilitates a structured decision-making process. By guiding users through the evaluation of drivers, capabilities, and trade-offs, it enables more informed and transparent decisions.

7 Application, Validation, and Insights

The practical value of the Decision Support Tool was evaluated through its application to a range of scenarios, including both real-world cases and conceptual project settings. This validation process was designed to assess not only the accuracy of the tool's outputs but also its usefulness as a decision-making aid. Participants in the validation process included professionals with experience in construction management, digital technology implementation, and project planning. These individuals were asked to apply the DST to their respective contexts and compare its outputs with their own initial judgments. This comparison provided valuable insight into how the tool influences decision-making.

One of the most significant findings was that the DST consistently challenged pre-existing assumptions. Many users initially believed that higher levels of digital twin maturity would be inherently beneficial. However, after using the tool, they often found that lower or intermediate levels were more appropriate for their projects. This shift in perspective highlights the importance of structured decision-making in overcoming biases and assumptions.

In addition to refining individual judgments, the DST played a crucial role in facilitating communication among stakeholders. Construction projects involve diverse participants, each with their own perspectives and priorities. By providing a clear and transparent framework, the tool enabled stakeholders to engage in more productive discussions. Decisions that might otherwise have been based on subjective opinions were instead grounded in a shared understanding of project drivers and constraints.

Another important insight relates to the tool's ability to enhance confidence in decision-making. Users reported that the structured nature of the DST made it easier to justify their decisions, both internally and to external stakeholders. This is particularly important in the context of digital transformation, where investments are often scrutinized and require clear justification. The validation process also highlighted areas for future improvement, such as enhancing user interface design and providing more intuitive visualizations, which have been addressed in the final version of the tool.

8 Implications for the Construction Industry

The findings of this research have several important implications for the construction industry, particularly in the context of digital transformation. One of the most significant implications is the need to move away from a purely technology-driven approach toward a more decision-driven approach. In many cases, digital transformation initiatives are defined by the technologies being adopted rather than the problems they are intended to solve. This often leads to misaligned investments and suboptimal outcomes. The framework and DST developed in this research address this issue by placing decision-making at the center of the adoption process. By focusing on project drivers and organisational readiness, stakeholders can ensure that technology choices are aligned with actual needs.

For project managers, this implies a shift in how digital strategies are developed. Instead of starting with technology selection, they should begin by clearly defining project objectives and evaluating the importance of different drivers. This approach leads to more targeted and effective use of digital tools. For organisations, the research highlights the importance of capability development. Digital twins require a combination of technical skills, organisational processes, and cultural readiness. Investing in these areas is essential for ensuring that digital twin systems are used effectively. This may involve training programs, changes in workflow, and the adoption of new management practices.

At an industry level, the findings point to a need for greater standardisation and guidance. The lack of clear frameworks for assessing digital twin maturity contributes to uncertainty and inconsistency in adoption. Tools such as the DST can play a role in addressing this gap, but broader efforts may be required to establish common standards and best practices.

9 Conclusion

This research has addressed a critical and often overlooked challenge in the adoption of digital twin technology within the construction industry: determining the appropriate level of maturity for a given project. By developing a multidimensional maturity model and integrating it into a practical Decision Support Tool, the study provides both conceptual insight and practical guidance. The central finding of the research is that successful digital twin adoption depends on alignment, rather than technological sophistication alone. A digital twin system that is well aligned with project objectives and organisational capabilities is far more likely to deliver value than one that simply incorporates advanced features.

The Decision Support Tool developed in this study offers a structured method for achieving this alignment. By guiding users through the evaluation of drivers, priorities, and capabilities, it enables more informed and transparent decision-making. The tool also supports flexibility, allowing stakeholders to explore different scenarios and adapt to changing conditions. Ultimately, this research contributes to improving the effectiveness of digital transformation in construction by shifting the focus from what technology can do to what it should do in a given context. This shift is essential for ensuring that investments in digital twin deliver meaningful and sustainable benefits.

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The methodology and theoretical framework developed in this project have been validated in a peer-reviewed publication. Readers interested in the detailed methodology, model development, and validation process are encouraged to refer to the following publication:

Mahdiyar, A., Sabri, S., & Adriaenssens, S. (2026). A Decision Support Tool for Determining the Suitable Multifunctional Digital Twin Maturity Levels in Construction Projects. *Journal of Construction Engineering and Management*, *152*(11), 04026196. https://doi.org/10.1061/JCEMD4.COENG-17977