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Validating Global Drivers of Digital Twin Adoption in Construction: A Systematic Review and Delphi Study Toward a Policy Framework for Bahrain

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Abstract

Digital Twin (DT) technology is being rapidly adopted across construction worldwide, but the literature still contains two gaps. Prior studies identify many drivers of DT adoption without integrating them into one framework, and few test those drivers empirically outside advanced economies, especially in the Gulf Cooperation Council (GCC). This study gathers the global drivers and examines how well they fit the Bahraini construction industry. We combined a PRISMA-based systematic literature review of 133 studies with a two-round mini-Delphi survey of 15 Bahraini construction professionals, defining consensus as a median ≥ 4.0 together with an IQR ≤ 1.0 and/or agreement $\geq 70\%$, with borderline items retained where qualitatively relevant to the Bahraini context. The review produced 81 drivers across five groups: operational excellence, technological enablement, safety and risk management, stakeholder and organizational drivers, and strategic and business value. After merging 11 semantically redundant items identified in Round 1, 70 drivers were evaluated in Round 2, of which 25 met the full consensus criteria and a further 2 were retained as policy-relevant items on contextual grounds rather than statistical consensus, yielding 27 drivers carried forward (38.5%). These results question the idea that such technologies transfer cleanly between countries, and they offer a repeatable way to test context-specific adoption in emerging economies. From the top-ranked drivers, we proposed a conceptual Policy Enablement Framework aligned to Bahrain's Economic Vision 2030 and UN SDGs 9 and 11. Whereas the drivers were confirmed through expert consensus, the framework's policy instruments were derived analytically. They are therefore presented as propositions for future validation rather than empirically tested instruments.



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Keywords: digital twins; construction industry; drivers; technology adoption; Delphi method; Bahrain; policy enablement; SDG 9; SDG 11

1. Introduction

The rapid development of the Architecture, Engineering, and Construction (AEC) industry has been influenced by advancements in the Internet of Things (IoT) and Cloud Computing. Consequently, adoption of Digital Twin (DT) technology has emerged as a driver of digital transformation in the Architecture, Engineering, and Construction (AEC)

industry [1–3]. Although DT technology originated in product lifecycle management and manufacturing [4,5], its rapid expansion into the construction industry has resulted in increased DT adoption. In the construction field, DTs are generally defined as virtual models of physical properties of existing structures which are continually updated by bi-directional data exchanges between the physical property and the DT model to assist in simulation, monitoring and decision making at all phases of the building life cycle [6–8]. Numerous research studies have been conducted on the various DT applications for use within the construction industry such as asset and facility management and smart city systems [9,10]. Additionally, DT extends Building Information Modeling (BIM) capabilities by providing real-time synchronization [2,3,11,12]. There has also recently been increasing interest in developing best practice processes for DT lifecycle activities, which include automated progress monitoring, predictive maintenance, energy efficiency optimizations, decarbonizing strategies, and resilient design methods [13–15].

These global developments are not equally relevant across national contexts, and Bahrain presents a distinctive case. As a small island nation in the Gulf Cooperation Council (GCC), Bahrain operates under land-scarcity constraints that place a premium on efficient asset lifecycle management. Bahrain offers a relevant but underexamined test of these global drivers. A national survey of Building Information Modeling (BIM) adoption, a closely related digital technology, in the Bahraini construction sector found that more than 72% of professionals knew about BIM, while only 39% put it into practice [16]. Technology-specific drivers established in other markets cannot be assumed to transfer directly to Bahrain. The country is running its own digital-transformation initiatives through the Information and eGovernment Authority and its National Digital Economy Strategy [17] and the gap between BIM awareness and BIM use suggests local conditions shape adoption on their own terms. Bahrain's Economic Vision 2030 sets a broader policy backdrop around sustainability, fairness, and competitiveness [18]. These factors make Bahrain a useful test case for assessing which globally identified digital-transformation drivers hold in a GCC construction market still early in its digital maturity. These priorities are consistent with both the efficiency, transparency and lifecycle optimization of assets, which are key features of DT technology and several of the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 11 (Sustainable Cities and Communities). Therefore, due to Bahrain's specific circumstances, it provides a useful and largely unexamined environment in which to assess whether globally recognized DT adoption factors apply in an emerging GCC construction market.

Despite this expanding literature, three distinct gaps remain. First, existing reviews of DT drivers, including the systematic review by Opoku et al. [19], which classified 50 drivers from 58 studies into a conceptual framework, offer fragmented coverage of drivers across the project life cycle without integrating them into a single evidence base [9,20]. Second, very few reviews subject identified drivers to empirical testing, and fewer still validate them outside advanced economies or map deployments geographically [21]; where empirical work exists, it tends to examine adoption drivers [19,22] or sector-specific barriers [23,24] in isolation, typically within a single disciplinary scope. Third, no existing review converts validated drivers into actionable policy instruments, leaving a disconnect between academic evidence on DT adoption and the practical tools policymakers need to accelerate it.

To address the identified gaps, this research has compiled a body of literature on DT adoption drivers from around the world; tested their applicability in the Bahraini Construction Industry; and translated the relevant drivers into policy tools that align with Bahrain's Economic Vision 2030. The specific methods used to achieve this are detailed in Section 2. Hence, the objectives of this research are as follows:

A. Identify the key drivers of DT adoption in the AEC industry through a global SLR.

- B. Validate the identified drivers through a Delphi study involving AEC experts in Bahrain.
- C. Prioritize Bahrain-relevant DT adoption drivers for construction investment and industry practice.
- D. Develop a Policy Enablement Framework aligned with Bahrain Economic Vision 2030.

The value of this research is to provide practitioners, regulators, and facility planning managers with the tools they need to plan, implement and manage DT deployment into the built environment, as well as to provide a solid empirical base upon which the academic community can build its work in developing the DT body of knowledge. In addition, it can provide a template for similar types of studies in countries with similar contexts that are interested in adopting DT.

2. Materials and Methods

The research uses both qualitative and quantitative approaches. An SLR is used as the first part of this study, which will provide an objective, transparent, and well-structured evidence base for DT adoption drivers. Next, the Delphi method is applied to validate and prioritize those identified drivers by experts' consensus.

2.1. Systematic Literature Review (SLR) Methodology

The increasing use of DT Technology in the AEC Sector requires a complete assessment that is structured to identify, select, and synthesize relevant studies [19]. An SLR provides a systematic and transparent way to assess the available literature in any subject area using pre-defined protocols to reduce bias and increase the validity of results [23]. In this research, PRISMA guidelines are used to ensure consistent methodology and transparency throughout the review process and to guide the analytical work through its three primary steps, as depicted in Figure 1.

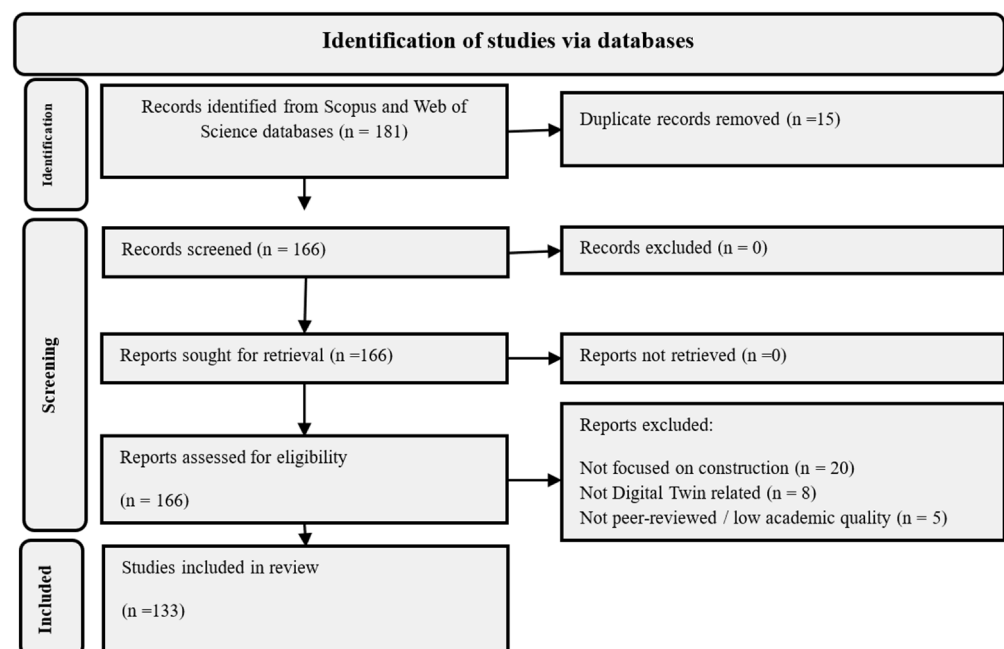


Figure 1. PRISMA 2020 flow diagram.

Identification: An in-depth exploration of a systematic search strategy using the following keywords: (“Digital Twin” OR “Digital Twins”) AND (“Construction” OR “Construction industry”) AND (“Adoption” OR “Implementation”) AND (“Drivers” OR “Benefits” OR “Advantages”). By utilizing this systematic approach, it enabled an even spread of

research from around the world and recent topics related to DT applications. Only peer-reviewed journal articles and conference proceedings published in English between 2015 and 2025 were eligible for inclusion. The database search, conducted in January 2026, covered the title, abstract, and keyword fields of Scopus and Web of Science. The same keyword logic was applied in both databases using their respective field-search syntax (TITLE-ABS-KEY in Scopus; TS in Web of Science), restricted to the title, abstract, and keyword field. A total of 181 relevant articles were retrieved from Scopus and Web of Science, which have the highest level of indexation and citation tracking. Screening and eligibility assessment were conducted by a single reviewer. The absence of independent dual screening is acknowledged as a limitation of this review, leaving a further 166 articles to be reviewed against the eligibility criteria described below.

Screening: All 166 remaining records were screened by title and abstract for relevance to DT technologies in the construction industry. No records were excluded at this stage; all 166 were judged potentially relevant and progressed to full-text retrieval (Figure 1).

Eligibility: Full-text reports were sought and retrieved for all 166 records. Each report was assessed against the eligibility criteria, and 33 were excluded; 20 were not focused on construction, 8 were not related to DT technology, and 5 were not peer-reviewed or were judged to be of low academic quality (Figure 1). This left 133 studies in the review. Findings were compiled using a systematic thematic approach to identify the drivers contributing to DT acceptance, such as cost, regulatory requirements, and technological infrastructure.

During the eligibility assessment, full-text records were evaluated against an overall quality rubric based on four criteria: (i) peer-review status, requiring publication in a peer-reviewed journal or peer-reviewed conference proceedings; (ii) methodological transparency, requiring a clear description of the method or evidence supporting claims made about DT drivers; (iii) relevance to DT drivers and their potential adoption in construction, addressing some aspect of adoption and/or benefit of DT drivers; and (iv) clarity of reporting, requiring findings to be presented in sufficient detail to permit driver extraction. The five records that are referred to in Figure 1 as “non-peer reviewed” or “of poor quality” did not meet all of these criteria. A formal tool assessing the risk of bias, like CASP or MMAT, could not be used because this review synthesized qualitative categories of DT drivers into themes rather than synthesizing quantitative estimates of effects; therefore, the rubric was considered proportionate to its synthesis aim.

2.2. Mini-Delphi Approach

After identifying and grouping the drivers, an expert panel was convened to assess and rank the identified drivers using a mini-Delphi method, which is a less formalized version of the traditional Delphi that allows for rapid consensus among an expert group within one to two rounds by providing anonymous, controlled feedback and statistical aggregation of responses [16]. The mini-Delphi method has become one of the most frequently used approaches for achieving a structured consensus among experts across various fields such as health care and real estate [20]. It also serves as an increasingly recognized and simplified alternative to the traditional Delphi method, providing a means by which researchers can effectively strike a balance between the methodological rigor required in research and the practical constraints of time and cost. The mini-Delphi can be especially useful when dealing with developing areas like DT where establishing a consensus on technological, organizational, and cultural aspects is important.

Panel members were selected purposively based on their professional role within Bahrain’s construction industry, spanning government bodies (including the Ministry of Works and the Ministry of Municipal Affairs and Urban Planning) and private-sector organizations (contracting companies, consulting firms, and property management or-

ganizations). Three inclusion criteria were applied to purposively select experts for this study. These were: (i) active professional engagement with Bahrain's construction industry; (ii) a decision-making or technical/advisory role in Bahrain construction projects; and (iii) familiarity with digital construction technologies, such as BIM, AI, IoT, or DT, as verified during round one. Purposive selection was used across both private and public sectors and throughout the project lifecycle (consultant, contractor, regulatory and academic roles). No minimum years-of-experience threshold applied; the panel's experience ultimately ranged from 5 to over 20 years. The initial pool of candidate experts was identified through industry associations and professional bodies within Bahrain's construction sector, as well as through direct approaches to established firms and relevant government ministries. Twenty experts received email invitations; fifteen completed both rounds, representing 75% overall retention and 100% retention among Round 1 completers. The conventional size of mini-Delphi panels is recognized to be sufficiently large to achieve a consensus when using panelists that have been selected based on their knowledge of the subject matter, rather than statistical representation [25–27]. Therefore, the 15 panelists selected for this study fall within the acceptable panel-size boundaries for mini-Delphi and expert consensus designs [28,29], which were also representative of other Delphi-based research involving DT. Participation was voluntary, and informed consent was obtained from all panelists prior to Round 1.

Panelists remained anonymous to one another throughout both rounds; their identities and individual responses were not disclosed to other panelists. The Round 2 materials incorporated statistically aggregated feedback from Round 1, including the refined 70-item driver list produced through the merging process described below, consistent with the controlled-feedback principle central to the Delphi method [16].

Round 1 was conducted using a structured questionnaire that included an open-comment component. The structural section documented participants' knowledge of BIM, AI, IoT, and DT. These data were expressed as frequencies. On the other hand, in the open comment section, participants were asked to evaluate which of the drivers identified through the SLR were relevant to their experience in the construction sector in Bahrain, and to report any overlapping or redundant drivers. The research team analyzed the comments received and merged semantically redundant drivers based on their definitions in the SLR to develop the Round 2 list. In Round 2, the participants evaluated the list of drivers reduced after Round 1, using a five-point Likert scale [17], as described in Section 3.2.4.

3. Results and Discussion

3.1. Systematic Literature Review Results

Drivers Identification and Categorization Process

Transformation in construction is commonly associated with the pursuit of improved performance, innovation, and sustainability; in this study, "drivers" refer to factors identified in the literature and perceived by experts as important to DT adoption. Through the SLR of 133 studies, this study identified 81 drivers. Additionally, the list of drivers was classified into categories to provide a structured understanding of the factors influencing DT adoption in construction.

Real-time data visualization emerged as the most frequently cited driver, referenced 18 times in the literature. This high frequency is indicative of an increasingly data-driven industry that relies heavily upon real-time insights to assess site conditions, collaborate with project stakeholders and make timely decisions. The remaining drivers contribute to the broader uptake of digital practices, including BIM, IoT, and predictive analytics. Taken together, these results suggest that, although a range of factors shape the path of DT, those

that enhance visibility and accelerate decision-making are regarded as the most frequently cited drivers of change within the construction industry.

Beyond citation frequency, the most important drivers of these areas also reflect distinct operational foci in the literature. Real-time data visualization is associated with monitoring and decision support. Safety Risk Management is associated with hazard detection and risk simulation. Enhanced decision making is associated with planning and managing throughout the lifecycle. Complete mapping of each driver to its corresponding body of literature is provided in Supplementary Table S1.

The rationale for grouping behind grouping DT drivers into thematic categories was to allow researchers to better understand the organizational motivations driving DT adoption as well as to clarify where DT sits in an organization's overall digital transformation strategy. Yet there is no settled consensus on how DT drivers should be conceptualized, and prior studies reflect distinct analytical perspectives. For example, ref. [23] presents four categories, concept-oriented, production-driven, operational success and preservation-driven, which balance strategic and practical dimensions. Ref. [18] utilized a function-based framework encompassing legal, technical, organizational, operational and value to stakeholders, while ref. [30] placed drivers along a spectrum ranging from conceptual principles to operational and conservation outcomes. Finally, ref. [12] identified two types of drivers, internal and external, and highlighted the relationship between internal capabilities and external pressures. These differences indicate that DT adoption is multi-dimensional and that each dimension is shaped by the theories or research context. In addition to the previous models for DT, the five categories presented here were developed using both inductive and deductive methods. A deductive method involves using pre-existing knowledge or theory to guide the research. The categories used in this study were developed based on the most common themes identified in prior classifications (strategic, operational, technological, and organizational), and each driver was assigned to the category that best fit its conceptual content with its conceptual content [12,18,23,25]. When there was a driver that did not clearly fit into one of these categories, the researchers refined the boundaries of the categories to accommodate the item. As such, while the development of the categories was primarily deductive, it also incorporated an inductive element through the iterative refinement of the categories. These five categories are described below and presented in Table 1: Operational Excellence, Technological Enablement, Safety and Risk Management, Stakeholders and Organization, and Strategic and Business Value. The complete list of 70 drivers with their SLR literature references is provided in Supplementary Table S1.

Table 1. Distribution of SLR-derived DT adoption drivers across the five thematic categories.

Category	Number of Drivers	Illustrative Examples
Operational Excellence	18	Better project management; improved planning; reduction in operational cost
Technological Enablement	19	Real-time data visualization; anomaly detection; capacity of improving building data
Safety and Risk Management	12	Safety risk management; real-time safety assessment; reducing the number of injuries
Stakeholder and Organizational	9	Effective stakeholder collaboration; effective stakeholder management; increased transparency of information
Strategic and Business Value	12	Enhanced decision-making; creation of asset value; deliver new products or services
Total	70	—

The first category includes drivers that represent the ability to manage organizational operations efficiently and effectively, representing Operational Excellence. It relates directly to the management of daily operations and has a direct impact on the financial performance of a business. This grouping aligns with the production-driven and operational success perspectives identified in earlier research [19], where DTs have been positioned as a means of reducing rework, strengthening coordination, and improving planning across projects [31]. In addition, such drivers reflect the industry's continued focus on measurable performance gains as a primary justification for adoption [28].

The Technological Enablement grouping encompasses drivers related to enabling technology. These include real-time visualizations of data, advanced predictive analytics, and sensor system integration. Many prior studies have stressed the significance of both interoperability and platform robustness. The reliability of the technological environment may also be a significant factor in determining whether to implement certain technologies. Reliability of the technological environment could represent an organization's ability to innovate and their digital maturity.

The Safety and Risk Management category includes all aspects of safety, environmental sustainability and regulatory compliance. Studies have recently shown that DT can identify hazards in real time during operations and model continuous risk simulation [15].

The fourth category is the "Stakeholders and Organizations", which reflects the internal and external factors that influence the practical implementation of technology. This includes leadership commitment to use technology, digital skills, governance alignment, and collaboration. Ultimately, it is the internal alignment of stakeholders and organizational preparedness that determines whether technological capabilities lead to successful implementation.

The fifth and final category is the "Strategic and Business Value", which considers long-term strategic advantage opportunities, such as increased competitiveness, innovative product or service development, optimal lifecycle cost management of assets, and creation of new business models. There are many studies which demonstrate how DTs provide better decision-making options and open possibilities for generating value through the provision of data-based services, thereby demonstrating DTs as strategic assets rather than solely as operational tools [29].

In general, this framework gives an integrated view of DT adoption drivers, demonstrating that, while efficiency and technological capability remain central, increasing emphasis is placed on organizational and strategic dimensions. There is confirmatory evidence from concept-oriented, function-based, and internal and external classifications in prior studies that DT adoption is a multidimensional process influenced by the interactions among the technical, organizational, and strategic factors involved in construction digital transformation [29].

3.2. Mini-Delphi Approach Results

3.2.1. Participants Profile

Demographic and professional data were collected from panel members, including their sector, role at organization, and level of experience. There was a broad range of roles represented by the panel, including five project engineers, three civil engineers, two architects, two executive-level management personnel, two faculty members, and one department head. In addition to these roles, the panelists included five consultants, four contractors/subcontractors, three clients/owners and others who work in government, research, and education. The reported experience levels were as follows: 26.7% had 5–12 years of experience, 33.3% had 12–20 years, and 40.0% had over 20 years of experience. Finally, 33.3% held positions of authority, e.g., leadership positions. Overall, the panel

provides a high level of reliability and knowledge base to assess which drivers influence DT adoption in Bahrain's construction industry, as recommended for mini-Delphi panels in terms of size to obtain strong agreement among experts about new technologies [26].

3.2.2. Round One: Technology Familiarity and Driver Refinement

The initial data-gathering process for round one involved an open-ended, semi-structured questionnaire, which captured expert opinions regarding how DT technology could contribute to Bahrain's construction industry. All participants (100%) reported their familiarity with several related enabling technologies, such as BIM, AI and IoT. Most of them stated that they had "hands-on" experience with these technologies, suggesting a solid technological foundation across the panel. When asked about familiarity with DT, responses were more dispersed, where 46.7% of respondents said that they were familiar with DT concepts but had not previously worked with DTs, 33.3% frequently work with DTs and therefore considered themselves knowledgeable, 13.3% stated that they had been exposed to DTs at the project level but do not consider themselves to be well-informed about DTs, and 6.7% self-reported as highly experienced users of DTs. Importantly, no participants reported being unfamiliar with DT.

These findings are consistent with broader trends in construction research, which point to a well-established knowledge base around enabling technologies such as BIM, AI, and IoT, alongside markedly more uneven experience with DT itself, where the application of DT occurs in a fragmented way, with little or no integration among stakeholders [32]. The bibliometric data also show that, although DT is being adopted by the AEC industry using existing digital tools and capabilities, the level of DT-specific technical expertise has been found to be irregularly distributed among both practitioners and researcher communities [27].

In addition to the level of familiarity, round one included experts' opinion on the 81 drivers, along with their perceptions of how DT could be used by the construction sector in Bahrain. Most of the panel members had positive views on adopting DT, mentioning that DT is a "Game Changer"; they believed that the integration of DT with BIM and IoT would create highly accurate analytical processes for both maintenance and life-cycle management. The comments from Round 1 also provided information that was used for a redundancy assessment of the 81 drivers. A driver is considered redundant if it meets both of the following conditions: (i) describes the same conceptual mechanism or outcome as another driver using different words and (ii) has overlapping SLR source definitions. The lead researcher identified candidates for redundant pairings based on these criteria and had them reviewed by the co-authors separately to ensure all parties agreed prior to merging of drivers. For example, "effective stakeholder collaboration" and "effective coordination between stakeholders" were deemed to describe the same conceptual idea and thus were merged. This process reduced the 81 drivers to a refined list of 70 for Round 2 (Supplementary Table S1). Merging conceptually identical items also prevented vote-splitting, in which panel agreement would otherwise have been divided across duplicate wordings of a single driver.

3.2.3. Round Two: Adoption Drivers for Bahrain's Construction Sector

The second stage focused on identifying priorities of drivers within the context of Bahrain's construction industry. The previously developed list of 70 drivers across the five categories was provided again to the same group of experts. All 15 participants who had participated in round one participated in round two, with a 100% participation rate achieved. This level of participant retention adds strength to the reliability and validity of the results and demonstrates an interest in the topic of the study. Participants then used a

five-point Likert Scale (1 = “Not Relevant”; 5 = “Highly Relevant”) to assess how relevant each driver was to the Bahrain construction context. To determine whether a driver could be considered, all items needed to meet established criteria based on consensus. Twenty-seven key drivers, representing the top DT adoption influences in Bahrain’s construction industry, demonstrate a much greater degree of focus and context-specific prioritizing of the most important drivers than was evident in Round 1.

3.2.4. Consensus Criteria

A driver was retained if it had a median score of 4.0 or higher, together with at least one of two secondary criteria: an IQR of 1.0 or lower or agreement of 70% or higher (the proportion of ratings of 4 or 5) [28,33]. Drivers meeting all three criteria (median, IQR, and agreement thresholds) were classified as high-priority drivers. Drivers meeting the median criterion together with only one secondary criterion went through a qualitative review, assessed against a documented criterion, clear strategic relevance to Bahrain’s national policy agenda, as reflected in Economic Vision 2030 and its associated SDG priorities, and were retained only if judged pertinent. Because this contextual judgment was made after the Round 2 ratings and fell outside the statistical consensus rule, drivers retained in this way are reported separately as policy-relevant retentions. They were excluded from all claims of statistical consensus. Full per-driver results against these criteria are reported in Supplementary Table S2.

3.2.5. Overall Findings

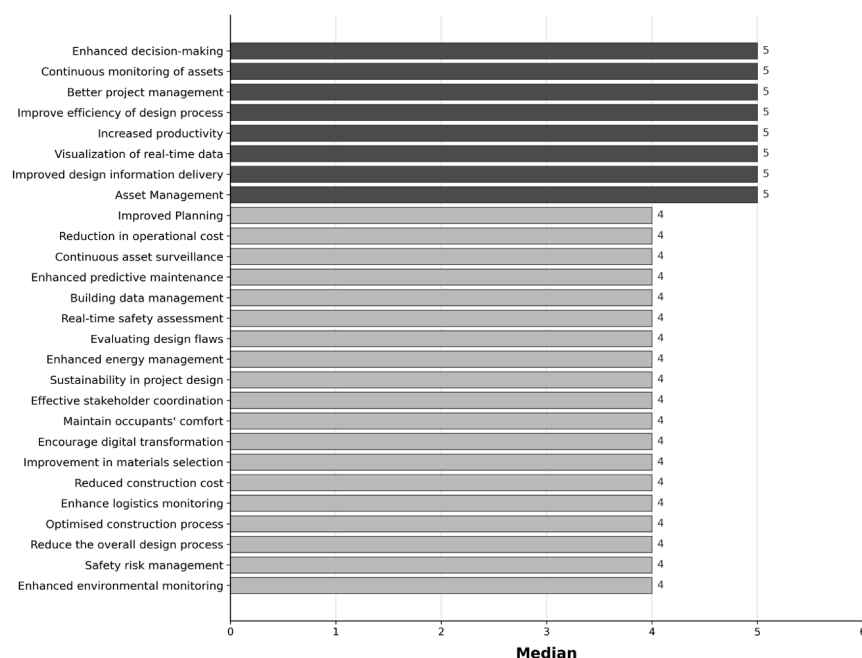
Applying the consensus rule to the 70 drivers evaluated in Round 2 resulted in a total of 25 drivers that met all three criteria (Median ≥ 4.0 , IQR ≤ 1.0 , and Agreement $\geq 70\%$); furthermore, two additional drivers (Safety Risk Management and Enhanced Environmental Monitoring), although they met the median threshold, failed one or both secondary criteria. The research team retained these under the qualitative review procedure (Section 3.2.4) and on documented grounds of strategic relevance to Bahrain’s national policy agenda; as this was a contextual judgment made after the Round 2 ratings, this report treats them as policy-relevant retention rather than a consensus retention. A total of 27 drivers were taken forward from the original set of 70. The remaining 43 drivers (61.4%) did not meet the retention rules and therefore were excluded. The full statistical profile of the 27 retained drivers is presented in Table 2. Supplementary Table S2 lists the complete Round 2 statistics for all 70 evaluated drivers: median, IQR, agreement percentage, retention status, and, where applicable, the qualitative justification for policy-relevant retention.

To assess the overall stability of agreement across the panel, Kendall’s Coefficient of Concordance was calculated for the Round 2 ratings of all 70 drivers, yielding $W = 0.370$ ($\chi^2(69) = 388.03$, $p < 0.001$). This indicates statistically significant, moderate agreement among panelists, consistent with the study’s finding that globally identified drivers do not transfer uniformly to Bahrain; the significant but moderate concordance reflects genuine divergence in how individual drivers were rated, which produced the selective retention of 27 context-relevant drivers.

The high percentage of excluded drivers shows that fewer than half of the potential drivers cited in past studies apply to the context in Bahrain. Therefore, there is a clear need for context-specific studies with respect to the subject matter, as opposed to using generic models or studies. Moreover, it illustrates how effectively the mini-Delphi technique narrows down many theoretical drivers into a core group of drivers applicable to the specific cultural, economic, and legal environment of each country. Figures 2–4 further demonstrate high median values, low response variability, and strong expert agreement across the retained drivers.

Table 2. Round 2 consensus statistics for the 27 retained Digital Twin adoption drivers.

#	Driver Name	Median	IQR	Agreement %	Retention Status
1	Enhanced decision-making	5	0	93.30%	Consensus
2	Continuous monitoring of assets	5	0.5	86.70%	Consensus
3	Better project management	5	1	93.30%	Consensus
4	Improve efficiency of design process	5	1	93.30%	Consensus
5	Increased productivity	5	1	86.70%	Consensus
6	Visualization of real-time data	5	1	86.70%	Consensus
7	Improved design information delivery	5	1	86.70%	Consensus
8	Asset Management	5	1	80.00%	Consensus
9	Improved Planning	4	0.5	93.30%	Consensus
10	Reduction in operational cost	4	1	80.00%	Consensus
11	Continuous asset surveillance	4	1	73.30%	Consensus
12	Enhanced predictive maintenance	4	1	80.00%	Consensus
13	Building data management	4	1	80.00%	Consensus
14	Real-time safety assessment	4	1	73.30%	Consensus
15	Evaluating design flaws	4	1	80.00%	Consensus
16	Enhanced energy management	4	1	80.00%	Consensus
17	Sustainability in project design	4	1	80.00%	Consensus
18	Effective stakeholder coordination	4	1	80.00%	Consensus
19	Maintain occupants' comfort	4	1	73.30%	Consensus
20	Encourage digital transformation	4	1	73.30%	Consensus
21	Improvement in materials selection	4	1	80.00%	Consensus
22	Reduced construction cost	4	1	73.30%	Consensus
23	Enhance logistics monitoring	4	1	73.30%	Consensus
24	Optimized construction process	4	1	73.30%	Consensus
25	Reduce the overall design process	4	1	73.30%	Consensus
26	Safety risk management	4	2	53.30%	Policy-relevant
27	Enhanced environmental monitoring	4	2	66.70%	Policy-relevant

**Figure 2.** Median scores of the 27 retained DT adoption drivers. Rankings include 25 drivers that met the full consensus rule and 2 drivers (Safety Risk Management and Enhanced Environmental Monitoring) retained on contextual grounds rather than statistical consensus, as described in Section 3.2.4.

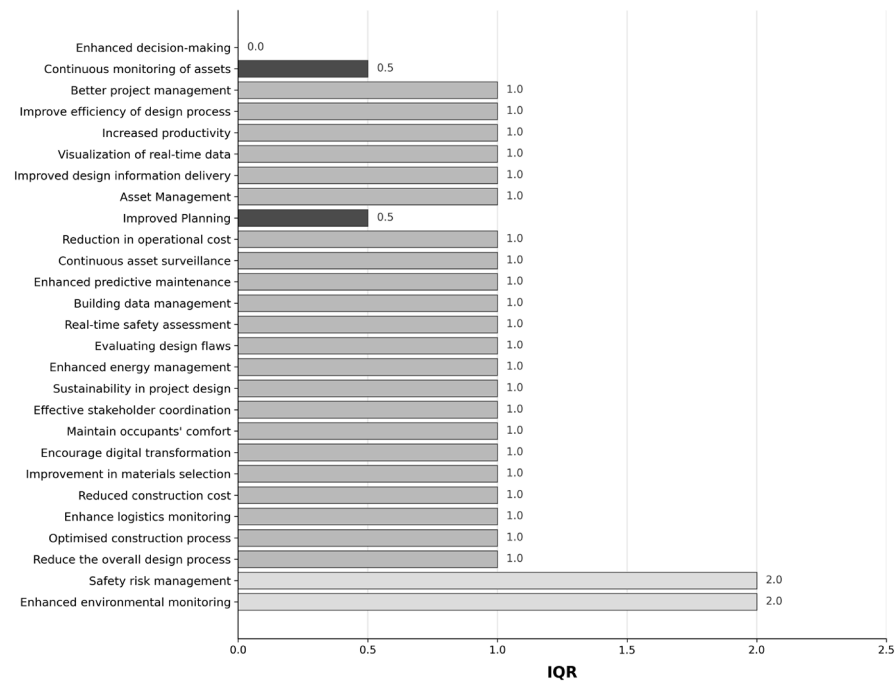


Figure 3. Interquartile range (IQR) of the 27 retained drivers. Two drivers (Safety Risk Management and Enhanced Environmental Monitoring, both IQR = 2.0) exceeded the consensus threshold of $IQR \leq 1.0$ and were retained as policy-relevant items under the qualitative review procedure (Section 3.2.4).

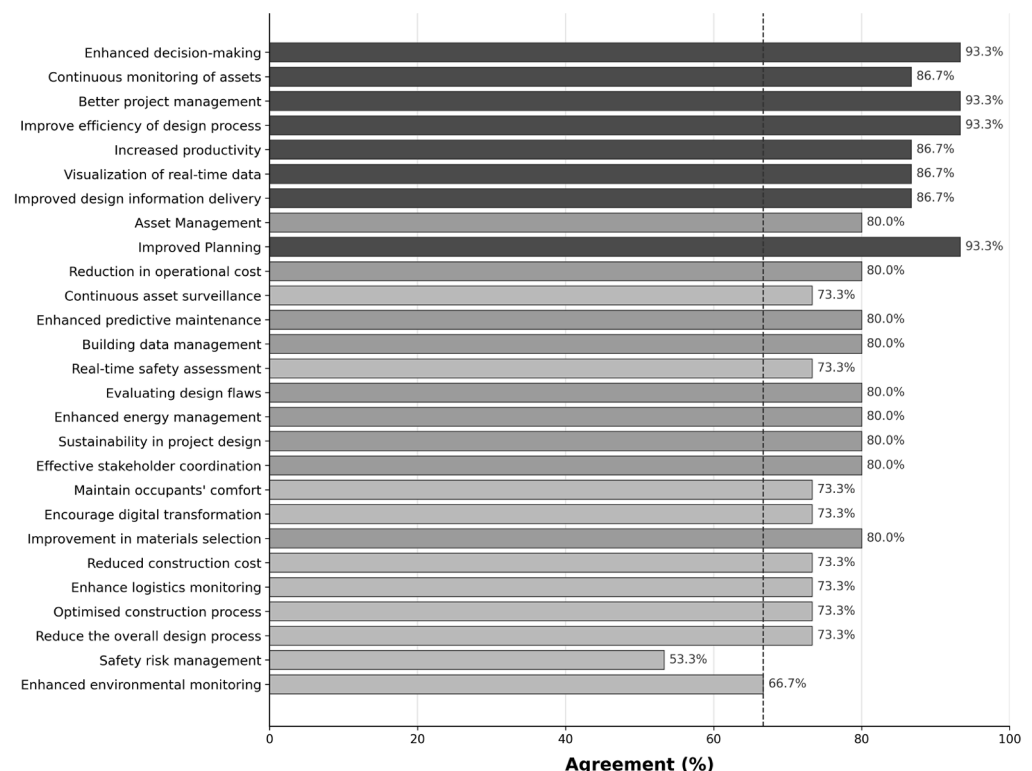


Figure 4. Agreement percentages of the 27 retained drivers against the 70% consensus threshold (dashed line). Two drivers below the threshold (Safety Risk Management, 53.3%; Enhanced Environmental Monitoring, 66.7%) were retained as policy-relevant items on grounds of strategic alignment with national policy priorities (Section 3.2.4).

Eight drivers received the highest median score of 5.0; all being considered the most important to DT adoption within Bahrain's construction sector. Of these, "Enhanced

Decision-Making” was found to be the driver with the highest level of agreement, followed by “Continuous Asset Monitoring”. Additionally, six other drivers also achieved an IQR of 1.0 at an IQR = 1.0 and had varying degrees of consensus ranging from 80 to 93.3%. In the case of “Enhanced Decision Making,” there is a near-universal agreement among all respondents that they would like to use DTs as a strategic tool to improve their ability to plan, coordinate and operate. This clearly reflects one of the most documented problems with construction management, that the process of exchanging information between stakeholders can be quite difficult and, when timely and accurate information is not available, decision makers have limited alternatives other than relying on rules-of-thumb that result in suboptimal decisions [34]. Moreover, the high level of agreement on “Continuous Asset Monitoring” suggests that respondents place considerable value on real-time visibility of asset conditions and performance.

Sixteen other drivers were found by many participants to have a high degree of consensus in terms of their application across different aspects of construction projects and asset management, thereby reinforcing the multifaceted nature of the DT implementation process. Most of the highly rated drivers in this research are focused on increasing efficiency within their organization as opposed to focusing on areas that can improve customer engagement or have a positive social impact. The patterns seen here are consistent with the expectations for a business or organization in an early to intermediate stage of digital maturity, although digital maturity was not measured in this research. One possible reason why many organizations may be taking this approach may be explained by the “Diffusion of Innovation” theory, which states that those who first begin to adopt technology are most interested in using it to increase efficiency and cost savings over the potential long-term value creation [35].

A notable variation in expert opinions was observed for two drivers, which achieved a median of 4.0 but recorded higher dispersion (IQR = 2.0), showing the effect of variety in professional roles, organizational contexts, and project responsibilities; despite this, they were retained due to their strategic relevance to Bahrain’s long-term objectives. In addition, “Safety Risk Management” is a priority for site-based professionals but may be less immediate for regulators or design-focused roles. Similarly, some drivers, such as “Environmental Monitoring”, are critical to achieving national environmental sustainability objectives; however, other stakeholders might have lower priorities. This resulting pattern aligns with the concept of stakeholder diversity in innovation adoption [23], where each entity within the construction system has different strengths, weaknesses, motivations, and constraints. Therefore, the motivation for each stakeholder group should be tailored to suit them individually rather than applying a standardized approach to all, thus creating a flexible system allowing all stakeholders to pursue those motivations that are most important to them to contribute to developing an effective national strategy in Bahrain.

Among the 43 eliminated drivers, “Improved Retrofitting” had the smallest median (3.0), with an acceptance rate of 26.7%; it can be concluded that it does not influence the context of Bahrain. In comparison with the previous studies carried out in Europe and North America, there was a larger emphasis on retrofitting and heritage preservation compared to new developments because of the abundance of historical buildings and regulations surrounding their preservation [36–38], thus illustrating how the developmental stage of a country can act as one of the largest moderator variables for DT technology adoption.

The five categories of drivers provide an order to determine how DT should be implemented within Bahrain’s construction sector, creating a clear hierarchical structure as demonstrated by Figure 5. At the base are “Operational Excellence” and “Technological Enablement,” suggesting that respondents regard robust digital infrastructure as a foundation for realizing broader benefits. Operational Excellence emerged as the dominant

category, encompassing eight highly ranked drivers, showing that the sector is focused on improving internal processes and efficiency as part of digital maturation before pursuing more strategic benefits. The middle level comprises “Safety and Risk Management” and “Stakeholders and Organizations,” capturing both the human and preventive dimensions of DT adoption and reflecting its recognition as a socio-technical system requiring attention to user experience, collaboration, and organizational culture. At the apex lies “Strategic and Business Value”, where “Enhanced Decision Making” ranked first with near-unanimous consensus, underscoring its critical importance. Collectively, the five categories are organized into one complete hierarchy where foundational technology is perceived to underpin operational excellence, which respondents associated with stakeholder value and risk resilience, ultimately culminating in strategic advantage through enhanced decision-making and optimal lifecycle asset performance.

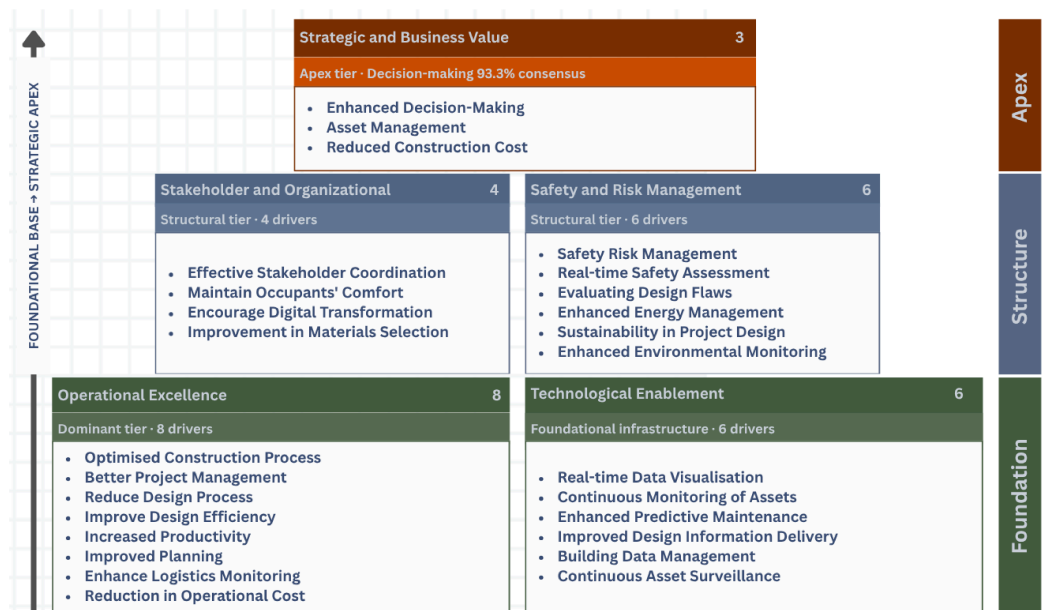


Figure 5. Categorization of the 27 retained DT adoption drivers across the five thematic categories, arranged from foundational (bottom) to strategic (top).

3.3. A Policy Enablement Framework for Digital Twin Adoption Aligned with Bahrain's Economic Vision 2030

3.3.1. Rationale: From Validated Drivers to Policy Levers

The conclusions from Section 3.2 show which factors that the Bahraini construction professionals consider most important for the adoption of DT technology. These conclusions outline the demand side of DT. However, this evidence by itself will not provide answers regarding how the acceleration of DT adoption may occur throughout the entire sector. The answer is simply that the individuals or organizations demanding DT adoption typically do not have the capacity to eliminate many of the structural impediments to the adoption of DT, i.e., fragmented data, inadequate skill levels, lack of standardized procedures and conflicting incentive structures. BIM provides an analogous example. In that case, the government was instrumental in resolving the same type of fragmentation as exists with respect to DT technology [39], through policies that established conditions under which the government could mandate interoperability among various systems. Bahrain offers an example of how governments can use a similar approach to leading integration domestically. The Ministry of Municipalities Affairs and Agriculture, in partnership with the Information & e-Government Authority, has developed a pilot project integrating BIM into the Benayat unified building permit application system. The pilot allows for automated reviews of

design models initially across a set of government and private-sector development projects before wider roll-out [40]. This precedent illustrates that the role of DT in mandating interoperability envisioned above is already being exercised at a smaller scale, through Bahrain's regulatory body. Therefore, a policy framework is required to create conditions that enable the realization of what the industry values, and conditions that a public agency can establish. The distinction is analytical, rather than organizational. Practitioners want enhanced decision-making; the tool that enables them to achieve enhanced decision-making at scale is mandating interoperable data standards. These standards ensure that the basic information contained within DTs can flow across systems [39].

This subsection presents a Policy Enablement Framework which categorizes the 27 validated drivers against the available policy mechanisms utilized by the government and maps these to Bahrain's Economic Vision 2030. There are two boundary conditions to this framework. Firstly, as regards its status, the drivers were validated via expert consensus; however, the mapping of each driver to a specific policy lever was produced via the mini-Delphi process and not empirically validated. Secondly, regarding the listed instruments, these serve to indicate the type of intervention for each level; they do not represent prescribed tools. The BIM policy literature classifies such instruments into Regulatory, Economic, Cooperative, Standard-Based and Communicative categories, and each category can be associated with outcomes [41]; thus, designing the appropriate mix of these for Bahrain would necessitate direct interaction with regulators.

3.3.2. Framework Structure

The three-tiered framework mirrors the driver hierarchy; additionally, several cross-cutting enabling factors affect each of these three tiers. The tiered format replicates the empirically identified hierarchical relationship as reported by the consensus survey; foundational technological and operational drivers have the highest level of agreement and the least dispersion at the top of this hierarchy, while strategic drivers, although also highly ranked, depend on the two tiers below them. In addition to illustrating an empirical hierarchical ordering among the drivers, this pattern is consistent with the Diffusion of Innovation model discussed in Section 3.2 [35], where early adopters focus first on gaining operational and infrastructural advantages prior to achieving greater value. As such, when viewed from the bottom up, the framework represents a series of prerequisites rather than being a selection list for independent options. Figure 6 presents the framework schematically, and Table 3 summarizes the three tiers together with the empirical anchors from this study that justify each tier.

Tier 1: Foundational Enablement

This tier corresponds to the basic technological enablement and operational excellence tiers and represents the foundational level of infrastructure needed for successful DT adoption efforts. The reasoning comes directly from the data: the two most supported items by respondents are "Enhanced Decision Making," and "Continuous Asset Monitoring"; both require a consistent, interoperable, and continuous real-time flow of data. A continuous flow of data is unattainable when information is isolated in different proprietary formats.

Three additional policy tools are being employed as follows. First is the creation of national data and interoperability standards. Second is an investment in common or open data-platform infrastructure to lower the cost barriers for small businesses. Third is a phase-in approach to DT requirements within public sector procurements as opposed to requiring all DT suppliers to meet all the DT requirements at the same time. As experience with BIM has shown, phased-mandate procurement approaches have generally provided some of the largest incentives for private companies to adopt new technologies; this is

largely because government represents by far the greatest single source of funding for these products and services and also establishes the standards for their use [39].

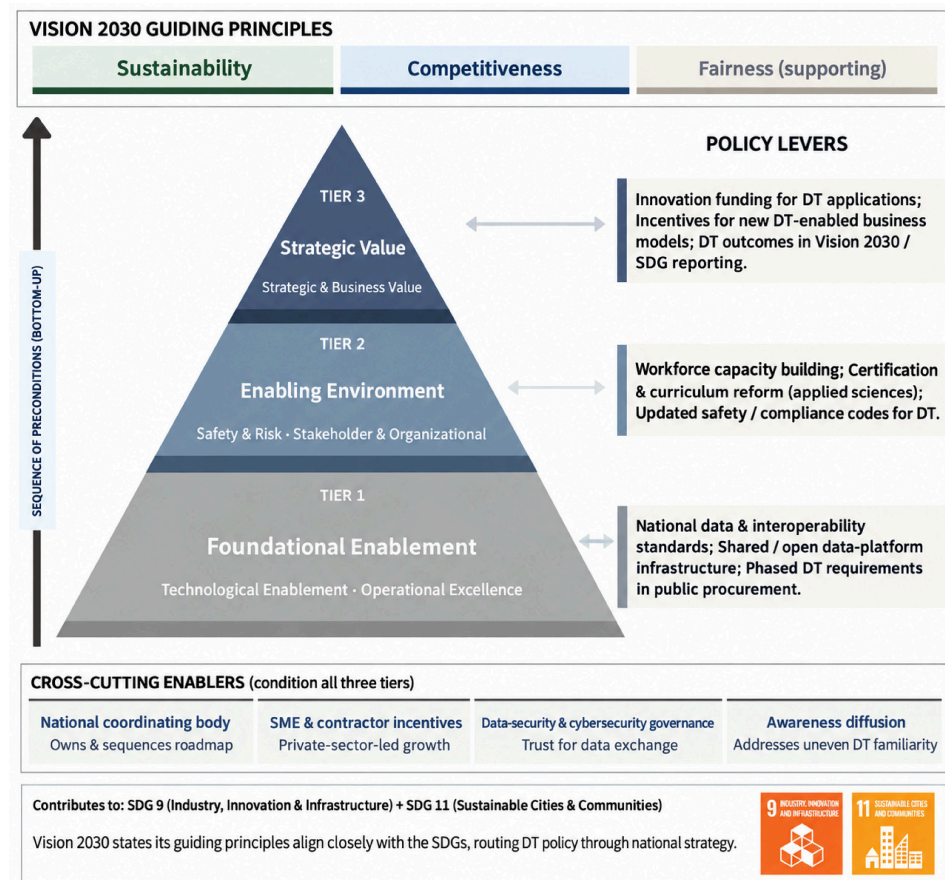


Figure 6. The Policy Enablement Framework: three ascending tiers with a Vision 2030 principal band, cross-cutting enablers, and a policy-lever column.

Table 3. Alignment of Bahrain Vision 2030 principles with DT Policy Enablement Framework.

Vision 2030 Principle/Commitment	Framework Tier	Representative Validated Driver(s)	Illustrative Policy Lever
Competitiveness	Tier 1 Tier 3	Enhanced Decision-Making; Continuous Asset Monitoring	Data/interoperability standards; innovation funding; phased DT requirements in public projects
Sustainability	Tier 2	Environmental Monitoring; Safety Risk Management	Updated safety/environmental compliance codes recognizing DT-based monitoring
Human-capital commitment (under sustainability)	Tier 2	Capacity-related Cross-driver	Certification; curriculum reform in applied sciences; public training investment
Private-sector-led growth	Cross-cutting	Enabling condition	Incentives weighed toward SMEs, contractors and subcontractors
Fairness	Cross-cutting	Governance-level	National coordinating body; transparent standards; fair tendering for DT-mandated works

Tier 2: Creating an enabling environment.

Tier 2 has overlapped in terms of risk-and-safety management and organizational-stakeholders middle tiers; it focuses on the fact that adoption is a social issue as well as a technological issue. Round one of the data clearly shows why capacity building should

be placed at or near the top of the policy agenda as 46.7% of the panel responded that they were familiar with DT concepts but had never used those technologies. It is evident from this response that there was a knowledge-to-practice gap that cannot be closed by infrastructure alone.

The most common ways of addressing such a skills shortfall include government-sponsored skill development schemes, curricula developed to meet industry requirements, and targeted investments in training [42]. As for the tools used to achieve these goals, these include capacity building, reforms to professional certifications and curricula in engineering and the applied sciences, and revisions to current safety and compliance codes to officially acknowledge DT-based monitoring. These goals are consistent with Vision 2030, which emphasizes developing human resources, particularly in the applied science fields as part of its stated objectives [17].

Tier 3: Strategic Value:

This is the tier at which there was an almost unanimous agreement that better decisions would be made by using DT technology. It is at this tier that policy will come into play; as opposed to providing support to organizations to develop and implement DTs, it provides financial incentives to organizations for developing and implementing DT solutions. At this tier, three levers are utilized to provide those incentives: funding for Innovation for Development of DT-Enabled Applications, Incentives for Organizations Developing New DT-Based Business Models, and Reporting of DT Outcomes within National Reporting of Vision 2030 and SDG 9 and 11 [17].

Overarching Enablers:

Four conditions are cut across every tier. The first is a national coordinating organization that is accountable for the roadmap and for coordinating the sequence of interventions. This logic follows from the fact that adoption is achieved through combinations of policy tools rather than one singular directive or mandate [41]. The second is directed financing, directing incentives toward actors with the greatest relative costs of adopting new technology, such as small and medium-sized enterprises, contractors, and subcontractors [42]. These two conditions are aligned with Vision 2030 goals of economic development led by the private sector [17]. The third condition is real-time data exchanged bidirectionally. For this to occur, the data exchanged must be trustworthy. Trustworthiness depends on a credible governance structure for cybersecurity and data security [43]. The fourth condition is awareness. Familiarity with DT remains uneven and fragmented, in this study as in the wider literature, so awareness must be actively built and kept up over time [27].

3.3.3. Institutional Responsibility for Policy Implementation

To translate generic mechanisms into operational policy, each lever can be associated with the Bahraini institution best positioned to implement it. Levers at the foundational tier related to national data and interoperability standards and shared data-platform infrastructure are aligned with the responsibilities of the Information & eGovernment Authority (iGA). The phased digital transformation in public procurement and revised building-code compliance regulations fall under the jurisdiction of the Tender Board and the Ministry of Municipalities Affairs and Agriculture, which would operate in conjunction with the iGA regarding the technical standards. Levers in the middle tier, including workforce capacity building and certification reform, would fit the scope of Tamkeen and Bahrain's higher education institutions. Levers at the apex tier, such as innovation-funding and integrating DT outputs into Vision 2030 and SDG reporting are consistent with the missions of the Bahrain Development Bank for SME and Venture Funding, the Economic Development Board (Vision 2030 Custodian and Cross-Agency Performance Monitoring), and national SDG-reporting channels (NCC/PMO), with EDB providing Vision 2030–SDG alignment

data and Tamkeen and BDB contributing sectoral inputs. This is offered as an illustrative proposition to be tested and refined through consultation with these bodies, rather than a prescriptive assignment of responsibilities.

3.3.4. Alignment with Bahrain's Economic Vision 2030

This framework distinguishes itself from other models by the evidence it provides for how it ties into the country's strategic vision. Vision 2030 is based on the same three pillars: sustainability, competitiveness and fairness. As stated in the vision document, these three are aligned very closely with the United Nations' Sustainable Development Goals [17], allowing this analysis to use SDG 9 and SDG 11 to support this research via a national strategy rather than an additional supporting argument. Table 3 sets out the mapping. The fit is strongest for two of the principles. Competitiveness, which the vision frames in terms of higher productivity and advanced infrastructure, and sustainability, which the vision ties to environmental protection and long-term well-being, both map clearly onto adoption drivers. Accordingly, the framework presents it as a supporting alignment, realized through the governance and coordinating-body enabler, instead of being pushed onto a driver it does not fit. Naming that partial fit is deliberate: it shows the alignment was derived from the evidence, not constructed retrospectively to produce a more coherent fit.

3.3.5. Contextual Policy Considerations

The framework has generated something that is relatively rare: an evidence-supported recommendation for actions that should be avoided. "Improved Retrofitting" was the lowest rate of the excluded drivers, as evidenced by its median score of 3.0 and support from just 26.7% of respondents. As such, it carries very little weight in the context of Bahrain. It is interesting when compared to discussions of DT within Europe and North America; these regions have large stockpiles of historic buildings and therefore tend to preserve many historic structures [36–38].

The key takeaway for policymakers in Bahrain is that they need to take a different approach than the heritage and retrofit focus used in many developed countries when using DT models. Instead of focusing on retrofit and heritage applications of DT models, policymakers need to prioritize applications for newly constructed or greenfield developments, as these are better suited to Bahrain's current stage of development. This has broader implications for how DT model adoption can be driven. The findings of this study indicate that the factors perceived as important to DT adoption in one context are unlikely to be equally relevant in another.

4. Limitations and Future Research

Several important limitations to this study need to be recognized. First, the mini-Delphi used a panel of 15 experts; while consistent with established mini-Delphi practice, this remains a small sample, and the findings reflect the collective judgment of this specific panel rather than a statistically representative survey of the sector. The second limitation was the issue of representation. While most government ministries were approached when recruiting participants, only one participant ultimately took part; thus, nearly all participants in this Delphi study process represented the private sector. Therefore, the Policy Enablement Framework primarily represents the interests of the private sector and does not capture the views of regulatory or policy stakeholders. This limitation has direct implications for the policy focus of the framework, which is why we recommend a second-round Delphi with governmental/regulatory representatives. Third, the Policy Enablement Framework is a conceptual model that provides a logical derivation of the policy instruments from the validated drivers; while built upon empirical findings, the

instruments themselves have not been subjected to expert consensus or empirical testing; thus, they should be considered speculative proposal for possible policy instruments rather than as empirically validated instruments.

The above-mentioned limitations provide direction for further research. An obvious next step would be a second Delphi round with individuals working directly in the government and regulatory sectors of Bahrain to validate, refine, or prioritize the proposed policy tools and assign them to appropriate institutions. Future surveys assessing the applicability of the 27 validated drivers to all stakeholders in Bahrain's construction sector, as well as other GCC countries, could help determine how broadly applicable the identified drivers are.

5. Conclusions

This study contributes to the literature on DT adoption. Using a mixed-method design combining a systematic literature review and a mini-Delphi study, it provides an assessment of DT adoption drivers in Bahrain's construction industry. An SLR of 133 studies led to 81 adoption drivers being categorized into five categories: Operational Excellence, Technological Enablement, Safety and Risk Management, Stakeholder and Organizational and Strategic and Business Value. The mini-Delphi process findings indicated that only 27 of the drivers were considered to have relevance in Bahrain. Therefore, globally recognized drivers of DT adoption are not uniformly applicable and emphasize the necessity of conducting contextual research. Based on these drivers, a hierarchical model was developed comprising Technological Enablement and Operational Excellence at the base, followed by Stakeholder Value and Risk Resilience at the middle level, and Strategic Advantage at the apex. Enhanced Decision Making was the highest-ranked driver, indicating that respondents place substantial importance on timely and reliable information across the project lifecycle. The framework also supports SDG 9, which aims to enable technology and develop resilient digital infrastructure, and SDG 11 through supporting safe, resilient, and sustainable construction processes. Collectively, the research provides four major contributions to the existing body of knowledge. Firstly, it presents a model of DT adoption drivers based on a literature review. Secondly, it validates and prioritizes these drivers for Bahrain through expert consensus. Thirdly, the paper also introduces a conceptual policy enablement framework, which takes the validated drivers from the empirical findings and sequences them as a list of potential policy instruments for government, mapping each instrument onto the three guiding principles of Economic Vision 2030 for Bahrain [44,45]. Although the 27 drivers were confirmed via expert consensus, the policy instruments were generated by means of analytical methods and were not themselves assessed in the Delphi process. As such, the conceptual framework is provided here as a theoretical proposal to assist policymakers, not as an empirically validated set of instruments. Finally, it provides a replicable methodology framework that could serve as a starting point for assessing DT adoption potential in other GCC countries and developing construction markets.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/buildings16204017/s1>, Table S1: List of 70 DT drivers Across Literature; Table S2: Complete Round 2 statistics for all 70 evaluated DT adoption drivers. References [46–127] are cited in Table S1.

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Abbreviations

The following abbreviations are used in this manuscript:

AEC	Architecture, Engineering, and Construction
AI	Artificial Intelligence
BIM	Building Information Modeling
DT	Digital Twin
GCC	Gulf Cooperation Council
IoT	Internet of Things
IQR	Interquartile Range
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SDG	Sustainable Development Goal(s)
SLR	Systematic Literature Review

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