Digital Twins: Towards an Overarching Framework for the Built Environment

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Astrid Bagireanu, Julio Bros-Williamson, Mila Duncheva, John Currie

***Abstract*—**Digital Twins (DTs) have entered the built environment from more established industries like aviation and manufacturing, although there has never been a common goal for utilising DTs at scale. Their assimilation into the built environment lacked its very own handover documentation: how should DTs be implemented into a project and what responsibilities should each project stakeholder hold in the realisation of a DT vision. What is needed is an approach to translate these requirements into actionable DT dimensions. This paper presents a foundation for an overarching framework specific to the built environment. For the purposes of this research, the project timeline is established by referencing the Royal Institute of British Architects (RIBA) Plan of Work from 2020, providing a foundation for delineating project stages. The RIBA Plan of Work consists of eight stages designed to inform on the definition, briefing, design, coordination, construction, handover, and use of a built asset. Similar project stages are utilised in other countries; therefore, the recommendations from the interviews presented in this paper are applicable internationally. Simultaneously, there is not a single mainstream software resource that leverages DT abilities. This ambiguity meets an unparalleled ambition from governments and industries worldwide to achieve a national grid of interconnected DTs. For the construction industry to access these benefits, it necessitates a defined starting point. This research aims to provide a comprehensive understanding of the potential applications and ramifications of DT in the context of the built environment. This paper is an integral part of a larger research aimed at developing a conceptual framework for the Architecture, Engineering, and Construction (AEC) sector following a conventional project timeline. Therefore, this paper plays a pivotal role in providing practical insights and a tangible foundation for developing a stage-by-stage approach to assimilate the potential of DT within the built environment. First, the research focuses on a review of relevant literature, albeit acknowledging the inherent constraint of limited sources available. Secondly, a qualitative study compiling the views of 14 DT experts is presented, concluding with an inductive analysis of the interview findings - ultimately highlighting the barriers and strengths of DT in the context of framework development. As parallel developments aim to progress net-zero-centred design and improve project efficiencies across the built environment, the limited resources available to support DTs should be leveraged to propel the industry to reach its digitalisation era, in which AEC stakeholders have a fundamental role in understanding this, from the earliest stages of a project.

***Keywords*—**Digital twins, decision making, design, net-zero, built environment.

I. Introduction

DIGITAL twins are replicas of a built asset, devoid of a unified purpose across industries. They hold a wide range of applications in multiple sectors, most notably in aviation and manufacturing [1]. Stakeholders can harness the potential of DTs to cater to specific production processes, enabling them to obtain comprehensive insights into an asset for a variety of uses, often within a timeframe relevant to the production process it replicates.

In the last decade, DT were mostly utilised for enabling proactive maintenance, operation diagnosis, and performance testing, contributing to an array of data-driven decision making [2]. Artificial Intelligence (AI) serves as the foundational framework for DT data analytics and simulation capabilities, and presents an ever-expanding array of possibilities for DT deployment across various sectors. This rapid growth in AI capabilities sets a challenge for the built environment industry, which has traditionally exhibited a slower pace in embracing technological innovations [3], [4], thus encountering difficulties in effectively embracing the DT potential. Recent literature shows that particularly for the built environment, the body of knowledge lacks a unified definition and direction for research [5], [6].

As digital data holders, DTs can be characterised by the data relationship between the virtual and the physical asset. Kritzinger et al. classified DTs as Digital Models (DM), Digital Shadows (DS) and Digital Twins (DT) – Fig. 1, highlighting the scarcity of literature on the last DT stage, as well as the interchangeable use of the terminology across the industry [6].

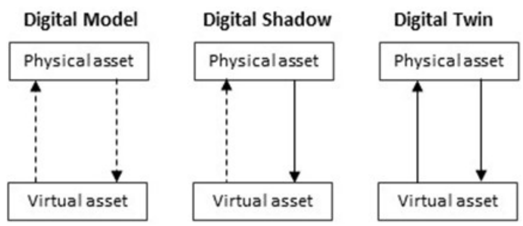

Fig. 1 Categories of DTs [6]

Therefore, DTs are categorised by the data connections between the asset and the virtual replica, and a rich dataset is at the core of DTs. Compared to other industries, the built

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environment data harvesting and effective utilisation remain a challenge due to the fragmentation and lack of standardisation. AEC and project stakeholders tend to work in isolation which leads to data silos, where information is dispersed across multiple platforms, formats, and systems, making it difficult to analyse and control from one single source. There are numerous data formats and conventions, often resulting in inconsistencies and errors. This has been a particular issue with data integration in Building Information Modelling (BIM) and collaborative processes, and it is true with DTs as well [7]. This hampers data reliability and interoperability, making it hard to derive meaningful insights.

Some of the most 'meaningful' insights in the built environment industry pertain to the mitigation of carbon emissions as a response to environmental concerns. In the race towards reaching net-zero targets by 2050 [8], an effective and sustainable utilisation of data plays a crucial role in aligning long-term vision with energy-efficient technologies, renewable solutions, and sustainable carbon reduction strategies, all mutually integrated with economic and social objectives. Data underpin the architecture of DTs, facilitating robust decision-making essential for supporting this vision. Indeed, DTs are seen as instrumental agents in the strategic pursuit of reaching net-zero targets, as they warrant accountability and transparency over carbon strategies implementation, fostering a continuous improvement approach. Traditional designing and constructing practices often fall short in aligning with net-zero objectives due to their limited emphasis on prioritising short-term considerations over long-term energy efficiency thinking. Even with BIM mandated processes, the exchange of information ends with the last construction stage (RIBA Stage 6 Handover), and it is not designed to consider whole-life cycle asset management phases [9]. DTs provide a dynamic representation that extends beyond RIBA Stage 7 (Use), into asset operation, maintenance and even smart city planning and infrastructure interconnectivity. This flexibility for understanding and optimising iterative data is native in DTs, with the built environment now poised to discern the means of harnessing its full potential.

II. Methodology

This paper applied the following qualitative methods: literature review (1), semi-structured interviews (2), and an inductive analysis (3) laying the basis for future research on DT framework development.

1) An analysis of existing scholarly works and industry literature concerning DTs in the built environment, focusing on deriving the characterisation, benefits, and barriers for DT implementation.
2) Semi-structured interviews conducted over a three-week period between 21/10/2022 and 13/11/2022, solicited the views of 14 DT experts in the UK with backgrounds in the built environment, enabling the collection of valuable insights on the interrogation of DT potential across the timeline of a project, following the RIBA Plan of Work 2020 Stages. Semi-structured interview format was chosen as the flexibility allows participants to probe deeper based on their expertise and understanding of the topic [10].

The interview participants represent experts from both academia and industry to ensure the research is representative of the latest developments in science and their applicability in the private sector – Fig. 2. The interviews were undertaken via remote video conferencing and all responses were subsequently anonymised. Further details regarding the background of the interview respondents are provided in Appendix 1.

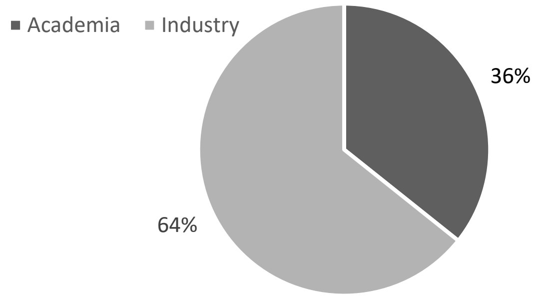

Fig. 2 Distribution of interview respondents

The interviews employed structured methodology with a quantitative Likert scale. This scale comprises a range of responses, from "Strongly Agree" to "Strongly Disagree," each assigned a numerical value from one to six. Participants are presented with statements related to the research objectives and are asked to indicate their level of agreement or disagreement on this scale. This approach enables the systematic collection of participants' opinions and perceptions, quantifying their responses to facilitate data analysis and interpretation [11]. Full question prompts and statements are provided in Appendix 2.

Before the interviews, key definitions and a summary of RIBA Plan of Work 2020 were provided [12]. These are outlined in Table I.

TABLE I
RIBA Project Stages

RIBA Stage	Description	Summary
0	Strategic Definition	Client led stage where requirements, objectives, risk and costs are assessed.
1	Preparation of Brief	Client team develops responsibility matrix, preparation of brief, feasibility study.
2	Concept Design	Team develops basis of design, determine project strategies, determine specialist subcontracting needs.
3	Spatial Coordination	Team considers constructability and spatially coordinated structural design.
4	Technical Design	Final design stage to enable manufacturing, clash detection and resolution.
5	Manufacturing and Construction	Construction begins on site.
6	Handover	Building contract concluded, post occupancy evaluation, and project performance evaluation opportunity.
7	Use	Building operation and maintenance stage.

3) The concluding chapter presents an inductive analysis of the expert opinions derived from interviews, highlighting opportunities for leveraging DT capabilities throughout RIBA Stages. This chapter consolidates insights from existing literature with the interview data, contributing

towards a comprehensive understanding of the potential applications and implications of DT in the context of the built environment.

TABLE II
KEY DEFINITIONS

Term	Definitions provided
DT	The concept of DT refers to the cyber-physical integration of data, and represents a virtual entity for a physical asset or process and the data connections in between them.
Procurement	Procurement in construction projects refers to a contractual relationship between parties which is established for the purposes of purchasing services and goods. In the context of built environment, procurement can be defined as the processes through which a project proceeds from its initiation to completion.
Net-zero	Net-zero refers to achieving a net balance between emitted and removed greenhouse gases from the atmosphere. For the built environment, it refers to the goal of designing, constructing, and operating buildings and infrastructure in a way that results in no net carbon emissions over the asset's entire lifecycle.
Benefits	The perceived advantages realised by implementing DT s, i.e. improved design, user behaviour, manufacturability, efficiency.
Barriers	The perceived challenges encountered by implementing DT s, i.e. cost, lack of knowledge, lack of trust.

This paper is an integral component of a larger research undertaking focused on the development of a comprehensive DT framework tailored to the built environment.

III. LITERATURE

Despite the recognised potential of DTs, defining research on the topic is still in its infancy, notably for the built environment compared to other industries. There is a gap in knowledge of publications to refer to DT potential for the earlier stages of a project (pre-operational) [1], [2], [13]-[15] such as specific to implementation principles [6], [12], [16]. There is a need for a theoretical framework harnessing this data [2], [17]. This can, in part, be attributed to the absence of unified technology or platform for DT [18]. Nevertheless, valuable insights and opportunities can be extrapolated from analogous industries through methods like case studies, simulation studies and early prototypes, as well as by fostering cross-disciplinary collaboration. Research highlights the capability of early-stage DTs to support design simulation and forecasting [12], [15], [19]-[22], coordinate collaboration and collaborative procurement principles [17], [23]-[25], increase transparency among stakeholders [26], assess project feasibility [27], [28] and underpin the enduring value of design choices in alignment with net-zero strategies [28]-[30], overall de-risking of innovation in the built environment [31].

Literature identifies benefits (Table II) and barriers (Table III), which serve as reference points during the subsequent interview process.

IV. INTERVIEWS: INDUSTRY FINDINGS

This section presents a summary of the interview findings, each corresponding to a Key Finding as presented in Table IV. Finally, the closing subchapter 'Digital Twin Framework Opportunities' offers a comprehensive summary of DT opportunities explored with the interview participants for the RIBA Plan of Work stages.

TABLE III
LITERATURE IDENTIFIED BENEFITS

Benefits	Paper(s)	Notes
Supports complex decision making	[7], [15], [32]-[34]	'real-time simulations', 'able to generate realistic forecasts', 'can predict unmodeled and emergent events', 'avoid costly redesign during implementation', 'what-if scenarios'
Increased transparency and stakeholders' collaboration	[15], [28], [32], [34]-[36]	'greater traceability and transparency',' improves the degree of stakeholder participation',' early involvement of construction and asset and facility management experts'
Supports net-zero and decarbonisation goals	[15], [28], [37], [38]	'reduce energy and resources consumption', 'reduces embodied carbon by comparing options'
Supports collaborative procurement methods	[1], [34], [37], [39], [40]	'shared knowledge resource', 'single source of truth'
Supports Modern Methods of Construction (MMC) and off-site manufacturing (OSM)	[41]-[43]	'the anticipation of risks', 'optimisation of techniques and strategies'
Seamless integration with IoT, data analytics and other DT	[9], [17], [32], [34], [44], [45]	'syncronisation and integration', 'transferability of the infrastructure'

TABLE IV
LITERATURE IDENTIFIED BARRIERS

Barriers	Papers	Notes
Cost associated with DT technology	[46], [47]	'digital twins… can be very costly' 'reusability'
Does not work with all procurement methods	[15], [17], [39]	'fragmented and siloed approach' 'no common formats'
Lack of knowledge	[6], [48]	'uncertainty over data ownership', 'unclear user roles', 'ambiguous definition'
Security concerns	[15], [41], [49]	'security and privacy challenges'
Likely to take longer to implement or delaying procurement	[15], [17]	'may lead to missing information', 'disruptions in productivity'
Construction industry's reluctance to change	[48], [50]	'low level of knowledge', 'cultural barriers', 'least digitalised sector'

TABLE V
KEY FINDINGS

Key Finding	Finding summary
1	A majority of respondents rated **Stage 7** RIBA Plan of Work (Use) as the **most important stage** for predominantly realising the DT potential.
2	A majority of respondents rated **Stage 0** RIBA Plan of Work (Strategic Definition) as the **least important stage** for realising DT potential.
3	The majority of respondents anticipate the adoption of DT for the earliest project stages and procurement as being **useful**.
4	The majority of respondents believe that the use of a DT for the earliest project stages **can help achieve net-zero targets**.
5	The main benefit for using DT for the earliest project stages is to **support complex decision making**.
6	The least important benefit for using DT for the earliest project stages is the **seamless integration with IoT and with other DT**.
7	**Lack of knowledge** is the main barrier for using a DT for the earliest project stages.
8	The least important barrier for using a DT for the earliest project stages is the **procurement method**.

A. Key Finding 1

The participants selected RIBA Stage 7 (Use) as the most important stage for harvesting the benefits for a DT, with a consensus between both academic and industry backgrounds. The top three most important RIBA Stages selected were: Use (Stage 7), Handover (Stage 8) and Manufacturing and Construction (Stage 5).

Respondents saw the greatest value in the operational stage, as leading literature suggests, with similar to observations from analogue industries. This dynamic is attributed to the way data accumulate to contribute value, which is best noted in the later stages of a construction project. Additionally, as DT are known for their operational role, this corresponds with RIBA Stage 7; the 'real-time' aspect of a DT, following definition of Kritzinger et al., is truly met when the operational stage becomes functional [6]. Some participants commented that:

> "The biggest value proposition is always in use." – IP06

> "There are a lot of things that that you get out of it each stage if you have a Digital Twin… and the benefits multiply with each stage until it gets to <<Use>>." – IP11.

DTs can also be used to evaluate the alignment between "as-designed" and "as-built" to ensure the sustainable objectives have been met. Through continuous tracking and assessment, stakeholders can learn more about the assumptions they had during the earliest project stages, and inform future stages and projects based on real-time data. DT can foster a cycle of informed decision-making and iterative improvement and ensure that data is utilised in service of its objectives, as mentioned by the participants below:

> "In my view, I think a DT is most useful or suitable for the <<Use>> stage, for Stage 7, because that's when you're getting all the information back." – IP13.

RIBA Stage 7 is also the longest stage, and thus the most complex.

> "The main reason is because (…) operation is the longest stage of the building and so you're more likely to get more benefits. There's also a lot more work that has been put into a digital training for operating buildings." – IP02.

The 'Use' stage is seen as the most important stage for extracting value out of a DT, because it is the stage where the full potential of a DT is realised. Data accumulation tracks progress and highlights continuous improvement opportunities, ensuring long-term targets are achieved in alignment with the project brief and sustainable goals., mentioned as follows:

> "Historically, [in the aerospace industry], when they are doing whole life cycle value assessments, 80%, even 90% of the value sits in operation. There are tangible benefits of course that sit in the early stages, but actually the real investment is in building operation."- IP06.

B. Key Finding 2

Stage 0 was considered the least important stage in harvesting value from a DT, by 86% of respondents. The second and third least important stages are, subsequently, Preparation of Brief (Stage 1) and Concept Design (Stage 2). This corresponds with the limited amount of data available for these earliest stages.

> "A Digital Twin is the amalgamation of information. So, the more information, the more the more data you bring together, the more insights you will get and the more knowledge you will get off the back of that." – IP06.

However, respondents determined that a strong DT foundation needs to be established during Stage 0, one which includes clear project objectives and alignment with strategic goals such as net zero readiness. The success of a DT is influenced by its early implementation, ultimately affecting subsequent stages and amount of data harvested during Use.

A distinction between 'real value' or 'a true Twin' was mentioned in regard to 'live data' by a participant:

> "The real value in [Digital Twins] is through the live data." – IP03.

Although commonly employed, live data can coexist with static data during the earlier stages of a project. Research highlights that data used for simulation and forecasting such as weather data and geolocation data, or data used for concept and technical design such as supply chain mapping, live costing, stock market data etc., indicate that the earliest stages can still support a multifaceted utilisation of data, not solely attributable to Stage 7.

C. Key Finding 3

Existing literature predominantly highlights the presence of DT in operational stages, but it often fails to identify the starting point of DT implementation. Even when designed solely for operational use, the project needs to incorporate and adapt to DT needs in order to demonstrate value during later stages. Most interview respondents (93%) envisioned the implementation of DT during the early-stage design and procurement processes to be a useful addition, where 58% of respondents found it "useful", and 36% of respondents found it "very useful".

> "… the whole idea of doing simulations and abstract designs before you actually do any real work is a big efficiency saving and cost saving, you can test out potential solutions, find out they don't work and… you haven't lost much time or any money. So yes, I think <<Very useful>>!" – IP10.

> "We need more informed procurement and Digital Twins will help." – IP13.

In response to net-zero and specifically energy-efficient strategies, respondents have highlighted how often in practice stakeholders fear innovation, or the perceived risks (and costs) associated with it. Allowing DT to act as a de-risking tool means leveraging its dynamic capabilities to minimize uncertainties, and to help visualise the impact of these decisions may have over the certainties of the project. A participant is noting:

> "Let's take a risk for example… We'll keep it rather simple: Escape distances in a building, for example. Somebody has to hold that risk that the design delivers and complies. So, if the model can demonstrate that, which you could model stuff and understand that it can be done in a very crystal-clear way, then if everybody understands that

the risk has been equalized, then it matters less about who holds that risk. Resolving the risk in the first instance and then there's a discussion on who then holds that risk going forward. And I think the Twin could help with all that." – IP08.

"Where that is risk there is cost. The Digital Twin can be an enabler to de-risking the project."- IP08.

It is also essential to recognise the utility of DT in the early-stage design and procurement processes. Notably, the incorporation of DT during these phases not only proves beneficial in its own right but also lays the groundwork for the eventual development of an operational DT in the future.

D. Key Finding 4

Respondents identified a compelling link between DT and its potential to support net-zero carbon, with 86% of respondents agreeing or strongly agreeing with the statement: "The use of a DT from the inception of a construction project can help achieve net-zero targets."; over 50% of respondents selected "Agree", and 36% of respondents selected "Strongly Agree".

"So, if we did have smooth Digital Twin workflows and capabilities, we should be able to say we planned for net-zero, we reached net-zero, and this is the proof of us getting to net zero. And now that the planned the operation, we can see we've got net-zero... [but] we are years away from that." – IP12

DT can demonstrate net-zero compliance by providing a verifiable trajectory toward net-zero goals. Currently, a significant portion of net-zero strategies remain reliant on conjectures, as the absence of a comprehensive methodology for accurately quantifying embodied or operational carbon emissions hinders accurate assessment. DT offer reliable evidence-based solutions by leveraging data, which can inform future projects or project stages to stay on target. This perspective on achieving net-zero is highlighted by a respondent:

"In some ways it is not even just to achieve [net-zero] on that particular project but how do you use it so that you can deliver net-zero more efficiently on your next project, for example" – IP05.

E. Key Finding 5

DT benefits previously identified in the literature were presented. 50% of respondents selected the most important benefit for DT is to 'Support complex decision making', followed by 'Increased transparency and stakeholder collaboration' and 'Supports net-zero and decarbonisation goals'. Participants ranking is illustrated in Table V.

'Supporting complex decision making' was notably prioritised by respondents with a background in industry, which demonstrated a marginal increase of 7% compared to those with an academic background.

Most identified benefits were seen as a direct response to the effective implementation of DT, leveraging the power of data, as highlighted below:

"Ultimately there should be no situation where [DT] doesn't work, because bringing that information together has to add value. It has to give you a greater insight. You might not know. You might not understand what question you need to ask, but the answer will be in there somewhere, and it's just a case of working out how to how to utilise it and how to try to extract the right set of questions which can give you the answer from the data." – IP06.

TABLE VI
DIGITAL TWIN BENEFITS

Benefit	Participants Ranking
Supports complex decision making (real-time simulations, forecasting abilities)	**1**
Increased transparency and stakeholders' collaboration	**2**
Supports net-zero and decarbonisation goals	**3**
Supports collaborative procurement methods	**4**
Supports Modern Methods of Construction (MMC) and off-site manufacturing (OSM)	**5**
Seamless integration with IoT, data analytics and other DT	**6**

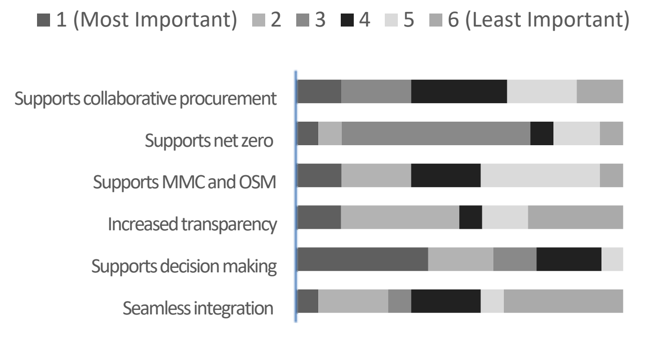

Fig. 3 Participants' selection of DT benefits

F. Key Finding 6

The 'least important' benefit was deemed the 'Seamless integration with IoT, data analytics and other DT', with 43% of respondents in favour. Reasons include integration not being a priority, or an assumed trust in existing managing systems.

"That's probably the least important because it's the last one you would do." – IP06

"Once you're at Stage 7 and beyond, you then get a whole list of different questions, which is migrating from different network connections, different integrations, different systems, different systems of systems, (…)" – IP06.

However, literature and case studies from analogue industries do highlight this as an important concern. Notably, a respondent with cross-sectoral experience articulated:

"When you look at the other sectors that have been using Twins, like the defense industry, even defense contractors are struggling with connecting Twins to one another (…). And even those industries that are spending billions into building a Digital Twin, (…) even they struggle with seamless integration with IoT. So, I think our industry is still far away from achieving that outcome." – IP04.

DT are envisioned to improve human-centred design, and bridge towards smart cities and a smarter built environment, by connecting a purposely built infrastructure of multiple DT. While identified literature noted challenges in achieving seamless connectivity and integration, the current emphasis on initial DT planning tends to overlook future interconnectivity. This has been mentioned as a 'Beyond RIBA Stages' activity, although stakeholders should be mindful of this requirement when formulating and developing DT.

G.Key Finding 7

The main barrier to the utilisation of DTs emerges as the 'lack of knowledge', resonating with 50% of the respondents shown in Table VI. Notably, respondents with a background in industry noted a slight increase of 7% in prioritising this barrier, in contrast to those with an academic background. The second and third most selected barriers were 'Cost associated with DT technology' and 'Construction industry's reluctance to change'. A comparative chart shows the relationship between these barriers as selected by participants in Fig. 3.

TABLE VII
DT BARRIERS

Barrier	Participants Ranking
Lack of knowledge	**1**
Cost associated with DT technology	**2**
Construction industry's reluctance to change	**3**
Security concerns	**4**
Likely to take longer to implement or delaying procurement	**5**
Does not work with all procurement methods	**6**

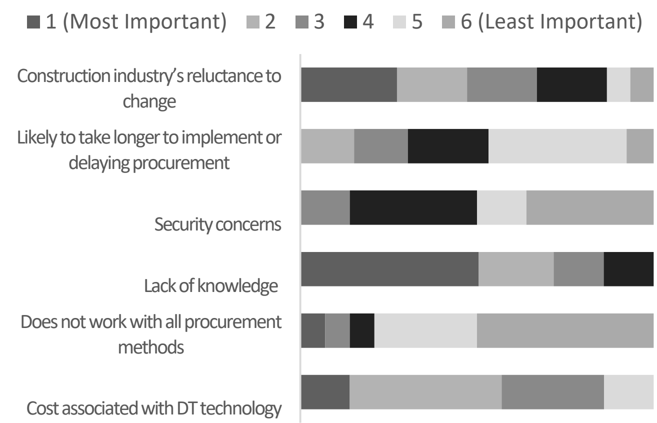

Fig. 4 Participant selection of DT barriers

The inclusion of 'lack of knowledge' as a barrier is not unexpected, considering the limited extent of research on DT in the built environment. Connecting with the previously identified benefits, a participant mentions:

"There is a lack of knowledge about what the benefits could be." – IP11.

This also translates into built environment-specific cultural barriers. The industry has traditionally been slower in embracing digital transformation compared to other sectors. There may be resistance to change, lack of digital literacy, and cultural barriers that hinder the adoption of advanced data-driven practices. However, the "demand" for embracing DT often outpaces the actual process of adaptation, and thus a digital trend is created before it is understood:

"The industry doesn't help itself either. The industry just loves a buzzword. The point where it's now got bored of its own buzzwords. So, it is completely cyclical… You go through these phases where they get really excited by technology and then literally about 18 months later, they're anti-technology (…) It's lack of knowledge and certainty." - IP04.

The 'Cost associated with DT technology' is understood as both perceived cost and actual cost. Respondents noted it is not just about the financial outlay, but also about understanding the value proposition, assessing benefits longer term and exploring alternative funding mechanisms for wider adoption:

"Everyone's saying there's a cost, right? But it's not the cost, it's the unknown value of doing it." - IP12

"But sometimes it's the perceived cost, people just think it's expensive (...) They don't look at the value over the cost (…) They just see the upfront cost but don't actually assess it over the project life cycle in terms of the benefits that it could bring." – IP13.

DTs are praised during the early project stages as a tool for assessing design option scenarios to include the ongoing operational costs into feasibility studies. DT can provide stakeholders with insights into the operational costs of an asset, providing a holistic view that extends beyond the construction phase:

"Procurement tends to be all about the upfront cost of actually building the building. The cost of maintaining and operating that building doesn't tend to be taken into account as much. I think that is somewhere a Digital Twin could be really beneficial." – IP13.

The construction industry's reluctance to change is in part a cultural concern, too. The lessons learned from the industry-wide implementation of BIM and the challenges it faced can also prove a valuable lesson for considering how industry will react to DT vision. Respondents discussed that it likely assumes structural change, especially in regards with technological literacy upskilling needs. Similarly with BIM, realising the DT potential hinges more on systematic changes rather than technology related issues:

"I think it's a [rather] contractual [issue]. I think for Digital Twin to work, you're going to have to get really a huge amount of buying from another companies into your organization. (…) Organizations [will] probably fundamentally have to change." - IP6.

H.Key Finding 8

Respondents have ranked the procurement method as the least important barrier for the utilisation of a DT, with 50% of respondents selecting 'Lack of suitability with various procurement methods' followed by 'Security concerns' with over 36% of respondents agreeing. The reason for this was highlighted as a trust in DTs capabilities of supporting procurement, rather than delaying it:

"We need more informed procurement and Digital Twins will help (…) that's why I've given that [barrier] a six." – IP11.

TABLE VIII
DT FRAMEWORK OPPORTUNITIES

RIBA Stage	Summary of observations
Stage 0	This stage marks the implementation of the DT vision, and it integrates initial sustainability considerations. As primarily an educational stage, stakeholders need to prioritise team upskilling and role assignment for a seamless DT integration. There is no design work at this stage, so different scenario modelling guides early project decision towards framing sustainability objectives. DT also set the foundation for team collaboration and engagement.
Stage 1	DT are tasked with conducting feasibility studies facilitating the creation of the project brief, considering site information and stakeholders expectations. DT can data-back decision making, and ensure brief is not overly prescriptive but serves projects objectives. Feedback from past project data and performance metrics provides valuable insights creation of brief, allowing AEC to visualise and compare potential outcomes longer term.
Stage 2	Design iterations, including simulations and optioneering, are coupled with embodied carbon optioneering. These can revolve around site orientation, MMC strategies, low carbon strategies and their implications across the masterplan.
Stage 3	DT can output iterations based on fixed design elements combined with the unfixed elements such as site-specific elements, façade treatment, below ground design or M&E elements. This can help create project specific design typologies which can be utilised across subsequent phases. The component standardisation means there is early cost certainty at a granular level with potential extension to the broader project for pre-procuring elements.
Stage 4	The project evolves from conceptual and developed design into detailed technical solutions and specifications. This transition involves integrating the low carbon decisions made in Stage 2 and Stage 3 into specifications and tender documents. The DT functions as a project data repository; sharing part of the model for Planning and regulatory purposes optimises data coordination and minimises inefficiencies. A shared DT fosters understanding, detects clashes, and streamlines subsequent stages, including value engineering.
Stage 5	Construction DT (CDT) are closer to the DT from manufacturing industries, particularly as the construction sector undergoes a transition towards more OSM practices. This is especially valuable for assessing the accurate carbon footprint of the asset throughout its lifecycle and uncovering opportunities for future construction strategies.
Stage 6	Handover marks the first performance validation through data transfer and integration into an operational DT. Documentation, manuals and relevant training can also be digitised through a DT. This stage equals an opportunity to allow building users access to DT, especially where energy consumption is user dependent.
Stage 7	Most important stage for leveraging DT capabilities, models can compare 'as designed' with 'as built' and ensure brief set targets and carbon objectives have been met. This stage can inform future phases and projects on the effectiveness of strategies employed, and feed back into AI for optimisation of design optioneering.
Beyond RIBA Stages	Data collected during all stages provide valuable feedback ('lessons learned') for future development iterations. Stakeholders can analyse real time performance against DT predictions, and report back on carbon measurement and progress tracking. A resilient network of DT can contribute to a robust infrastructure and provide a platform for scenario modelling, impact assessment, and the continuous refinement of strategies aimed at minimising carbon emissions including achieving carbon positivity.

Although security concerns appear to be significant in other sectors, the emerging experimental utilisation of DT in the built environment might result in a relatively subdued emphasis on security issues. Participants with an industry background were inclined to prioritise security as a slightly more significant concern, despite both participant categories assigning it a relatively low level of importance. Similarly with 'Lack of suitability for procurement methods', the successful integration of DTs often hinges on broader, more disruptive organizational level changes, such as data management capabilities and contractual alignment, which transcend the scope of traditional procurement methods.

I. DT Framework Opportunities

Interview participants were invited to discuss opportunities for DT integration during each RIBA Stage, whilst assigning rankings to their responses. The respondents' perspectives are synthesised to formulate distinct DT opportunities for each RIBA Stage, presented in Table VII.

V. INSIGHTS AND ANALYSIS: REFLECTIONS FOR FRAMEWORK DEVELOPMENT

The interview findings shed light on both the potential and the challenges of DTs within the built environment. Largely, insight from the interviews corresponded with literature findings, across the participants diverse perspectives, expertise and professional backgrounds. Although the differences between participants with an industry background compared to an academic background were small, this section delves deeper into their concurring or contrasting intersection with literature.

Interview participants see the biggest 'value proposition' in use, which aligns with existing literature, given the prevailing focus on operational DT applications. Directing the discussion towards the earliest stages of project prompted interview participants to consider the impact of these early stages on the realisation on DT principles, thereby addressing a gap in knowledge. While the emphasis on early DT integration may not have been as pronounced in the responses, its value remains significant for several reasons: early stakeholder engagement is key for net-zero realisation, early mitigation of design flaws, de-risking innovative methods of construction to name a few. It was also seen as an opportunity to focus on items AEC stakeholders – particularly designers – never had a chance to prioritise. Participants with a background in industry, particularly IP05, IP08 with expertise in collaborative procurement have highlighted the importance of delegating standardised tasks that DT can manage during the initial design stages. These delegations serve to allocate more time for addressing side-lined tasks, the so-called "nice to have", often of environmental and social nature, and often lost to value - engineering tasks. Visualising risks and enhancing project clarity, especially concerning costs, can mitigate challenges in subsequent stages and foster greater confidence in the adoption of innovative practices.

Across both barriers and benefits discussion, the consensus on 'least impactful' was the procurement method. The responses might have skewed towards other aspects due to various factors, including respondent backgrounds, experience, and indeed, familiarity with novel procurement practices. With the advent of digitalised procurement, e-contracts and alliances, it is possible misconceptions exist between academics and industry practitioners, potentially due to lack of exposure to digitalised procurement. However, despite the consensus rating procurement impact as low, literature underscores its significance. Especially for the realisation of net-zero objectives, novel procurement practices foster increased collaboration, knowledge sharing, and more precise quantification and allocation of risk - factors which participants did indeed mention while discussing the impact of DT on net-zero goals. Further investigation into the interplay of these concepts – collaborative procurement, net-zero and their intersection with DT — warrants exploration in upcoming research endeavours.

The DT benefits selected by participants showed little variation, with the potential to 'support decision making' being selected as most important, mirroring findings in the literature. The participants also highlighted an additional benefit: compliance. As a 'blueprint' of data, DT can prove regulatory, health and safety checks and quality assurance of elements. Another suggestion came from a participant suggesting the utilisation of DT to replace Energy Performance Certification (EPC) and other similar compliance measures. This extends beyond Stage 6 (Handover), and sets a remarkable practical example of DT opportunity in the built environment. The information exchanges identified in literature often focus on the establishment of novel exchanges, and less so on the replacement of existing, inefficient ones. Thus, the creation of a comprehensive framework should encompass both existing and innovative data exchanges.

Further instances of practical DT applications emerged during the examination of barriers. Mirroring literature, participants viewed DTs as a de-risking tool in the uptake of innovation. Participants have discussed how DTs can embody a (contractual, even) demonstration of "*risk ownership*" (IP08, IP06). This can be leveraged during design and procurement stages, operational stages and beyond, encompassing not only the AEC sector but also the supply chain, manufacturers and subcontractors. DT acts as a detailed timestamp, capturing a detailed account of the stakeholder actions, their sequencing, and the corresponding timelines, effectively serving as a comprehensive blueprint of the project' progression. Incorporating this aspect becomes crucial in the context of developing a framework, which should aim to comprehensively cover of the roles and responsibilities of project stakeholders to effectively manage and mitigate risks throughout the project lifecycle.

Among all barriers, 'lack of knowledge' elicited notably distinct perspectives, despite the similar ranking. Whilst the academia respondents mostly saw it as a failure of the technology platforms providers to deliver (and for AEC stakeholders to identify DTs from "*glorified BIM models*"- IP04), participants with a background in industry perceived this barrier as a matter of failing to instil trust in the concept's potential to deliver. These perspectives likely stem from their diverse experience with the concept of DT as an evolving tool; the academic perspective does align with the scholarly endeavours to define, classify, and comprehend DTs, such as Kritzinger DS, DM and DT while the industry counterpart is more inclined to place distrust in prevailing rigid cultural norms [6].

Similarly, 'cost' and 'reluctance to change' were viewed interchangeably by the participants. Their perception is that industry's reluctance is actually an aversion to risk, rooted, to some extent, within the prevailing culture. This is, in part, attributed to industry's low profit margin, which hinders the appetite for innovations. This perception fuelled a specific critique of DTs as predominantly applicable to large organisations or governmental bodies. Similar undertones exist in literature, stemming from factors like data volume, complexity and available resources. These interconnected barriers – cost, risk and cultural reluctance to change – are distinctly manifested within the built environment, highlighting their significance for inclusion in a forthcoming framework.

Some participants (IP01, IP04, IP06, IP10) have mentioned an additional 'lack of standards/lack of framework' as one of the biggest barriers to DT adoption. IP10 recognised that the absence of standards not only hampers large-scale transformation but also adds to the ambiguity surrounding the definition of DT within the built environment. Literature has called for a theoretical framework ever since Kritzinger et al. paper in 2018, therefore the participants' call for standards resonates with the ongoing discourse in the literature [6].

In the discourse within manufacturing literature, the operational stage often envisions an implied user in the form of an asset manager or administrator. The built environment is different in this regard due to its inherent fragmentation and asset lifecycle which likely involves multiple users interacting with the DT and with one another. Identifying user roles is crucial for a comprehensive framework and should be delineated for each project stage. This undertaking holds significance not only in terms of shaping the overall operational context but also in terms of data ownership, as highlighted by literature.

In the context of manufacturing and analogue sectors, discussions about asset performance typically revolve around the 'Use' stage, considering the perspective of the intended user and the value added by a DT. However, understanding the 'true' performance of a built environment asset entails recognizing distinct viewpoints. For instance, a managing local authority's perspective differs from that of a homeowner, a tenant, an asset manager, a building operator, and that would differ throughout project stages and the lifecycle of the asset. Essentially, there is a link to be made between the 'true' performance of the asset and the value (or the improvement opportunity) of the asset. There could be multiple value propositions to explore simply based on value added and the user role. The DT serves various roles in this scenario. For homeowners, it replaces the traditional home report and contributes to increased asset value and subsequent pricing. Tenants and building users benefit from real-time operational insights visualising cost, carbon, and other projections. Transitioning to a DT infrastructure could lead to incentives like council tax adjustments based on home performance or product-specific discounts for contracting alliancing. Establishing a link between value and performance becomes pivotal in the pursuit of achieving net-zero objectives, and this aspect should be integral to a comprehensive framework.

A. Reflections for Framework Development

This study underscores the iterative utility of DTs throughout project stages, identifying unique prepositions, challenges, and benefits. This paper contributes to a larger research endeavour focused on establishing a comprehensive DT implementation framework for the built environment. This section will succinctly outline the key framework considerations for this advancement.

The semi-structured nature of the interviews allowed for a flexible discussion around each question, drawing insights from participants' diverse expertise in DT applications. It has been important in discussing each project stage, following the RIBA model, and identifying unique opportunities. These findings need to be systematically organized across a project timeline, stage by stage, to emphasize the iterative utility of DT and its continuous value compounding throughout project progression. This is particularly relevant for framework development given the interconnected and sequential nature of design, procurement and constructing tasks. It is not merely a matter of maintaining chronological coherence, but it also introduces a visualisation dimension for good practices around data management and early-stage collaboration.

Several emergent themes emerge for the development of the framework:

1) Early DT lifecycle integration: The framework should emphasise Stage 0 DT adoption in alignment with collaborative procurement principles.
2) De-risking and risk ownership: The framework should identify stage-specific risk mitigation approaches and their impact on cultural behaviours and attitudes to risk.
3) Inclusive stakeholder roles and responsibilities: The framework should adopt a user-centric approach, fostering collaboration and clear responsibilities.
4) Collaboration and knowledge sharing: The framework should promote stakeholder collaboration, knowledge and best practice sharing.
5) Enhancing DT understanding and value propositions: The framework should demystify and leverage on DT benefits for its use by highlighting practical core tasks, and ensuring clarity on DT contribution throughout project phases.
6) Collaborative governance structure: Framework should highlight DT's reliance on a governance structure that fosters collaboration, accountability, and transparent decision-making.
7) Data exchanges, data management and data visualisation: The framework should emphasize good practices around data exchanges, addressing the importance of effective data handling throughout the project lifecycle.
8) Procurement and collaboration: Despite a consensus on low procurement impact, the framework should explore the synergy between novel procurement practices and net-zero objectives, illustrating the specific DT opportunities within this context.
9) Feedback loops and continuous learning: The framework should establish continuous feedback loops for ongoing refinement of DT applications, fostering adaptive learning, 'lessons learned' and improvement throughout project stages.
10) Interconnected barriers: Framework should address the identified barriers and strive to alleviate their impact on DT integration.
11) Scalability and seamless data integration with systems, projects, and phases: Framework must cater to projects of diverse scales and complexities, enabling both expansion and contraction. Modular DT components can enhance adaptability and scale integration. Integration should extend to existing systems such as for demonstrating compliance and regulatory assurance.

These considerations lay the foundation for advancing towards a comprehensive DT framework initiative. These requisites, stemming from the intersection of industry and academia perspectives, highlight the significance of nurturing a robust framework to facilitate the realisation of DT progress within the built environment.

Appendix I

TABLE IX
Interview Participants Profiles

Identifier Profile	Background	Professional Overview
IP01	Industry	Business Development Manager for a large OSM company in the UK, facilitating biomaterials and net-zero digital tools.
IP02	Academia	Reader at a university in the UK with expertise in construction and infrastructure data management. Leads a research laboratory using innovative reality capturing technology.
IP03	Industry	Director of Projects for a Virtual Reality (VR) and AI firm in the UK, responsible for the development and delivery of large-scale DT projects in UK the Middle East region.
IP04	Academia	Possessing extensive industry experience, they led multiple research projects for the EU Commission and UK Research and Innovation (UKRI) on DT business models.
IP05	Industry	Associate Director for a public body organisation of the Scottish Government. Previously lead the development of various housing schemes across Scotland for Local Authorities and Registered Social Landlords, pioneering net-zero strategies through collaborative procurement methods.
IP06	Industry	Chief Product Officer for a digital platform in the UK, owning their overall product development strategy incorporating many aspects of project management, design, procurement and engineering. Founding member of one of the largest applied visualisation forums in the UK.
IP07	Academia	Industrial Researcher Fellow with active research activities in DT, including the largest DT tunnel systems in Europe.
IP08	Industry	Senior Associate Director in a public body organisation of the Scottish Government. They lead an infrastructure technology team and have experience in both DT and collaborative procurement.
IP09	Academia	Research Fellow at a UK university with expertise in DT sensoring OSM elements for new builds.
IP10	Academia	Lecturer and Head of Computer Systems at a UK university, leading several commercial design and development projects, including a DT research laboratory.
IP11	Industry	Leading innovation projects for the Scottish Government Digital Strategy, within the Building Standards Division at The Scottish Government.
IP12	Industry	Director of Digital Integration in the UK for one of the companies pioneering DT applications in the world, owning one of the few fully functioning in-house DT.

IP13	Industry	Head of Digital at a non-profit organization dedicated to facilitating the UK built environment's transition to net-zero.
IP14	Industry	Director of Enterprise for a DT visualisation company in the UK, with a background in architecture and design.

Appendix II

TABLE X
INTERVIEW QUESTIONS

Iteration	Questions
Q1	In which project stages do you consider Digital Twins most suitable for? Please number them in order of importance, with 1 being most important and 8 being the least. 1) Strategic Definition (RIBA Stage 0) 2) Preparation of Brief (RIBA Stage 1) 3) Concept Design (RIBA Stage 2) 4) Spatial Coordination (RIBA Stage 3) 5) Technical Design (RIBA Stage 4) 6) Manufacturing and Construction (RIBA Stage 5) 7) Handover (RIBA Stage 6) 8) Use (RIBA Stage 7) Please discuss your answer.
Q2	How useful do you anticipate the adoption of Digital Twin for the earliest project stages? 1) Very useful 2) Useful 3) Neutral 4) Not useful 5) Not very useful 6) Don't know. Please discuss your answer.
Q3	To what extent do you agree with the following statement: *"The use of a Digital Twin during the earliest stage of a construction project can help achieve net-zero targets."* 1) Strongly agree 2) Agree 3) Neutral 4) Disagree 5) Strongly disagree 6) Don't know. Please discuss your answer.
Q4	What do you think are the main benefits of using a Digital Twin during the earliest stage of a construction project? Please number them in order of importance, with 1 being most important and 6 being the least. 1) Supports collaborative procurement methods 2) Supports net-zero and decarbonisation goals 3) Supports Modern Methods of Construction and off-site manufacturing 4) Increased transparency and stakeholders' collaboration 5) Supports complex decision making (real-time simulations, forecasting abilities) 6) Seamless integration with IoT, data analytics and other Digital Twins. Please include any other benefit not listed. Please discuss your answer.
Q5	What do you think are the main barriers in using a Digital Twin during the earliest stage of a construction project? Please number them in order of importance, with 1 being most important and 6 being the least. 1) Cost associated with Digital Twin technology 2) Does not work with all procurement methods 3) Lack of knowledge (uncertainty over data ownership, unclear user roles) 4) Security concerns 5) Likely to take longer to implement or delaying procurement 6) Construction industry's reluctance to change . Please include any other barrier not listed. Please discuss your answer.

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