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BALANCING DECARBONISATION AND CLIMATE RESILIENCE THROUGH LEAN AND DIGITAL TWINS

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ABSTRACT

The construction sector is a major contributor to global carbon emissions and is also highly vulnerable to the impacts of climate change. Balancing decarbonisation with climate resilience has emerged as an important industrial goal. However, both these objectives are usually addressed independently in current practices and research, with limited attention to integrated strategies. The synergy between Lean methodology and Digital Twin technology has been explored in this study that can help balance decarbonisation and climate resilience in construction projects.

A qualitative research design was adopted, including a systematic literature review and semi-structured interviews with five industry experts. The findings suggested that Lean and Digital Twins can complement to balance decarbonisation and climate resilience, but their adoption is influenced by organisational and cultural hurdles, stakeholder influence, and strategic integration for long-term benefit. They also indicated that climate resilience is frequently considered as a secondary objective, underlining the importance of a framework that combines Lean and Digital Twins to successfully balance decarbonisation and climate resilience. The findings of this study facilitated the establishment of a proposed framework that presented Lean and Digital Twins as equal promoters for balancing decarbonisation and climate resilience, rather than focusing solely on efficiency improvements.

KEYWORDS

Climate resilience, decarbonisation, digital twins, lean construction, sustainability.

INTRODUCTION

The construction and built environment sector contributes to about 38% of global carbon emissions (United Nations Environment Programme (UNEP), 2024). Climate change is a rising concern, with climate-related disturbances affecting more than 85% of the world's population (UN-HABITAT, 2024). In this context, decarbonisation and climate resilience are frequently presented as related objectives (Sesana & Dell'Oro, 2024). Decarbonisation refers to achieving net-zero greenhouse gas emissions by eliminating the anthropogenic release of greenhouse gases, particularly carbon dioxide (Deloitte, 2021). In parallel with decarbonisation, climate resilience in the construction sector is typically characterised as the constructed asset's ability to anticipate, absorb, adapt to, and recover from climatic effects climate-related hazards such as heatwaves, flooding, and extreme weather events (Aduwa et al., 2025).

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Early planning and design-stage choices affect both decarbonisation and climate resilience and include material selection, system configuration, construction methods, and asset lifespan. They are crucial in determining overall carbon performance and long-term environmental adaptability, thus facilitating the adoption of low-carbon materials and adaptive and responsive strategies (Khatib & Chileshe, 2025). However, rather than being limited to a single design parameter, decarbonisation and climate resilience span all project lifecycle stages, requiring decisions that reduce greenhouse gas emissions and enhance adaptability, durability, and long-term performance under changing climatic conditions (Seidu et al., 2025).

Decarbonisation and climate resilience are recognised as performance attributes that must be defined, acquired, examined, and tracked across the project lifecycle, including planning, design, construction, and operation (Aduwa et al., 2025). In addition, addressing them separately and not as integrated lifecycle objectives may lead to missed opportunities and wasted effort (Tetik et al., 2019).

Lean methodology enhances value by minimising waste, improving efficiency, and promoting collaboration as it operates across four levels: philosophy, principles, methods, and tools (Owais et al., 2024). Its philosophy emphasises respect for people and continuous improvement (Kaizen); principles include flow and visual management; methods involve LPS and Takt planning; and tools such as Value Stream Mapping (VSM), Plan-Do-Check-Act (PDCA), Target Value Design (TVD) and Just-in-time (JIT) that support practical implementation, improving time, cost, and resource performance (Owais et al., 2024). A Digital Twin is a real-time digital version of an actual structure that links the physical and virtual worlds. It allows for continuous data interchange, monitoring, and analysis (Araújo et al., 2022). In construction, Digital Twins aid decision-making processes, 3D & 4D simulations, performance evaluation, sequencing, logistics modelling and predictive insights through predictive simulations, historical data, and scenario-based analysis, hence enhancing efficiency, safety, and overall project management (Alnajjar et al., 2025; Araújo et al., 2022).

The construction industry functions as a complex and dynamic system that encompasses multiple stakeholders, processes, and independent activities across different project phases (Bajare et al., 2025), where risks and performance outcomes are interconnected (Aduwa et al., 2025). Decisions taken at each phase impact the overall performance and delivery of construction projects, which often cover the lifecycle (Popovychenko et al., 2024). As a result, these decisions also influence both carbon emissions and climate resilience performance, highlighting the need to consider these aspects in an integrated manner.

LITERATURE REVIEW

A summary of the literature review related to lean & digital twins for decarbonisation & climate resilience, is presented in the following three key themes.

DECARBONISATION AND CLIMATE RESILIENCE IN THE CONSTRUCTION SECTOR

Construction is frequently described in the literature as being carbon intensive. This is because of the energy use, the creation of materials, and the complex structure of project supply chains. Thus, making it a crucial industry for undergoing change (Sesana & Dell'Oro, 2024). Climate estimates, which indicate the possibility of exceeding the 1.5°C warming barrier by 2035 show the necessity of major changes in emission-intensive industries like the construction sector (Das & Ghosh, 2023).

In this context, decarbonisation and climate resilience are frequently presented as related objectives. Management seeks to lower carbon emissions (both operational and embodied), while resilience concentrates on making sure infrastructure and buildings can endure, adjust to, and recover from the effects of climate change (Sesana & Dell'Oro, 2024). However, an

ongoing concern in the literature is that decarbonisation and climate resilience are usually viewed as distinct goals in evaluation methodologies, planning, and delivery procedures (Tetik et al., 2019). This segregation can lead to fragmented strategies. The construction sector focuses on carbon reduction through design and material choices while neglecting or dismissing resilience issues, especially during the construction and operating stages (Pikas et al., 2024).

Sesana & Dell'Oro (2024) have provided an interesting example of this fragmentation. They argue that existing evaluation methodologies frequently focus on energy efficiency and compliance while failing to appreciate the overall potential of decarbonisation and climate resilience. Their PRISMA-based assessment finds no evidence of frameworks that thoroughly examine both criteria in an organised manner.

Throughout the reviewed literature, a variety of decarbonisation approaches are proposed. These include recycled and circular materials, engineered timber products, and carbon capture solutions to reduce embodied emissions. They also include design measures such as improved interiors, environmentally friendly approaches, and the incorporation of renewable energy to lower operational emissions (Dixit & Stefańska, 2024). However, transforming these technical alternatives into uniform project delivery criteria requires coordinated effort. It involves efforts from financiers, designers, manufacturers, and contractors, which highlights business inefficiencies and governance fragmentation (Jaglan & Korde, 2023). This provides credibility to the idea that decarbonisation is more than just a technological difficulty. It is also a management and coordination concern that necessitates related roadmaps and decision-making procedures.

A frequent subject in the literature is the ongoing implementation gap between the idea of design and real-time delivery. According to studies, delays in communication and a lack of real-time monitoring during construction typically impair sustainability and performance goals, especially for energy-efficient structures (Piaia et al., 2024). While digital technologies like BIM, AR, and Industry 4.0-enabled inspection systems can help close these inefficiencies, the literature consistently shows that technology alone is insufficient in the absence of aligned processes and stakeholder coordination (Pikas et al., 2024). This validates lean construction concerns that fragmented planning and poor production management hinder the delivery of value. The findings underline the need for integrated socio-technical systems that include digital technologies, process integration, and collaborative project governance for effective decarbonisation and climate resilience (Tetik et al., 2019).

Besides developments in technology, literature emphasises organisational, cultural, and institutional aspects as essential facilitators of decarbonisation and climate resilience. Knowledge gaps in civil engineering education, as well as a lack of exposure to circular building and climate adaptation, hinder workers' ability to compete (Calle Müller et al., 2024). Short-term project frameworks, fear of risk, and fragmented stakeholder connections all contribute to the difficulty of coordinating climate action. Climate resilience results are highly influenced by professional decision-making, cross-sector collaboration, and supporting policy frameworks (Onus et al., 2025). These issues get worse in underdeveloped countries, where resources, institutional capability, and policy coherence remain scarce and highlight the need for integrated frameworks that link technology, lean processes, governance, and the enhancement of capabilities (Das & Ghosh, 2023).

LEAN CONSTRUCTION AND DECARBONISATION

Lean construction has been characterised as a systematic method to reduce waste, improve efficiency, and enhance project delivery performance. Lean construction is based on lean manufacturing concepts such as value maximisation, continuous improvement, and the removal of non-value-adding processes (Sarhan & Pretlove, 2021). The review of literature on lean and decarbonisation revealed that waste minimisation and process optimisation reduce resource consumption and emissions while enhancing time and cost performance (Pozzer et al., 2025).

However, sustainability activities in construction have been driven by certification frameworks such as BREEAM and LEED (Pikas et al., 2024). Whereas lean methods are frequently viewed largely via efficiency targets (Sarhan & Pretlove, 2021). A repeated finding is that using lean and sustainability toolkits separately could mean missing out on the larger value that can be produced with system and process integration (Sarhan & Pretlove, 2021). This is consistent with Chen et al. (2024), who identified synergies between lean and sustainable construction (waste reduction, cost savings, safety improvements).

Connecting lean construction approaches to environmental objectives is paramount. It can't be assumed that efficiency gains simply result in emission reductions. Braglia et al. (2024), demonstrated this change using the Greenhouse Gas Emissions Deployment (GED) strategy. It adjusts manufacturing cost expenditures to specifically target emissions that cause losses in production. This shifts sustainability from a regulatory burden to an operational advantage. Empirical studies support the relevance of early-stage decision-making, with design simplification found as a particularly effective lean element for carbon reduction (Pozzer et al., 2025). However, the literature suggests that lean methods may accidentally increase carbon intensity depending on energy usage, logistics, and surroundings, emphasising the importance of lifecycle-based review when implementing lean for decarbonisation (Pejić et al., 2023).

Lean construction is also embedded in wider environmental and governance objectives. Hasan et al. (2024) demonstrated how lean principles correlate with the UN Sustainable Development Goals. They not only improve environmental performance but also transparency, accountability, and institutional governance. Similarly, Wu & Feng (2012) suggest that limited, client-oriented theories of value hinder lean's ability to meet broader societal and environmental goals, and advocate for broadened value ideas across the project lifecycle. Digital integration enhances Lean's sustainability effect. According to (Pejić et al., 2023), combining lean concepts with BIM and digital technologies improves coordination and decision-making. It ultimately aids decarbonisation initiatives. Overall, literature portrays lean construction as a powerful enabler of decarbonisation. This happens when environmental goals are rooted in lean processes and supported by organisational learning and digital technology (Hasan et al., 2024).

DIGITAL TWIN AND CLIMATE RESILIENCE IN CONSTRUCTION

The literature generally recognises Digital Twin technology as a promising tool for improving climate resilience in building and infrastructure systems. Digital twin uses real-time sensor data. It also uses sophisticated modelling, and simulation to help with asset lifecycle monitoring, forecasting, and scenario-based decision-making. Riaz et al. (2023) studied the expanding use of digital twins in disaster management, infrastructure maintenance, and urban planning. They also highlight it for dealing with climate-related risks including severe heat, flooding, and storms. Their findings emphasise the need for early warning systems, dynamic simulations, and scenario modelling for proactive risk management and adaptive responses to climate change. These characteristics establish digital twins as a critical tool for moving from reactive to anticipatory resilience planning in the built environment (Riaz et al., 2023).

Despite this, there is limited adoption of digital twins. Many systems remain conceptual, with little maturity in delivering strong two-way data flow between physical assets and their digital representations (Riaz et al., 2023). Allan et al. (2024), cite findings from the Melbourne Forum on Digital Infrastructure for Climate Resilience. They claim that urban digital twins and large-scale data analytics may greatly contribute to Sustainable Development Goal 11 (sustainable and resilient cities). However, it is emphasised the need for aggressive deployment, strong government leadership, and successful cross-sector cooperation. Fragmented stakeholder collaboration, legal ambiguity, and variable data quality are persistent challenges. These challenges limit the scalability and practical application of digital twin systems (Allan et al., 2024).

Additional studies broaden this approach by placing digital twins into integrated digital ecosystems. Argyroudis et al. (2022), underline the joint significance of Digital Twins, IoT, AI, and BIM in enhancing the climate resilience of vital infrastructure. They highlight that systems targeted just for efficiency frequently lack flexibility. Digital twins use automated forecasting and real-time monitoring to improve efficiency and resilience. But their performance is dependent on shared standards, collaborative platforms, and an awareness of system interactions (Argyroudis et al., 2022). Practical applications, such as evacuation simulations and flood and drought prediction systems (Henriksen et al., 2023), highlight the benefits of scalable models and feedback mechanisms. Still, organisational impediments remain. These include uncertainty about BIM and digital twins, skills shortages, cost concerns, and a lack of standards (Henriksen et al., 2023). Real-world examples, such as the smartBRIDGE project, demonstrate that digital twins have the potential to greatly improve safety, maintenance, and long-term infrastructure performance (Wenner et al., 2022).

SYNTHESIS AND RESEARCH GAP

The literature across the reviewed themes revealed that decarbonisation in construction and climate resilience necessitate coordinated policies rather than fragmented mitigation and adaptation efforts (Sesana & Dell'Oro, 2024). Lean construction provides process-based methods to minimise waste and increase flow. This can help with decarbonisation when value concepts are directly incorporated into environmental objectives (Hasan et al., 2024; Wu & Feng, 2012). Digital twins provide modelling, monitoring, and prediction capabilities. It can aid in climate resilience planning and risk-conscious decision-making, but it confronts implementation challenges due to standards, skills, data quality, and governance (Riaz et al., 2023).

Despite their complementary potential, significant research gaps exist. First, there are a few integrated initiatives that explicitly use Lean with Digital Twins to address both decarbonisation and climate resilience. Second, climate resilience is frequently isolated from decarbonisation goals and considered as a distinct or secondary priority. Third, there is still a gap between the development of theoretical frameworks and digital breakthroughs in the literature and their actual use in active construction projects. These limitations emphasise the need for an integrated and practical framework that combines Lean and Digital Twins to assist the balanced delivery of decarbonisation and climate resilience in construction projects.

RESEARCH METHODOLOGY

This study adopted a qualitative research approach using semi-structured interviews to capture in-depth, practice-based insights from construction professionals. The exploratory nature of the research justified the use of qualitative methods (Gray, 2022; Robson & Robson, 2024) , with insights from a targeted systematic literature review informing the development of interview questions and interpretation of findings.

The study's specific objectives were to:

1. To explore the synergies between Lean and Digital Twins in construction projects in relation to sustainability objectives.
2. To identify the key organisational, technical, and practical challenges associated with implementing Lean and Digital Twin approaches in construction projects aimed at decarbonisation and climate resilience.
3. To propose a conceptual framework for integrating Lean and Digital Twin approaches to balance decarbonisation and climate resilience in construction projects.

Primary data were gathered through semi-structured interviews with construction professionals involved in project execution, sustainability, and digital implementation and were

all located in the United Kingdom. Semi-structured interviews were chosen to provide for flexibility in analysing participants' perspectives while ensuring consistency throughout interviews (Adams et al., 2015). Interviews were held online and lasted between 40 and 45 minutes, with participants from various professional backgrounds.

Participants were selected using purposive sampling for their direct construction project experience and knowledge in Lean, digital technologies, sustainability, or climate-related management. They also had at least three years of professional experience. A total of five semi-structured interviews were conducted with industry professionals representing diverse roles within the construction sector. Participants were anonymised as P1-P5 to maintain confidentiality. Table 1 summarises their profiles, including experience, sector, and familiarity.

The semi-structured interviews had been designed in accordance with the research objectives and included 8-10 open-ended questions. The questions were divided into three categories: descriptive questions to investigate current practices related to decarbonisation and climate resilience, reflective questions to capture participants' experiences and perceptions of Lean Construction and Digital Twins, and scenario-based questions to investigate potential integration approaches. This structure made sure that all research questions were approached in a methodical manner. Table 2 includes a brief interview guide detailing the structure of the questions, as well as examples of interview questions.

An inductive thematic analysis supported by NVivo software tool was used to analyse interview data. The transcripts were examined several times, and codes were created entirely from the data, with no predetermined themes. Similar codes were iteratively sorted into themes. Coding was done by a single researcher, with continuous comparisons between transcripts to maintain uniformity. Themes were developed until no new patterns emerged, indicating saturation, and with the addition of representative quotes. The results were then interpreted considering insights from the literature. This allowed for analytical triangulation, which strengthened the credibility of results. It also guided the creation of the proposed conceptual framework.

DATA ANALYSIS & RESULTS

This section presents the results of a thematic analysis of data collected from five semi-structured interviews. The interview data were processed using an inductive coding method assisted by NVivo software tool. Five major themes were discovered, along with one additional emergent insight about participants' perspectives on the integration of Lean and Digital Twins. The themes are presented in Table 3, supported by verbatim quotes from participants to ensure transparency and traceability of the analysis.

Overall, participants indicated a complementary relationship between Lean and Digital Twins, with process efficiency and data-driven insights supporting project delivery. Decarbonisation emerged as a central driver, frequently emphasised owing to its measurable nature and connection with project objectives, while organisational, cultural, and stakeholder problems were suggested as important barriers to effective integration. Early and purposeful implementation of Lean and Digital Twins was deemed crucial for long-term success. Another emerging insight suggests that climate resilience receives very little attention in the contexts studied, either being viewed as a secondary outcome or confused with sustainability.

Table 1: Participants' profile

Participants	Role / Position	Total Experience (Years)		Project Types Delivered	Number of Projects Delivered
		Industry	Lean + Digital Twin		
P1	Senior Project Manager	8	5	Residential, infrastructure (roads, bridges), commercial buildings	5
P2	Senior Mechanical Design Engineer	9	4	Building services, HVAC systems, commercial and institutional projects	6
P3	Technical Director	11	6	Large-scale infrastructure and multidisciplinary construction projects	8
P4	Section Engineer	4	2	Road construction, site execution (urban and rural projects)	2
P5	Design Lead	3	3	Architectural and engineering design, commercial and residential projects	2

Table 2: Sample interview questions

Question Type	Sample Questions
Descriptive	How are decarbonisation and climate resilience addressed in your projects?
Reflective	What combined benefits have you observed between Lean and Digital Twins?
Scenario-based	What approaches could support better integration of Lean Construction and Digital Twin?

Table 3: Summary of themes and supporting participant quotes

Major Themes	Participant Quotes
1. Roles and synergy of Lean and Digital Twins	*"... is to maximise the value and also minimise waste. So all of our projects have got those objectives, and obviously, the most effective way to maximise that value is by using digital tools. So, yes, I can say there is definitely an overlap". (P1)* *"... lean and digital to complement each other by bridging process efficiency with real-world performance". (P3)*
2. Sustainability and decarbonisation as central drivers	*"... again combining both of these lean construction and digital tools, it definitely helped us identify what key priorities are because again, for reducing carbon, you need to understand what the objectives from the beginning, what you are trying to gain". (P1)* *"... why wouldn't we put something in there which will last for a 100 years because you're reducing replacements and manufacturing processes".... (P3)*
3. Organisational and cultural barriers and challenges	*"... Oh, definitely, yes, because the first thing is cost, when you adopt digital tools, there is a cost associated with it". (P1)* *"... Yeah, I think cultural resistance as well, I think the whole generation of industry, the experience we have in the industry at the moment, it's quite 50, I think most of the experience is in to 60s old". (P5)*
4. Stakeholder influence and alignment	*"... if the main contractor is well equipped to adopting lean construction principles or using BIM models or Digital twin, it just makes it so much easier for the entire team to adopt it". (P1)* *"... government and the stakeholders need to sit down and truly decide what they want to do". (P4)*
5. Strategic integration for long-term value	*"... if one contractor is really good at working on site, or both of them are good at working on site, but one of them has a clear advantage because they've delivered ten other projects with a digital twin". (P1)* *"... earlier is how you monitor your budget, to be honest, how you need to make sure your workforce is well equipped, embedded between these two approaches from the early stages and also throughout the whole project cycle". (P4)*
6. Limited consideration of climate resilience (Emerging Insight)	*"... we need to show how much carbon, the carbon footprint of the asset we're designing". (P1)* *"... limited understanding of strategies, how to incorporate climate resilience considerations into construction projects". (P5)*

DISCUSSION

This study explored the use of Lean and Digital Twins as facilitators for balancing decarbonisation and climate resilience in construction projects. The findings suggest that, while both are increasingly being used in practice, their combined use remains limited.

Participants frequently identified carbon targets, efficiency indicators, and waste reduction tactics as significant drivers of Lean and Digital Twins adoption within their project contexts. This supports existing literature (Pozzer et al., 2025), indicating that carbon reduction often takes priority in sustainability goals because it can be quantified and included in project controls. However, the findings suggest that this approach limits the use of both Lean and Digital Twins to efficiency and carbon reduction, rather than broader climate resilience goals.

The organisational and cultural challenges identified in this study are consistent with previous research (Chen et al., 2024), with participants highlighting resistance to change, skill shortages, and fragmented roles as key constraints to integration. The interviews provide empirical depth by demonstrating how these constraints differ by position, with site-level teams focusing on urgent delivery pressures and strategic roles grappling with capabilities and investment issues. This lends support to the argument that effective integration necessitates not only technological solutions but also organisational learning, leadership commitment, and cross-functional collaboration.

The findings highlight the necessity of early-stage integration. The participants agreed that Lean and Digital Twins are most effective when integrated into the planning and design stages, which is consistent with research promoting early decision-making (Hasan et al., 2024; Sarhan & Pretlove, 2021). Late adoption reduces their impact on decarbonisation and resilience results. This emphasises the need to include both decarbonisation and climate resilience requirements in early project decisions. Thus, ensuring that technically possible options with reduced emissions and better adaptability are selected.

This study provided preliminary empirical insights suggesting that climate resilience remains underdeveloped within the contexts examined, despite its growing popularity in academic and policy discourse. While recent research supports integrating mitigation and adaptation methods (Onus et al., 2025; Riaz et al., 2023), interview data revealed that climate resilience is rarely stated directly and is frequently confused with sustainability. Despite its established potential for predictive simulations, testing scenarios and stress analysis, digital twin technology was mostly employed to assist coordination, efficiency, and carbon reduction goals. Also, Lean is positioned as a framework for continuous improvement (Kaizen) that may support lifecycle decision-making, yet its potential to address climate resilience remains underutilised. This illustrates that the climate resilience gap found in the literature is not only conceptual, but also practical. Thus, emphasising the need for a more specific implementation framework.

This study contributes to the literature by offering initial empirical observations that link theoretical concepts to practice. The study demonstrates how, within the contexts examined, the integration of Lean and Digital Twins is shaped by practical constraints and industrial priorities. The findings indicate the need for a structured and implementation-focused approach that supports the balanced consideration of decarbonisation and climate resilience. Thus, the findings may support the development of integrated frameworks for sustainable and climate-resilient construction.

PROPOSED FRAMEWORK

Building on these insights, this study addressed decarbonisation and climate resilience as lifecycle performance attributes rather than distinct or conflicting goals in construction projects. A conceptual framework is proposed for integrating Lean and Digital Twins to support the

balanced delivery of decarbonisation and climate resilience in construction projects. Figure 1 illustrates the suggested conceptual framework and demonstrates the linkages among process improvement, data-driven decision-making, and environmental outcome. This proposed framework is yet to be validated. It is suggested that expert validation using Delphi technique as a possible research method.

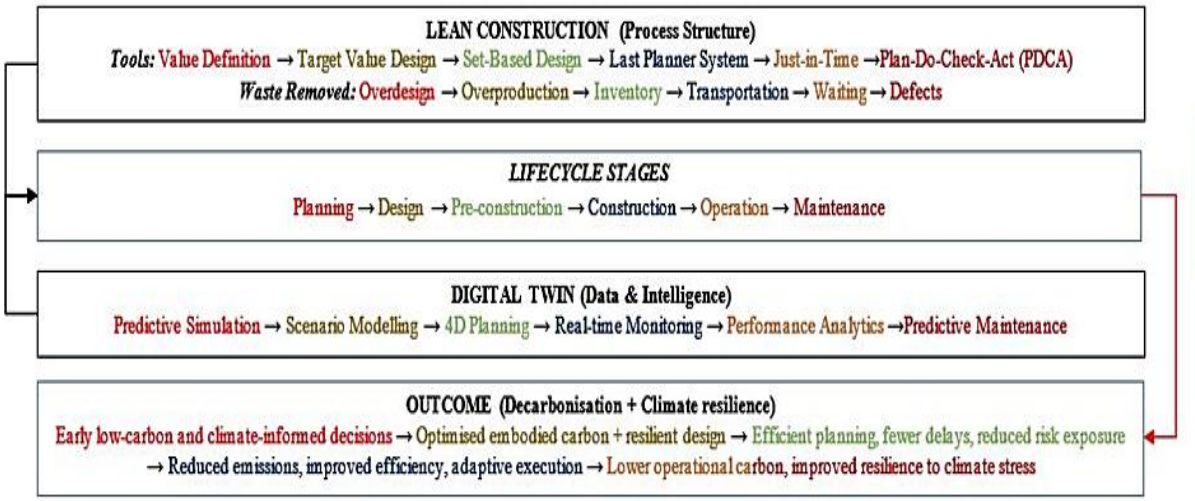


Figure 1: Illustration of the proposed conceptual framework

SUMMARY & CONCLUSIONS

This study explored how Lean methodology and Digital Twins can be combined to assist the balanced delivery of decarbonisation and climate resilience in construction projects. The findings suggest that, within the contexts examined, while decarbonisation is increasingly addressed through measurable targets and digital technologies, climate resilience is often positioned as a secondary outcome or competing priority, rather than being integrated within lifecycle-based performance approaches. A conceptual framework has been proposed to demonstrate how Lean and Digital Twins can serve as complementary enablers for both goals. However, the framework is yet to be verified. The study was limited by time constraints, which restricted opportunities for longitudinal observation and practical implementation. Future research should focus on applying and validating the proposed conceptual framework on real-world projects, involving a wider range of stakeholders, employing the Delphi technique to establish expert consensus, and using quantitative indicators to assess environmental and climate resilience performance.

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