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Optimizing Digital Twin for Net-Zero Retrofitting for UK Existing Building Stock

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Abstract

The urgent need to decarbonize the UK’s aging building stock presents both a challenge and an opportunity for innovation. With nearly 80% of the buildings expected to be in use by 2050 already constructed, traditional retrofitting methods often fail to provide scalable, cost-effective, and data-driven pathways to achieve net-zero. Digital Twin (DT) technology, through real-time simulation, scenario modeling, and predictive analytics, offers a transformative solution to optimize retrofitting decisions and lifecycle performance. This research aims to develop a Digital Twin-Driven Framework to optimize net-zero retrofitting strategies for the UK’s existing building stock. A mixed-method approach was used. A peer-reviewed articles (Scopus, 2015–December 2025) and grey literature provided the theoretical basis with survey of 383 stakeholders administered, gathered empirical insights into current practices, barriers, and enablers of DT adoption. Results reveal a significant knowledge gap in applying DTs in this context, as well as limited awareness among stakeholders and the lack of interoperable data environments. The proposed framework shows how DTs can support adaptive, cost-efficient, and performance-oriented retrofitting aligned with the UK’s Net Zero Strategy. The study recommends policy support for investments in DT infrastructure, collaboration between industry and academia, and workforce upskilling to accelerate the net-zero transition through digital innovation.

1. INTRODUCTION

Decarbonizing the United Kingdom’s (UK) building stock is vital to its climate action plan, as the built environment accounts for nearly 25% of the country's carbon emissions. Reaching the legally required net-zero target necessitates creative, scalable retrofit techniques because around 80% of the buildings anticipated to exist in 2050 are already constructed [1–4]. While traditional retrofit methods improve energy efficiency, they lack the fast, data-driven flexibility needed for net-zero transitions. Digital Twin (DT) technology, dynamic, data-rich virtual representations of physical assets, has emerged as a transformative tool for enhancing decision-making in the built environment. DTs enable predictive modelling, lifecycle analysis, and real-time performance simulations, offering strong potential to optimise retrofit strategies for existing UK buildings [5,6]. Stakeholders can evaluate various energy-efficiency scenarios, enhance occupant comfort, and lower operational and embodied carbon emissions by including DTs into retrofitting procedures [7, 8]. However, its application for net-zero retrofits is still understudied, even if DT adoption in design, building, and facility management is receiving more attention [9–15]. Key barriers include fragmented data infrastructures, limited interoperability standards, stakeholder readiness, and high upfront costs [14, 16–18]. These challenges highlight the need for a systematic framework that aligns retrofit objectives with DT capabilities.

Therefore, to optimize net-zero retrofitting strategies throughout the UK's current building portfolio, this study suggests a novel framework driven by digital twins. It focuses on three areas: (1) determining the shortcomings of existing retrofit procedures, (2) analyzing how DTs might close these gaps, and (3) determining the willingness of industry players to embrace DT-based frameworks. By tying digital innovation to retrofit tactics, these fields enhance theory and offer workable solutions to hasten the UK's

net-zero transition. Globally, buildings account for nearly 39% of energy-related CO_2 emissions, underscoring the urgency of optimised retrofit interventions [19]. In addition to societal repercussions like growing energy insecurity and heightened occupant vulnerability, the UK runs the risk of missing its 2050 climate targets if digital technologies like DTs are not integrated. This research provides a route for carbon-neutral retrofitting by bridging the gap between digital transformation and environmental imperatives by proposing an organized DT-driven strategy.

The key research questions guiding this study are:

How can digital twin technologies be systematically applied to optimise retrofit strategies in existing UK buildings?

What are the technological, institutional, and behavioral barriers to DT adoption in retrofitting practices?

How can a stakeholder-informed framework support scalable, cost-effective, and carbon-efficient retrofit interventions?

In conclusion, despite extensive research into digital twin technologies in the fields of design, construction, and facility management, their use in net-zero retrofitting of existing buildings in the United Kingdom is still in its infancy. An organized, stakeholder-informed framework that addresses both technical and socio-institutional hurdles and combines DT capabilities with retrofit aims is lacking in current research. By putting forth a methodical DT-driven approach that is adapted to the UK context, this study closes this gap. It makes theoretical contributions by applying digital innovation to the optimization of retrofit strategies, and it makes practical contributions by offering doable solutions for carbon-efficient, scalable, and affordable retrofit interventions.

2. Literature Review

Digital Twin (DT) technology has emerged as a promising tool for improving building performance, particularly in energy management, maintenance, and lifecycle assessment. However, existing buildings, particularly those constructed before 1990, have received little attention because the majority of studies have focused on new construction or isolated building systems [9, 20–25]. Real-time modeling and monitoring are difficult in these legacy buildings since they frequently lack digital infrastructure and asset-level data. Conceptual ambiguities further complicate adoption: some studies equate DTs with Building Information Modelling (BIM), while others extend the definition to include IoT-driven feedback loops and AI-powered decision engines [6, 9, 26–28]. This lack of a unified, context-specific understanding underscores the need for a framework tailored to existing buildings. This study is framed through Systems Thinking and Lifecycle Assessment (LCA). Systems Thinking allows for modelling dynamic interactions within the building energy policy nexus, while LCA provides a method for quantifying carbon impacts across a building's lifecycle [29–32]. Guided by this theoretical lens, the review identifies gaps in theory and practice, forming the basis for developing a stakeholder-informed Digital Twin framework for net-zero retrofitting.

2.1 Digital Twins in the Built Environment: A Conceptual Evolution and Application

A Conceptual Evolution

Digital Twin (DT) technology, initially developed for aerospace and manufacturing, has rapidly evolved into a transformative tool for the built environment [9, 20]. Real-time sensor data is integrated into DTs, which are dynamic, data-rich digital representations of physical assets that provide predictive optimization, modeling, and monitoring [20, 34]. DTs expand functionality through artificial intelligence (AI), Internet of Things (IoT) integration, and continuous feedback loops, enabling advanced performance analysis and decision-making, while Building Information Modelling (BIM) established the foundation for digital representation (6,7, 35].

Three major phases can be used to describe the conceptual development of DTs in the built environment. Using BIM-based digital models for design and construction coordination was the initial step [15]. IoT, AI, and sensor technologies were integrated in the second stage, allowing for real-time building performance monitoring [36]. The third stage, which is only beginning to take shape, expands the DT paradigm to include lifecycle carbon management, adaptive retrofitting techniques, and integration with smart energy systems to achieve sustainability goals [28, 37]. This development shows that DTs are an extended framework that incorporates data-driven intelligence into the built environment rather than just a BIM substitute. Accordingly, DTs are becoming increasingly seen as a vital component of net-zero retrofitting, serving as a link between dynamic performance optimization throughout the building lifecycle and conventional modeling techniques [38–39].

Applications and Limitations of Digital Twins in Construction

Digital Twins (DTs) offer substantial benefits in construction, particularly for highly digitised or newly constructed buildings. They enhance maintenance scheduling, energy management, and lifecycle assessment, enabling more efficient and sustainable building operations [6, 59]. However, there is still little DT implementation in legacy or current buildings. Their efficacy and uptake are limited by issues like insufficient data records, antiquated infrastructure, and structural inefficiencies [34, 40]. To fully realize the potential of DT technology across the broader building stock, these restrictions underscore the need for targeted initiatives to retrofit legacy systems and improve data availability.

2.2 Retrofitting Existing Buildings for Net-Zero: Current Practices and Barriers

Current Practices

Net-zero retrofitting aims to reduce operational carbon emissions in existing buildings through interventions such as insulation, HVAC upgrades, renewable energy integration, and smart building systems [19, 41]. Retrofitting is essential to reaching national climate targets because about 80% of the

UK's 2050 building stock has already been built [1, 42]. However, current retrofit procedures are still disjointed. A "performance gap" between anticipated and actual energy savings is caused by low digital maturity, a lack of performance feedback, and high operating expenses [21, 35]. The static modeling techniques used by SAP and SBEM, two examples of current simulation tools, are insufficient for capturing dynamic building performance over time [22]. Optimization is further hampered by the lifespan effects of retrofit materials and postponed performance monitoring [43, 44].

Barriers and Limitations of Net-Zero Retrofitting

Retrofit efforts are acknowledged to be important, but several obstacles limit their efficacy and scalability. The digital infrastructure needed for precise data collection, real-time monitoring, and predictive performance modeling is frequently absent from existing buildings [5, 36]. This limits chances for optimization by causing fragmented data flows and poor compatibility amongst energy management systems [13]. Economically, high upfront costs, uncertain return on investment, and limited financial incentives deter both homeowners and developers from undertaking deep retrofit projects [22, 44]. Even when funding mechanisms exist, fragmented supply chains and limited economies of scale further increase costs [25].

Social and institutional barriers also play a significant role. Homeowners and occupants often lack awareness of retrofit benefits, while stakeholders such as contractors and facility managers may face knowledge and skills gaps in deploying advanced solutions [30, 34]. Additionally, policy frameworks remain inconsistent, with fragmented regulations, limited enforcement, and misaligned incentives across the construction and energy sectors [43, 45]. Finally, methodological limitations exist in current retrofit assessment tools. Static models fail to capture occupant behavior, long-term performance degradation, and material lifecycle impacts [15]. These limitations hinder the development of scalable net-zero retrofitting and perpetuate the performance difference. Despite the potential benefits of Digital Twins (DTs), their adoption in the UK construction sector faces significant barriers, including high implementation costs, limited skilled personnel, challenges in data integration, and insufficient regulatory guidance [16, 32]. However, there are opportunities to assist sustainable building operations by using real-time data analytics, leveraging open standards for interoperability, and aligning DTs with UK retrofit legislation [38, 45].

2.3 Integration of Digital Twins with Retrofitting: Potentials and Challenges

Emerging Potentials

Integrating Digital Twins (DTs) with retrofit strategies offers transformative opportunities for enhancing energy efficiency, lifecycle performance, and cost-effectiveness in existing buildings [5, 46]. DT-enabled retrofitting allows stakeholders to conduct scenario testing, energy modelling, and lifecycle carbon assessments before implementation, supporting informed decision-making and risk reduction [5, 12, 45]. Furthermore, collaborative efforts among engineers, architects, facility managers, and policymakers are

facilitated by shared digital platforms, which enhance overall project outcomes and operational sustainability [13–15].

Adoption Barriers

Despite this potential, several adoption barriers constrain widespread implementation. High initial costs, fragmented and inconsistent data, low digital literacy among retrofit practitioners, and the absence of standardised ontologies limit uptake, particularly among small- and medium-sized enterprises and public housing authorities [17, 40,47]. Open questions also remain regarding DT data lifecycle management, including the optimal timing for DT creation, the scope of integrated data (e.g., occupant behavior, energy flows, climate conditions), and appropriate governance structures to ensure reliable, secure, and usable digital assets [26, 48].

Research Gaps

Current literature on DT-enabled retrofitting reveals several gaps. First, there is limited empirical evidence on the long-term performance and cost-benefit outcomes of DT implementations in retrofitting projects. Second, there are no standardized frameworks for combining various data kinds, such as energy flows, climate inputs, and occupant behavior. Third, there aren't many studies that look at ways to help retrofit professionals become more digitally literate or how to help SMEs and public housing agencies successfully implement DT solutions. Lastly, there are still questions around data security, ownership, and lifecycle management due to the underdeveloped governance and data management standards. To fully utilize DTs in sustainable retrofitting, these gaps must be filled.

2.4 Synthesis and Thematic Gaps

The literature reveals five key thematic gaps in the application of Digital Twins (DTs) for building retrofitting:

1. **Technological Integration**: No unified DT model exists that is calibrated specifically for retrofit scenarios across different building typologies.
2. **Lifecycle Performance Analysis**: Few studies integrate both operational and embodied carbon tracking within a dynamic, data-driven framework.
3. **Data Interoperability**: Current DT efforts show poor interoperability across platforms, disciplines, and stakeholders.
4. **Stakeholder Engagement**: Minimal research has explored co-producing DT frameworks with stakeholders to ensure usability and adoption.
5. **Policy Alignment**: DT applications in retrofitting remain weakly aligned with national retrofit strategies and funding mechanisms.

Building on these gaps, a key limitation in the literature is the lack of a comprehensive, stakeholder-driven framework that connects DT capabilities with retrofit goals for the UK’s existing building stock [5, 34, 43]. Existing research has mostly focused on isolated systems or new buildings, ignoring the

combination of scenario-based optimization, lifespan analysis, and stakeholder readiness. Addressing this gap requires the development of a systematic DT-driven framework that combines digital innovation with carbon reduction targets. Such a framework would provide both theoretical contributions and practical pathways, enabling scalable, cost-effective, and evidence-based retrofit interventions while supporting the UK's net-zero transition [9, 20, 37, 40, 49].

3. RESEARCH METHODOLOGY

3.1 Research Design

This study employed a quantitative, questionnaire-based design to investigate the potential of Digital Twin (DT) technology for optimising net-zero retrofitting strategies in the UK's existing building stock. The structured approach enabled empirical insights into stakeholder perspectives on current practices, barriers, and opportunities for DT adoption.

3.2 Sampling and Participants

A total of 383 respondents were purposively selected to represent diverse stakeholders in the retrofit sector, including retrofit consultants, architects, housing association officers, digital engineers, policymakers, and contractors. This broad distribution ensured a representative mix of professional roles, experience levels, and exposure to various building typologies.

3.3 Data Collection

Data was collected through an online questionnaire structured into five sections:

1. **Respondent profile** (roles, experience, project focus, familiarity with DTs).
2. **Current retrofit practices and challenges** (techniques, performance gaps, barriers).
3. **Perceived potential of DTs** in retrofit processes.
4. **Barriers and enablers to DT adoption** (skills, costs, interoperability).
5. **Framework development and future outlook** (policy support, investment, priorities).

Closed-ended items (Likert scales, ranking, and multiple-choice) were complemented by one open-ended question to capture qualitative insights. The instrument was pre-tested with experts to ensure clarity and reliability. Participation was voluntary, and anonymity was maintained.

3.4 Data Analysis

The dataset was analysed using both descriptive and inferential statistical techniques. Frequencies, means, and cross-tabulations summarised stakeholder perspectives, while Likert-scale scores and ranking analysis highlighted relative priorities. Thematic coding of open-ended responses identified recurring enablers and barriers, such as funding, skills, interoperability, and policy alignment. Visual tools (bar charts, pie charts) were used to enhance interpretation and transparency.

4. RESULT ANALYSIS

4.1 Overview of the Data

The study analysed three hundred and eight-three valid questionnaire responses obtained from professionals involved in building design, construction, and retrofit projects across the United Kingdom. The responses covered a broad range of professional roles, levels of experience, and project types. The data collected provided a comprehensive picture of how industry stakeholders understand and perceive the application of Digital Twin (DT) technologies in retrofitting existing buildings towards achieving net-zero emissions. The results are presented in five major parts. The first outlines the characteristics of the respondents. The second discusses the current practices and challenges in retrofit projects. The third addresses the perceived potential of Digital Twin technologies in retrofit applications. The fourth identifies barriers and enabling factors affecting DT adoption, while the fifth presents findings related to the future outlook for DT-driven frameworks and stakeholder priorities.

4.2 Respondent Characteristics

The analysis of the respondent profile revealed a well-distributed sample across the main professional categories involved in retrofitting the built environment. Table I and Figure I summarises the demographic characteristics of the 383 respondents, showing a balanced distribution across professional roles, experience levels, and project typologies. The majority of respondents engage in retrofit-related projects for at least one-quarter of their professional workload. The participants included architects, engineers, digital consultants, contractors, housing association officers, project managers, and policy specialists. This diversity ensured that insights were drawn from every major segment of the retrofit value chain, ranging from design conception and construction implementation to management, policy, and post-occupancy evaluation. In terms of professional experience, the participants represented all career stages, from early-career practitioners with one to five years of experience to senior professionals with over twenty years of practice. This wide range of experience levels allowed the research to capture generational differences in digital adoption, with younger professionals often expressing higher awareness of new technologies but less practical exposure, while more experienced practitioners demonstrated greater managerial insight but often relied on traditional processes.

The types of building projects handled by respondents covered residential, commercial, mixed-use, and heritage developments. This range is important, as it reflects the diversity of the UK building stock and the complexity of applying retrofit measures across different building types. Heritage buildings, in particular, presented unique challenges because of conservation restrictions, older construction materials, and complex energy profiles. When respondents were asked about the share of their work dedicated to retrofit projects, the majority indicated that between 26% and 50% of their professional workload involves retrofit-related activity. A smaller group reported lower levels of involvement (0–25%), while some respondents, mostly from engineering and housing institutions, reported greater than 50% engagement. These figures confirm that retrofit work now forms a substantial portion of construction-

sector activity in the UK, in line with government commitments to reduce operational carbon emissions from existing buildings.

Table I: Demographic Profile of Respondents

Variable	Category	Frequency (n)	Percentage (%)
Professional Role	Architect	92	24.0
	Engineer	84	21.9
	Project Manager	54	14.1
	Contractor / Builder	41	10.7
	Policy / Government Official	36	9.4
	Digital Consultant / BIM Specialist	36	9.4
	Housing / Facilities Manager	40	10.5
Total		383	100
Years of Experience	1–5 years	69	18.0
	6–10 years	88	23.0
	11–15 years	83	21.7
	16–20 years	72	18.8
	Above 20 years	72	18.8
Total		383	100
Building Typology	Residential	133	34.7
	Commercial	103	26.9
	Mixed-use	80	20.9
	Heritage	67	17.5
Total		383	100
Retrofit Proportion	0–25%	95	24.8
	26–50%	183	47.8
	51–75%	71	18.5
	Above 75%	33	8.6
Total		383	100.0
Source: Authors Fieldwork, 2025			

Figure I: Combined demographic profile of respondents (professional role, experience, building typology, and retrofit exposure

Source: Author's Device, 2025

4.3 Familiarity with Digital Twin Technologies

Table II indicates measurements on the level of familiarity with Digital Twin technologies, which revealed a moderate understanding of the concept across the industry. On a five-point Likert scale (1 = not familiar at all, 5 = highly familiar), the mean score hovered around the midpoint, with a visible spread across all categories. Most respondents positioned themselves between levels two and three, indicating awareness of the concept but limited technical experience in deploying DT systems. This result demonstrates that while the Digital Twin concept has entered professional discourse, practical implementation remains relatively low. The majority of respondents associated DTs with enhanced monitoring and simulation capacities but noted that their exposure to DT use cases was mostly theoretical or limited to pilot projects. This indicates that DTs are still at an early diffusion stage within the retrofit sector, with industry-wide adoption yet to be realised. It also reflects the broader global pattern where new digital technologies first gain conceptual traction before achieving operational maturity.

Table II: Familiarity with Digital Twin (DT) Technologies

Familiarity Level	Frequency (n)	Percentage (%)
1 – Not familiar	**52**	**13.58%**
2 – Slightly familiar	**97**	**25.33%**
3 – Moderately familiar	**145**	**37.86%**
4 – Very familiar	**63**	**16.45%**
5 – Highly familiar	**26**	**6.79%**
Total	**383**	**100%**

Mean = 2.77, SD = 1.04

Source: Author's Device, 2025

4.4 Current Retrofit Practices

The section of the questionnaire addressing current retrofit practices examined how respondents evaluate the accuracy, efficiency, and monitoring of retrofit projects. The responses provided insights into the degree to which digital tools are currently integrated into project processes (as shown in Table III). On average, respondents rated energy savings accuracy at M = 3.00 (SD = 1.15), indicating moderate

confidence in the performance outcomes of retrofit interventions. However, the question on post-handover performance tracking recorded one of the lowest scores, M = 2.08 (SD = 1.16), suggesting that systematic evaluation of retrofitted buildings after completion remains limited. This highlights the continuing gap between design expectations and real-world building performance, a problem often referred to as the “performance gap” in retrofit research.

In contrast, respondents strongly agreed with the importance of real-time data integration in project processes. The item on real-time data importance achieved a high mean score of M = 3.94 (SD = 1.18), revealing that the industry recognises the value of continuous data streams for tracking building performance, managing energy use, and supporting predictive maintenance. Despite this awareness, responses to BIM–DT understanding indicated relatively limited comprehension of how Building Information Modelling transitions into Digital Twin systems, with an average rating of around M = 2.08. Together, these results suggest that while professionals acknowledge the importance of data-driven management, the technical understanding and integration of advanced digital processes remain incomplete.

Table III: Descriptive Statistics for Key Retrofit Practice and DT Perception Variables

Variable	N	Mean	SD
Energy savings accuracy	383	3.00	1.15
Post-handover tracking	383	2.08	1.16
Real-time data importance	383	3.94	1.18
BIM–DT understanding	383	2.08	1.19
DT usefulness for the performance gap	383	3.88	1.19
Carbon data importance	383	3.90	1.20
Digital skills capacity	383	3.20	1.10
Interoperability significance	383	3.75	1.08
Policy funding importance	383	3.70	1.15
Current policy effectiveness	383	2.90	1.10
Industry–academia collaboration	383	3.85	1.09
Framework adoption likelihood	383	3.55	1.16
Occupant feedback role	383	3.80	1.14
Climate metrics integration	383	3.92	1.10

Source: Author's Device, 2025

4.5 Perceived Potential of Digital Twin Technologies

Responses to questions evaluating the perceived usefulness of DTs for retrofit projects showed generally positive attitudes. Most respondents agreed that Digital Twin technology could play a significant role in addressing performance and data integration challenges in existing buildings. The mean score for DT usefulness in closing performance gaps was M = 3.88 (SD = 1.19), while the importance of carbon data integration averaged around M = 3.9 (SD = 1.2), as represented in Table 4.2. These results indicate that the respondents conceptually understand the relevance of Digital Twins to achieving lifecycle optimisation and carbon reduction in retrofitted assets. The data reveal an interesting pattern: although practical familiarity with DTs is low, professionals are conceptually convinced of their potential benefits. This suggests a readiness for adoption if enabling factors such as cost reduction, training, and data standards are provided. The optimism observed in these responses establishes a foundation for strategic investment in digital infrastructure and policy development that can convert conceptual acceptance into real-world implementation.

4.6 Barriers and Enablers to Digital Twin Adoption

The analysis of questions relating to barriers and enablers identified several major factors influencing the adoption of DTs in retrofit processes. Two prominent issues, digital skills and interoperability, emerged as the strongest constraints. Respondents reported that although awareness of DTs is growing, the skill sets required to manage, interpret, and maintain data-driven systems remain scarce across many professional groups. This shortfall limits the sector's ability to embed digital technologies into everyday practice. The second major barrier, interoperability, reflects the technical and organisational difficulties associated with integrating multiple digital platforms. Respondents repeatedly highlighted the incompatibility between proprietary software systems, the absence of standardised data protocols, and the reluctance of organisations to share data across project boundaries. This challenge is not purely technical; it also involves institutional culture and data governance issues that hinder collaboration and limit the scalability of digital solutions.

Policy-related items provided further context. Participants rated policy funding importance highly, indicating a belief that strong government support and financial incentives are necessary to drive digital adoption. However, the mean rating for current policy effectiveness was considerably lower, suggesting dissatisfaction with existing frameworks. Many professionals perceived government strategies as conceptually sound but poorly implemented at the operational level. This disconnects between policy intent and practical support reinforces the need for more consistent and enforceable policies that encourage innovation while ensuring accountability.

4.7 Framework Readiness and Future Outlook

The responses concerning the future outlook for DT-driven retrofit frameworks presented a more optimistic perspective. Across questions relating to collaboration, framework adoption, feedback, and environmental monitoring, respondents expressed a positive attitude toward the digital transformation

of retrofit practices. Most respondents agreed that collaboration between academia and industry **i**s essential for advancing DT applications, as it would allow for the exchange of research insights, technical skills, and empirical validation. The mean score for framework adoption likelihood showed that respondents are generally open to adopting a structured DT-based approach, provided it demonstrates clear benefits in performance optimisation and cost reduction.

Items related to **occupant feedback** and **integration of climate metrics** received particularly high ratings. These responses demonstrate that professionals increasingly recognise the importance of incorporating user experiences and environmental indicators into the design and operation of retrofitted spaces. The inclusion of such data aligns with a growing shift in sustainability practice from purely technical efficiency to broader environmental and social performance. Together, these findings suggest that there is sector-wide readiness for change, but it will require a coherent framework to transform willingness into consistent practice.

4.8 Relationships Among Key Variables

Correlation analysis was performed to determine the relationship between respondents' familiarity with Digital Twins and their perceptions of related factors such as data management, policy support, and framework readiness (Table IV). The Spearman rank correlation results indicated that the associations between DT familiarity and other variables were weak and statistically insignificant. The coefficients generally ranged between 0.01 and 0.06, with the highest observed relationship being between DT familiarity and interoperability significance ($\rho = 0.055$, $p = 0.097$).

This result suggests that while familiarity with DTs may contribute marginally to more positive attitudes toward digital processes, it is not yet a decisive factor shaping professional perceptions or behavior. In other words, awareness alone does not guarantee adoption. The lack of strong correlation may also be attributed to the uneven distribution of experience across roles and the early stage of DT implementation in the UK context.

Table IV: Spearman Correlation between Digital Twin Familiarity and Key Variables

Variable	Spearman's ρ	p-value	Interpretation
Energy savings accuracy	0.018	0.512	Ns
Post-handover tracking	0.027	0.389	Ns
Real-time data importance	0.045	0.182	Ns
BIM–DT understanding	0.035	0.244	Ns
DT usefulness for the performance gap	0.039	0.198	Ns
Carbon data importance	0.041	0.179	Ns
Digital skills capacity	0.052	0.125	Ns
Interoperability significance	0.055	0.097	Ns
Policy funding importance	0.029	0.353	Ns
Current policy effectiveness	0.026	0.398	Ns
Industry–academia collaboration	0.048	0.153	Ns
Framework adoption likelihood	0.044	0.186	Ns
Note: Ns denotes Not significant			
Source: Author's Device, 2025			

4.9 Predictors of Framework Adoption Likelihood

An ordinary least squares regression model was used to test whether certain variables predict a respondent's likelihood of adopting a Digital Twin-driven retrofit framework. Table V displays the regression model predicting framework adoption likelihood. The predictors collectively account for less than 1% of the variance, and none reach statistical significance ($p < 0.05$). This indicates that adoption intentions are not strongly influenced by the individual factors tested. The dependent variable was Framework Adoption Likelihood, while the independent variables included Digital Skills Capacity, Interoperability Significance, Policy Funding Importance, Policy Effectiveness, and Digital Twin Familiarity.

The model yielded an R^2 value of 0.008, indicating that the variables collectively explained less than one percent of the variance in framework adoption. The F-statistic of 1.37 with a p-value of 0.232 confirmed that the model was not statistically significant. None of the predictors showed a significant individual effect on adoption likelihood. Although the regression produced weak statistical associations, the finding is informative. It implies that individual attitudes toward digital skills, policy, or technology are not sufficient to determine adoption behavior in isolation. Instead, adoption is likely driven by systemic and organisational factors such as institutional policy alignment, project funding structures, and cross-sector collaboration that operate beyond individual perceptions.

Table V: Regression Model Predicting Framework Adoption Likelihood

Predictor Variable	β (Unstandardised)	Std. Error	T	Sig. (p)
Constant	3.22	0.19	16.89	0.000
Digital skills capacity	0.032	0.028	1.13	0.259
Interoperability significance	0.041	0.029	1.37	0.172
Policy funding importance	0.016	0.031	0.52	0.604
Policy effectiveness	−0.022	0.030	−0.73	0.467
Digital Twin familiarity	0.028	0.034	0.82	0.414
Source: Author's Device, 2025				
Model Fit:				
$R^2 = 0.008$, Adjusted $R^2 = 0.002$, $F = 1.37$, $p = 0.232$, $N = 900$				

4.10 Priority Rankings and Success Factors

The open-ended sections of the questionnaire, which asked respondents to identify their top priorities and critical success factors for achieving effective DT-driven retrofits, provided valuable qualitative reinforcement to the quantitative results. Analysis of frequency counts revealed a high level of convergence among participants' responses. Table VI summarises the five most frequently mentioned priorities and success factors identified by respondents. Data interoperability ranked highest, followed by standardisation, funding, collaboration, and skills development. Across all rankings, data interoperability emerged as the most frequently mentioned priority, followed closely by standardised frameworks, funding and incentives, stakeholder collaboration, and training and skill development. The same pattern was observed in responses to the question on critical success factors, where these five themes dominated the dataset. Specifically, data interoperability received the highest number of mentions (83), followed by standardised frameworks (77), funding and incentives (77), stakeholder collaboration (76), and training and skills (70).

These responses clearly demonstrate where professionals believe efforts should be concentrated. They suggest that the success of any digital transition in the retrofit sector depends on a combination of technical, financial, and institutional enablers. Respondents consistently emphasised the need for government-backed standardisation, improved digital literacy, and coordinated action across professional boundaries to ensure that DT-driven retrofit strategies are scalable, efficient, and inclusive.

Table VI: Priority Rankings and Critical Success Factors

Item	Frequency (n)	Percentage (%)	Rank
Data interoperability	83	21.7%	1
Standardised frameworks	77	20.1%	2
Funding and incentives	77	20.1%	3
Stakeholder collaboration	76	19.8%	4
Training and skills development	70	18.3%	5
Source: Author's Device, 2025			

4.11 Framework Development

Results were used directly to develop a DT-based approach to net-zero retrofitting. The understanding of stakeholders informed the definition of core goals (e.g., carbon reduction, resilience, adaptability), mapping of DT applications across retrofit stages (assessment, design, monitoring), and finding of enabling conditions of adoption. In the current paper, the results indicate the preparedness and disintegration of the retrofit industry in the United Kingdom in the path towards achieving net-zero emissions. The descriptive findings revealed a good conceptual understanding of Digital Twin (DT) technologies and how they can be used to improve the lifecycle performance. Nevertheless, rates of familiarity, the lack of skills, and data integration indicates that the applied usage of DTs in retrofit projects is still on the developing level. The correlation and regression results also highlighted that no particular factor, including the level of digital dexterity, interoperability, as well as the efficiency of the policy, solely predicts the possibility to adopt a framework based on DT. This means that the shift to digitally empowered retrofit sector is not something that was triggered by a set of isolated determinants but is a systemic event, which needs to be multi-layered in its alignment.

As a result, the model suggested within the context of this study is not only technological but also socio-technical and institutional. It seeks to integrate data systems, human capacity, and governance systems into a model that can enable the decarbonisation of the current building stock to be much faster. The framework is based on the themes of consensus that are recurrent in the data interoperability, standardisation, funding support, stakeholder collaboration, and capacity building. A combination of these five priorities will be the core of a national Digital Twin-based retrofit strategy.

Theoretical Foundations: The suggested framework conceptually relies on the socio-technical systems theory, the theory of innovation diffusion, and the digital ecosystem model of built-environment transformation. The socio-technical theory focuses on the interdependency between technological innovation and human institutions; the diffusion theory of innovation describes the spread of new technologies by awareness, persuasion, decision, and adoption in social systems; and digital ecosystem thinking relates to interoperability based on data across various actors. Based on these theoretical underpinnings, the framework appreciates that the implementation of Digital Twin technologies as a net-zero retrofitting tool cannot be effective unless it has advanced digital tools, empowering organisational

structures and supportive policies, and a culture of learning and collaboration. The model thus becomes a multi-dimensional construct that incorporates the technological, institutional, policy, and human capacity dimensions in a feedback mechanism that is continuous.

4.11.1 Structure of the Proposed Framework

The selected framework consists of four common pillars, which were a direct result of the empirical findings (see Figure II): Data Integration and Interoperability; Policy Alignment and Financial Support; Capacity Building and Digital Skills Development; and Collaborative Governance and Knowledge Exchange. All pillars deal with a particular barrier, which was pointed out in the results, and also empower the others. This framework is aimed at operating in a cycle manner to guarantee that there are continuous learning, adaptation and improvement within the value chain of retrofit.

1. Pillar One: Data Integration and Interoperability address the most overwhelming uncovering of the data, the significant role of data interoperability, and the existing deficiency of the same. The broken digital infrastructures constantly emerged as the main barrier to the actual implementation of DTs among the respondents. Data integration is considered by the proposed structure as the enabling factor of all the other functions. This pillar pursues a national retrofit data ecosystem, in which Digital Twin models, Building Information Modelling (BIM) databases, IoT sensor networks, and energy-performance datasets are standardised to the common metadata and interoperability protocols. By creating common data standards, the stakeholders would be able to share and harmonise information between the pre-assessment and design simulation and the in-use monitoring and post-occupancy assessment phases of the retrofit life cycle. Interoperability would be imposed by use of open-space APIs and shared data environments as well as government approved data-exchange specification such as the UK BIM Framework. The addition of real-time feedback to the Digital Twin setting would allow the constant recalibration of the retrofit models and minimize the performance difference noticed by the results. Essentially, the pillar will turn data silos into a digital ecosystem that is interconnected, which will support credible decision-making and performance tracking.
2. Pillar Two: Policy alignment and Financial support are based on the realization that though respondents held a high opinion of policy funding, they indicated that they did not approve the effectiveness of the existing policies. It is therefore essential to have a consistent and unwavering policy environment in order to attract investment and accountability. Within this pillar, it is suggested by the framework that national and local governmental agencies should establish a Digital Retrofit Policy Package that will tie the adoption of DT to fiscal and regulatory incentives. Some of the most significant actions would be the grants or tax credits of digital Twin performance tracking on retrofits, low-interest loans to support digital-innovation projects, and procurement structures based on prioritised data-compliant retrofit proposals. Building-performance certification (e.g., EPC or NABERS UK) with the addition of DT verification would also make the application of digital tools as compliance tools more legitimate. Policy alignment entails aligning of regulations within the departments of housing, energy and technology. The aim here is to prevent the issue of policy

fragmentation and to also make sure that the objectives of digital-innovation are incorporated into all the programmes related to retrofit. This would offer the financial security and institutional understanding that is required to convert theoretical preparation into popularization.

3. Pillar Three: Capacity Building and Digital Skills Development deals with the shortage of digital skills happening on an industry-wide scale, which is another significant impediment identified by the survey. However, even with the readiness of professionals to work with DT technologies, the research demonstrated the evident lack of technical literacy in terms of data management, real-time analytics, and integration of systems. To deal with this, the framework incorporates systematic capacity-building approaches in the realms of professional education, training, and research. On the academic level, universities and technical schools would incorporate the modules of retrofit based on DT in architecture, engineering, and building sector. On the professional side industry organizations like RIBA, CIBSE and CIOB would set Digital Retrofit Accreditation Schemes that would certify skills in Digital Twin modelling, data interoperability and lifecycle analytics. The government-funded continuous professional development (CPD) grants and joint research between universities and industry firms would support these programmes. Also, capacity building does not consist solely of technical knowledge; it includes digital leadership and management as well. The organisational leaders should be trained to appraise digital investments, change management processes and align DT adoption to the strategic sustainability objectives. This pillar will make the digital transformation sustainable, equitable, and inclusive by establishing a human capability alongside technological capacity.
4. Pillar Four: Collaborative Governance and Knowledge Exchange acknowledges the fact that the shift towards DT-enabled retrofitting will not be successful without successful cooperation between the parties. The researchers discovered that there is overriding evidence of the enhancement of industry-academia partnership and cross-sector associations. This pillar thus advocates a networked collaborative style of governance as opposed to the hierarchical style of management. On a national scale, there would be a Digital Twin Retrofit Alliance (DTRA) that facilitates the coordination of the efforts of the public agencies, individual business firms, educational institutions, and professional associations. The alliance would facilitate data-sharing arrangements, dissemination of research, pilot-project testing, and sharing of best-practices. On the regional scale, local retrofit hubs or living labs would be used as a demonstration setting where prototypes and performance data could be tried in realistic buildings. The collaboration pillar also proposes the establishment of a National Digital Retrofit Observatory, an open-access site that will store anonymised data of the completed projects. This result would facilitate benchmarking, machine-learning analytics, and feedback loops on policies, transforming the experience of single projects into a shared learning process. By having such shared infrastructure, the sector would come up with a transparency and continuous improvement culture.

4.11.2 Implementation Pathways

The suggested framework operationalisation can be achieved under three progressive stages; foundation, integration, and optimisation. Under the foundation stage, advancement should be done on the establishment of national data standards, interoperability protocols, and pilot projects demonstrating the usefulness of DTs in retrofitting. It is also a stage in which the initial investment in the training programmes and awareness campaigns to relevant professional bodies. The process of integration entails the development of DT tools within the mainstream retrofit practices. Digital Twin models are implemented by organisations in the control of energy performance, occupancy comfort, and asset maintenance. The policy mechanisms in the form of the grants and procurement requirements are used to provide a reward to the compliance with the data-interoperability standards. There are increased cross-sector partnerships between government, academia and industry in demonstration projects, which prove the verifiability of carbon savings. Lastly, the optimisation stage implies the state of maturity whereby the whole retrofit ecosystem is run within a single digital framework. The real-time data on performance flow between buildings and national databases. The predictive analytics will make it possible to perform proactive maintenance and design. Checked building data is used to inform government policy, and this produces a self-correcting system, which constantly enhances its accuracy and efficiency.

Figure II: Digital Twin-Driven net-zero retrofit Framework

Source: Author's Device, 2025

5. DISCUSSION

The results of the given research contribute to and broaden the growing body of research concerning the application of digital twins (DTs) when retrofitting existing buildings. Although the descriptive outcomes prove that industry practitioners appreciate the significance of real-time information, performance tracking, and the incorporation of carbon, which shows that the concepts are conceptually aligned with the goals of sustainability, the poor correlation between statistics and the lack of cohesiveness in attitudes demonstrate more serious structural issues that can be attributed to what several authors in the literature have already declared as crucial barriers. To start with, the finding that the importance of real-time data was rated relatively high by respondents (mean = 3.94) and that the respondents had identified the potential potential that the DTs could close performance gaps (mean = 3.88) confirms the general attitude towards the concept of DTs as something that is critical in improving the performance of retrofitted assets. This is consistent with the previous analysis: e.g., DTs are capable of supporting the retrofit of already existing built assets, and that 80 percent of the homes we will be inhabiting in 2050 are already constructed, which is why the urgency of retrofit using DTs, in the first place [6, 45, 50]. Similarly, the recent analysis by Lu et al. [51] has also indicated that DTs are being mentioned more in building-operation and retrofit stages, and not in new design and construction.

There is however an empirical gap when the familiarity with DTs is in the middle of the range and the adoption is low, which was demonstrated by the phenomenon of clustering around the levels of self-

reported familiarity in this study, which are level 2–3. This discrepancy between theoretical background and practice corresponds to the literature: Shen et al. [43] observe that the use of DT in existing buildings in the UK is not extensive, that there is a lack of empirical case studies, and that complexities of implementation of real-time data integration and interoperability were identified as part of the challenges. Therefore, the outcome provided a clue of a sector that is ambitious about digital transformation but has not implemented it at scale, which is also in line with the literature in the built environment. The insignificant links between DT familiarity and other attitudes (all Spearman 0.01–0.06 all non-significant) offer a better understanding: familiarity (or awareness) itself does not predict more positive attitudes towards the retrofit practice, policy, data use, or adoption probability. This indicates that the key problem is not a matter of awareness alone, but rather structural and systemic enablers (or disablers). In literature, high initial investment cost, the lack of skilled workforce, and the problem of interoperability of data are presented as the authors Jiang et al. [4] refer to as the best internal and external obstacles to DT adoption. The qualitative rankings in this study are dominated by the barriers (data interoperability, standardised frameworks, funding/incentives, collaboration, skills), which is why the problem in the sector cannot be reduced to a technological issue or behavior one; it is an institutional and organisational problem.

In addition, the regression model predicting the levels of adoption of a framework ($R^2 = 0.008$) basically validated that the least aspect of willingness to adopt a retrofit framework based on DT is the individual perceptions of skills, interoperability, policy funding/efficacy and familiarity. That is, according to the model, the ultimate determinants are not within the mind of the individual respondent, but might be in organisational culture, project funding arrangements, client demand, regulatory implementation or systemic interoperability circumstances. This is connected to the literature of digital transformation, which indicates that the socio-technical context is paramount to the success of technologies such as DTs. To mention just one example, Shen et al. [43] highlight that practitioners must not simply know about the technical nature of DT systems, but also new digital infrastructures, organisational processes, and collective data ecosystems. These results have a solid implication on the UK building retrofit industry. Even though the professionals are open to the potential of DTs, despite the high performance of post-handover tracking (mean ~ 2.08), there is evidence that the feedback loops required to verify the performance are still weak. This is of particular concern to the performance-gap problem of the built environment as the energy savings projected are not realised in practice. The high value of the mean of the importance of real-time data shows the awareness of the problem, and the low value of the practices rating shows that the industry has not firmly integrated monitoring and evaluation in the project processes. According to Boukaf et al. [47], DTs may be used to promote improvements in energy-efficiency and better indoor environmental quality, although few studies report real energy savings.

The suggested the-pillar DT-based model becomes particularly topical. The findings demonstrate that the key concerns identified by the respondents are interoperability, standardised structures, funding/incentives, collaboration and training, which are absolutely consistent with the significant elements of the framework. This is supported in the literature to mean that data integration and interoperability are some of the most intractable problems with DT diffusion in buildings. For instance,

Shen et al. [43] highlight that the difficulty of data integration and interoperability in real-time is a significant obstacle. Discussing these issues directly in the context of the first pillar of the framework (Data Integration and Interoperability), the model reacts directly to the empirical findings. On the same note, the policy and financial aspect is also prioritized in literature: IET report suggested that digital twins would encourage the confidence of lenders in their investments in retrofitting initiatives provided that they are backed by effective monitoring and verification networks [19, 21 = 23, 38]. Respondents in this study rated the importance of policy-funding high and rated the current policy-effectiveness as low (mean = 2.90). In such a way, the second pillar (Policy Alignment and Financial Support) has solid empirical and theoretical foundations.

The capacity building and digital skills are prominent in survey outcomes and literature. Luo et al. [52] mention the lack of skills as one of the key obstacles. The result of the findings also put training and skills among the five most significant success factors. Thus, the third pillar (Capacity Building and Digital Skills Development) answers the key human and organisational aspect, which is often ignored in technical models. Lastly, collaborative governance and knowledge sharing became a result of the open-ended rankings as well as the existing literature as something required in order to implement DT practices throughout the value chain. According to the review by Liu et al. [53], the use of DT in the built environment usually focuses on the systems, including those related individually, but not holistically. The fifth pillar, then, offers the institutional mechanisms, alliances, living labs, and shared observatories which can translate concepts to practice. A combination of the framework grounded in empirical evidence and consistent with the existing literature makes this study strong in the argument to take a holistic instead of a piecemeal approach in digital twins in retrofit. The point behind this is that implementing a DT-based retrofit approach does not merely entail the implementation of a digital model, rather involves re-organizing data flows, developing interoperating standards, harmonizing fiscal and regulatory frameworks, reskilling professionals, and facilitating collaborative ecosystems [54–58]. Most of the past research has been very limited towards technological component of DTs (sensors, simulation, monitoring) and has not given enough attention to the organisational, policy and human component of the research [54–64]. Tao et al. [24] touch upon the technological merger between sensors and ontology frameworks, the research points out that the willingness of professionals and the organizational culture can be a no less significant factor.

Practically speaking, the industry of retrofit in the UK needs to transform into scalable standardized digital ecosystems, rather than the fragmented pilot projects. These findings indicate the fact that a significant number of the respondents are aware of the usefulness of DT but most of them do not have structures to implement it on an operational level. This recognition/implementation disparity demonstrates that the foundation stage of the framework standardisation of data, training and funding models are needed to ensure the success of the integration and optimisation stages. It is these foundations that make DTs appear as an experiment instead of an embedded tool. To sum up, the results not only support but also add to the existing knowledge: they confirm the existing obstacles like skills, cost, and data integration, and further the research by demonstrating that individual awareness has little to do with the likelihood to adopt retrofit among retrofit professionals. The argument is that

systemic alignment and not digital tools are the elements of a successful retrofit strategy led by DT. The suggested framework, as such, addresses a theoretically and empirically anchored direction that the UK can take to scaleable, cost-effective and carbon-efficient retrofit. With connections between data, policy, capacity, and collaboration bringing them all together in a single model, the sector can bridge the digital ambition and real-life operational reality and take a more assured step towards the 2050 goal of net-zero.

6. CONCLUSION AND RECOMMENDATIONS

This paper has examined how Digital Twin (DT) technology can be deployed systematically to optimise the use of retrofit strategies in the current stock of buildings in the United Kingdom. The results indicated that although the industry experts widely appreciate the importance of real-time data the potential of DTs to bridge performance gaps, as well as the significance of carbon-data integration, the real-life preparedness is low. There was no awareness of DTs around mid-levels and rarely did monitoring practices like post-handover tracking was rated high. The correlation and the regression analyses also showed that familiarity with DTs, perceived skills capacity, interoperability importance, and policy-support perceptions do not significantly predict willingness to adopt a DT-based framework, individually. These findings are a picture of an industry that is conceptually consistent with the ambitions of digital retrofit but still operationally disjointed the proverbial know but not doing. The empirical evidence is focused on systemic factors and not on the technological or individual factors. The most urgent issues highlighted by the professionals are the poor integration of data platforms, proprietary software ecosystems, insufficient training and the enforcement of the policies.

Based on these results, the following recommendations could be made. To start with, the stakeholders in the UK retrofit industry need to focus on creating interoperable data systems with sensor to model feedback and enable DTs to go beyond simulating only the static world into useful dynamic tools. The lack of this kind of infrastructure will ensure that DTs will not be established, but experimental. Second, policy frameworks should shift out of grants and ad hoc incentives to develop long-term, coherent programmes that entrench DT requirements within the retrofit funding and regulation. As an example, the retrofit subsidies might have a performance-checking mechanism through a DT platform, thus, establishing a connection between digital modelling, energy outcome, and policy adherence. Third, capacity building should be planned in a systematic way: professional education, constant training, accreditation to digital-twin modelling, and lifecycle analytics is required to shift the workforce to fluency. Fourth, it needs to be collaboratively-governed: industry, academia and government partnerships must be converted into officially-organised retrofit alliances or observatories, which would collect and benchmark retrofit performance data. Such partnerships have the potential to transform single cases of success into common learning and practice.

In conclusion, as much as the rise of DT awareness to broad-scale use in retrofit is not an issue of technology maturation, it is, nevertheless, an issue of ecosystem change. The suggested data integration framework, policy alignment, capacity development and collaborative governance blueprint provides a blue print that is specific to the UK. When used wisely, it can help to evolve piecemeal retrofit

programs into a fully-fledged, resilient and digitally-empowered retrofit sector that can fulfill the UK net-zero goals. The future direction requires organization, investment and change of culture, yet the momentum shown in this paper has been that the industry is willing to make that bold move.

Artificial Intelligence Disclaimer:

Author(s) stated that NO generative AI tools such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this study.

Declarations

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Figures

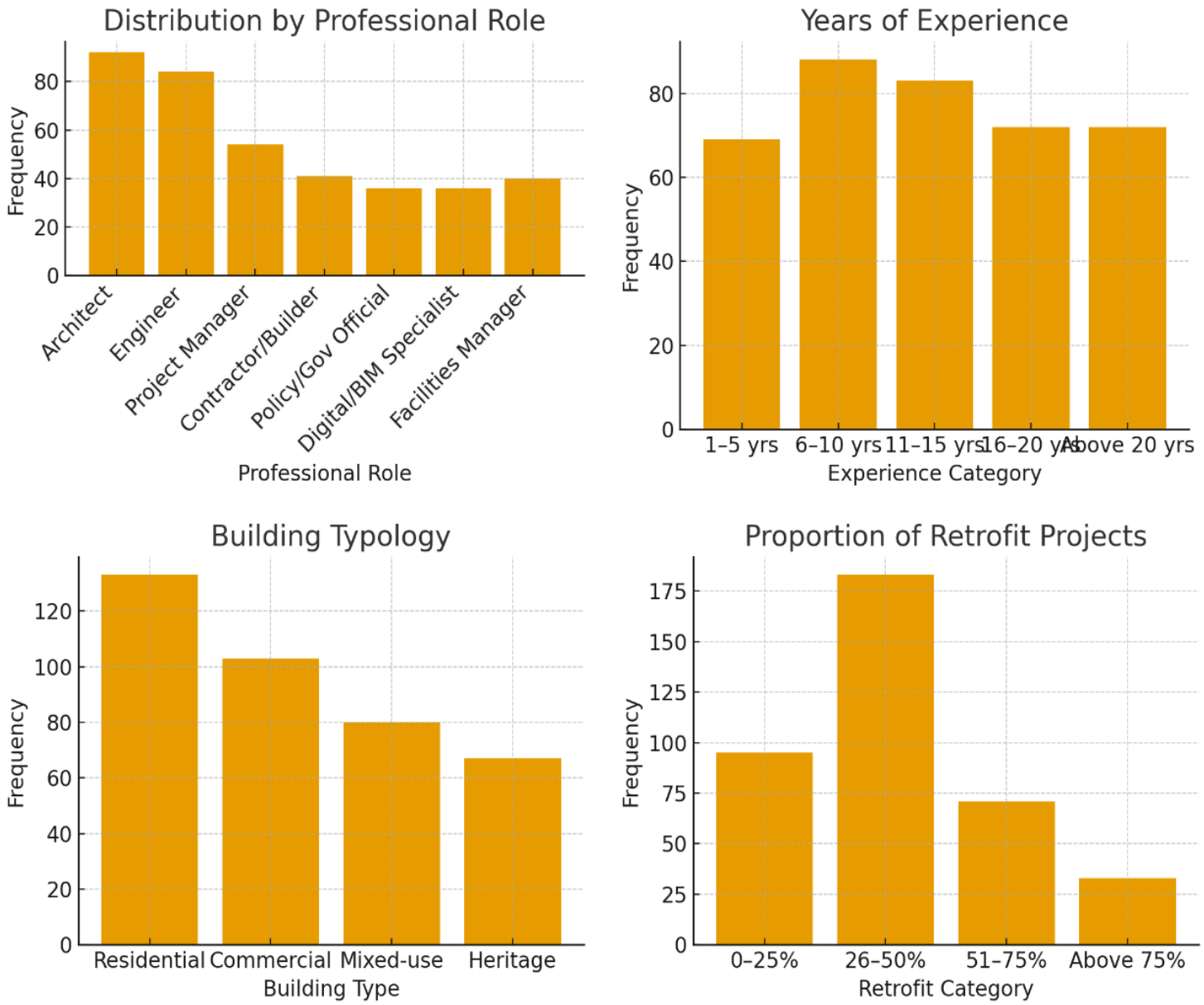


Figure 1

Figure I: Combined demographic profile of respondents (professional role, experience, building typology, and retrofit exposure

Source: Author's Device, 2025

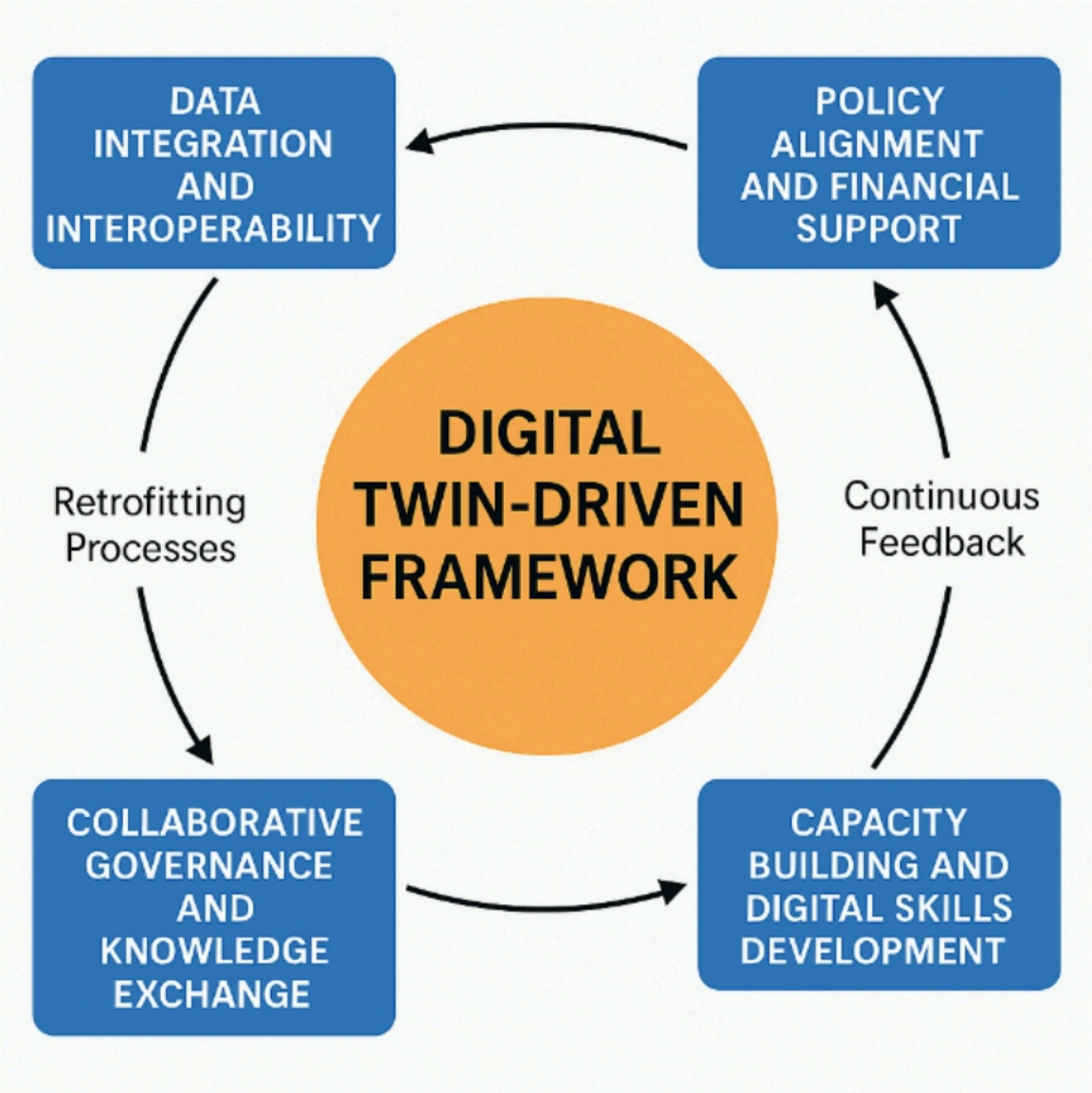


Figure 2

Figure II: Digital Twin-Driven net-zero retrofit Framework

Source: Author's Device, 2025

Supplementary Files

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- TableforNetZeroRetrofittingforUKBuildingStock.docx