

# EXPLORATION OF SOCIO-TECHNICAL APPROACH FOR IMPLEMENTATION OF DIGITAL TWINS FOR PREDICTIVE MAINTENANCE IN THE UK

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Digital Twins can provide adaptable comfort models, energy-saving techniques, and optimisation of building comfort for predictive maintenance in residential buildings. Predictive maintenance optimisation research has overlooked the interdependencies among technology, organisation, users, and processes in residential buildings. This study aims to address this gap by exploring a socio-technical approach to implementing DT for predictive maintenance in the UK, supporting technological and sustainable solutions. Thematic analysis was employed to interpret data from twenty-one semi-structured interviews with industry practitioners; the resulting subthemes and themes aligned with the socio-technical pillars: technology, organisation, users, and processes. The research findings indicate that a socio-technical approach aids in analysing the often-neglected challenges associated with predictive DT maintenance in residential buildings within these four pillars: technology (e.g., issues with scalable sensors), organisations (e.g., culture and competence), users (e.g., insufficient technical skills), and processes (e.g., operational inefficiencies); by addressing human interaction and impacts, engagement (stakeholders and supply chains), as well as equality and ethical considerations. This study provides a comprehensive analysis of the socio-technical pillars for implementing DT in predictive maintenance, offering holistic and sustainable cost-saving solutions.

Keywords: digital twin; maintenance; predictive; socio-technical

## INTRODUCTION

According to the Committee on Climate Change, 29 million existing homes in the UK will need retrofitting by 2050, as 85% of these homes are expected to remain in use by then (Wentworth and Howlett, 2021). The housing sector is crucial for study due to residents' energy consumption levels and insecurity during the UK's ongoing cost-of-living crisis (Cotton *et al.*, 2024). Crucially, the Fire Safety (England) Regulations 2022 and the Social Housing (Regulation) Act 2023 are significant, particularly considering the Grenfell Tower fire and the death of Awaab Ishak incidents (Gov.UK, 2023a; Gov.UK, 2023b).

In recent years, social housing in the UK has experienced various health issues, such as fire, overcrowding, and energy consumption due to poor maintenance, costs,

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limited resources, and a growing population. In the UK, energy use in residential buildings accounted for 13% of GHG emissions in 2019. Space and water heating accounted for most of these emissions. Consideration should be given to occupant behaviour, liveability, effects on the environment, well-being, and comfort, as well as suitable metrics, standards, and funding for future-proof retrofits (Wentworth and Howlett, 2021).

It has been demonstrated that a step towards implementing a predictive DT can potentially manage these issues and lower lifecycle maintenance costs (Arsiwala *et al.*, 2023; Hosamo *et al.*, 2023; Khajavi *et al.*, 2023). Traditional digital operational and maintenance management in the built environment has not resulted in cost savings or workforce engagement due to repetitive data collection, a lack of defined purposes, and overlooked socio-organisational challenges (Khajavi *et al.*, 2019; Murguia *et al.*, 2024). Likewise, the necessity for predictive maintenance (Arsiwala *et al.*, 2023).

This paper aims to highlight the exploration of a social-technical approach to the potential implementation of DT for predictive maintenance for existing housing in the UK for adaptable comfort models, energy-saving techniques, and building comfort optimisation for residential buildings. The research questions the study answered was: How can the ST approach address the barriers of implementing DT predictive maintenance to optimise energy-saving techniques and building comfort for residential buildings through DT predictive maintenance?

## **Conceptual Background**

The UK construction and built environment sectors increasingly adopt DTs technologies for systems integrations, structural health, lighting and ventilation monitoring and maintenance (Arsiwala *et al.*, 2023; Hosamo *et al.*, 2023) for asset lifecycle management, energy efficiency, and cost reduction. However, a significant gap exists in implementing DTs for predictive maintenance, particularly for existing residential buildings.

These gaps are due to technical barriers to DT Implementation, including interoperability issues, regulatory challenges, and reliance on legacy infrastructure (Cotton *et al.*, 2024). DTs, combining IoT, AI, and data analytics which can resolve these issues. However, face challenges like legacy systems, skills shortages, and regulatory issues (Hosamo *et al.*, 2023). Likewise, undefined data sources and the lack of socio-technical (ST) integration framework to guide (Cotton *et al.*, 2024).

Socio-technical barriers to predictive DT implementation involve a lack of organisational commitment, user resistance and misalignment between technology and workforce training (Jin *et al.*, 2020). A ST approach is needed to align technology with human, organisational, and regulatory factors, including stakeholder engagement (Arsiwala *et al.*, 2023; Cotton *et al.*, 2024; Khajavi *et al.*, 2023).

Socio-Technical Systems (STS) theory, developed in the 1950s, emphasizes the interconnectedness of social and technical subsystems in organisations (Abbas and Michael, 2023). It offers a balanced framework for implementing technology in UK housing, enhancing usability, cost savings, and sustainability (Saurin *et al.*, 2013). However, challenges like stakeholder consensus and complex integrations remain. STS approach contrasts with purely technological implementations, integrating users, processes, and organisations, unlike the Unified Theory of Technology Acceptance (UTTA), which focuses on behavioural intentions (Abrahão *et al.*, 2016). STS theory (Abbass *et al.*, 2021) considers the interdependence of technical and social factors.

Case studies in construction and related industries highlight the importance of ST systems for implementation (Merschbrock *et al.*, 2018), learning engagement and ownership (Atour and Ahmad, 2023); interoperability issues affecting energy efficiency performance and collaboration (Hosamo *et al.*, 2023). The UK can enhance DT implementation for predictive maintenance in residential buildings by addressing technical and social challenges. Other studies highlight the importance of employee orientation in addressing these concerns and promoting monitoring technologies to enhance safety, efficiency, and productivity (Jin *et al.*, 2020).

A holistic socio-technical approach is essential for optimising predictive maintenance DTs, ensuring technological efficiency and organisational effectiveness (Cotton *et al.*, 2024; Murguia *et al.*, 2024). The construction industry has historically overlooked this balance, impacting usability and performance. By integrating DTs with an STS perspective, their implementation can be optimised for both technical efficiency and organisational effectiveness (Jedbäck, 2022; Murguia *et al.*, 2024). While traditional technology implementation models overlook human dynamics, STS theory bridges this gap, fostering innovation, collaboration, and sustainability in the built environment.

## **METHOD**

Qualitative methods for capturing conceptual frameworks support multiple bodies of knowledge (ontological or epistemological role) in various disciplines, like sustainable development (Jabareen, 2009). An iterative and reflective thematic analysis process (data extraction - evaluation) was utilised, an emerging information and integrative concept approach, which involved six steps: data extraction, familiarisation, coding, theme generation, review, and writing up (Braun and Clarke, 2020).

In this case, the purpose of the research study is to inform or provide a solution. The benefits also include a structured approach to handling data and examining the perspectives of different research participants, as well as identifying similarities and differences to produce unexpected insights. However, thematic analysis prevents researchers from making assertions concerning the use of language (Braun and Clarke, 2020). Notably, thematic analysis is essential for researchers to eliminate preconceptions during the identification of key themes (Braun and Clarke, 2020) and the trustworthiness of outcomes to support researchers using data analysis for the research method.

Critically reviewed open-ended semi-structured questions facilitated in-depth exploration of the topic and objectives for better understanding to suit each participant's clarity and to encourage open dialogue between them and the researcher; the process was carried out in line with the ethical guidelines. The focus on the research objectives determines the sample size (Naeem *et al.*, 2024). Hennink and Kaiser (2022) systematic review indicated that 9-17 interviews reached saturation and nothing less than 15 samples were stated for thematic analysis (Brzozowski, 2021). However, 21 interviews conducted to add depth and prevent saturation from losing coherence (comprising strategic BIM, asset, and facilities experts in commercial and residential construction management projects with years in the industry average of 28 years) digitally interviewed to gather their perspectives on the research study. Prior to recording, the interviewees' informed consent forms were collected, presented in writing, and briefly explained at the commencement of each interview. An average of 60 minutes was the length of each interview. The recorded videos were transcribed.

The process of thematic analysis of six steps was followed (Braun and Clarke, 2020) using NVivo 14.0 software.

## **FINDINGS**

The key findings derived from the interviews reveal three central themes: human interaction and impacts, stakeholder and supply chain engagement, and equity and ethical considerations, all of which are critical for facilitating predictive digital twins in residential building maintenance. Each theme was analysed through the lens of the four socio-technical pillars: technology, organisations, users, and processes.

### *1: Human interaction and impacts*

The Human element is vital for comprehensive outcomes. One of the participants stated, “DT can be a powerful tool, with significant benefits. But I suppose it also comes with challenges, in terms of human technology interaction and sustainability.” - P\_01.04. The participants report that the O&M and facility managers have been operating the digital technologies provided with a lack of purpose and value. Purpose and value are vital for DT predictive maintenance implementation for existing housing because human interactions impact technology processes. These require ST approach that connect technological systems with humans (society) and organisational factors, leading to sustainable improvements in performance and efficiency under the four socio-technical pillars.

**Technology:** DTs enable real-time monitoring and predictive maintenance for housing, improving operational efficiency. However, their effectiveness depends on integrating advanced technologies like IoT sensors, AI, and data analytics. Currently, excessive manual data collection and skill shortages hinder implementation in the UK. Participants highlighted the need for seamless interaction between DTs, legacy data, and human operators to enhance accuracy and decision-making. DT technologies implementation remains low, as one participant noted, “We’re still at the bottom of that implementation curve. Achieving full digital integration requires reducing paperwork and increasing API-based automation.” - P\_01.05. as commented by another participant.

**Organisation:** The findings revealed that organisational structures and culture should be adapted to support the integration and operation of DTs for predictive housing maintenance. This includes establishing cross-functional teams that combine technical expertise with operational knowledge, promoting collaboration between IT and maintenance departments, and creating governance frameworks that oversee the ethical use of data. The findings reported that many digital technologies have been adopted for DT implementation but are often redundant in organisations due to attitudes and cultural saboteurs. As one participant expressed, “In terms of making DT safe and secure, the weakest link on any project is going to be a human. It is not going to be the software, to be fair. It is going to be a human. Are they competent to be on the project team?” - P\_01.05. The findings suggested that organisations should also consider the implications of DTs on their business models and be prepared to adjust strategies to capture the value generated by predictive maintenance capabilities. One of the participants mentioned: “This is where people come; I mean, it is part of what I call effective digital leadership, which is having people in place who will be able to tell what noise is, what is critical substance to exploit.” - P\_01.15.

**Users:** Human interaction is crucial to the successful deployment of DTs. Operators, maintenance personnel, and decision-makers should be adequately trained to interpret

and act upon the data provided by DTs. Building trust in predictive analytics and fostering a culture that embraces data-driven decision-making is essential. One of the participants attested that “The symbiosis between digital tools optimisation, DT and workers increase productivity and mutual benefits.” - P\_01.07. The findings acknowledged that engaging stakeholders through skill training and participatory implementation walkthroughs beforehand can enhance user acceptance and commitment, ensuring that the technology meets the practical needs of its users to save operating costs. To affirm this, shared by one of the participants: “There is a huge degree of training that is needed for those using the systems and for all of those involved in the process.” - P\_01.09.

**Processes:** The findings emphasize that implementing DTs for predictive maintenance necessitates reengineering existing maintenance workflows for housing in the UK. Predictive maintenance shifts the focus from reactive to proactive strategies, requiring the development of new processes that leverage predictive insights. P\_01.03 stated, “Purposeful schedule maintenance in advance with the data and the database focused on improving the operation and maintenance for DT beyond the process or standard.” This transition involves redefining task sequences, establishing protocols for data-driven decision-making, and ensuring that maintenance activities are aligned with predictive analytics outputs. One of the participants highlighted, “Absolute interoperability is one of the biggest challenges I face daily, believe it or not. And it primarily has to do with file formats and file types.” - P\_01.11. The findings stated that clear guidelines and procedures should be established to facilitate the integration of DT insights into daily operations for predictive maintenance outcomes.

By addressing these human-interaction impacts on the technology, organisation, users (people) and processes; organisations can ensure that the implementation of DTs for predictive maintenance for housing in the UK is not only technologically sound but also aligned with human and organisational dynamics, leading to sustainable improvements in performance and efficiency through stakeholder and supply chains engagement.

## *2: Engagement (stakeholders and supply chains)*

The findings articulated that the active involvement of stakeholders (facility managers, maintenance personnel, and supply chain partners) is crucial. Engaging these groups in the design and implementation phases fosters collaboration, user acceptance, and commitment, leading to more effective predictive maintenance strategies and energy and cost savings. One participant stated, “There are naysayers, fearful of new technology; good communication and education will increase uptake.” - P\_01.07. Although DTs can serve as a unified platform for predictive maintenance of existing housing in the UK, enhancing communication and decision-making across various organisational levels is vital. However, it is still lacking among the O&M senior managers and strategic decision-makers. The communication and language used are too technical for comprehension among the non-technical stakeholders that can influence change or invest in DT implementations. One participant emphasized, “We use lots of jargon terminology, and this does not help a client buy into that or a user buy into. We have to try to keep it as simple as possible.” - P\_01.01.

The findings also indicated that integrating DTs into the supply chain offers significant benefits for predictive maintenance in the UK housing sector. DT provides real-time visibility into inventory levels, manufacturing rates, and shipment statuses, enabling organisations to promptly monitor and adapt to shifting business

requirements. Supported by P\_01.20 “The supply chain needs to be provided with a lot of the data for predictive DT.” Supply chain collaborations with asset information management requirements will allow transparency, standards alignment, and good procurement decision-making.

To reduce the carbon footprint concerning the procurement of materials, the supply chain sector requires an understanding of operations and maintenance activities for cost-saving decisions through implementing DT for predictive maintenance in the UK. A reactive approach generates more costs and carbon footprints in some cases. Therefore, collaborative integration would optimise coordination and quality assurance of the procurement processes. The participants echoed this, with one highlighted: “It has been slow. I would say there are some parts of the industry that are still reluctant. The supply chain is one of them.” - P\_01.18.

Supply chain integration improves transparency, proactive maintenance, resource allocation, and operational efficiency. A holistic DT implementation requires addressing four socio-technical (ST) pillars: The technology aspect, deploying advanced DT systems with stakeholders and supply chain collaboration; the Organisation aspect, aligning policies and structures to support DT integration; the User aspect, training supply chain personnel to effectively use DT interfaces and predictive data and the processes aspect, redesigning workflows to utilise predictive insights from DTs. Stakeholder engagement and supply chain integration ensure a balanced approach, enhancing system reliability and performance. However, ethical and equality considerations should also be addressed.

### *3: Equality and Ethical Considerations*

The findings revealed that the equality and ethical considerations approach for implementing DT for predictive maintenance is required for housing in the UK to ensure that the deployment is not only technically sound but also ethically responsible and socially equitable. Highlighted by one of the participants, “Think about wheelchair users, AI usage, emotional and well-being behaviour; there are equality issues and inclusiveness in the building.” - P\_01.02

The findings emphasize the importance of involving end-users in designing and implementing systems to ensure they meet their needs and avoid adverse outcomes. It also highlights the need for a clean, secure environment but also acknowledges potential consequences like increased surveillance. The study also emphasizes the need for DT for predictive maintenance and the need to consider the demographics of residents to avoid biased computational solutions. It concludes that a more equitable society in the UK should actively check algorithms and data sources for biases.

## **DISCUSSION**

Human Interaction and Impacts - Realigned human-technology interaction is essential for purposeful and valuable DT implementation (Merschbrock *et al.*, 2018) in existing residential buildings, as a socio-technical system approach that addresses operational challenges, which add to the current understanding through literature (Cotton *et al.*, 2024; Hosamo *et al.*, 2023). Balancing automation with human oversight remains challenging, as AI-driven decision-making enhances efficiency (Wang *et al.*, 2022) and urban planning by enabling data-driven approach in terms of sustainability, compared to traditional paperwork (Wang *et al.*, 2022).

Aligning DT strategies with corporate culture and objectives enhances collaboration and data-driven decision-making at the organisational level (Murguia *et al.*, 2024).

However, gaps in digital literacy and resistance to change impede implementation (Atour and Ahmad, 2023; Dawkins *et al.*, 2018). Continuous training and the promotion of a digital culture are essential; however, they necessitate substantial investment and commitment (Atour and Ahmad, 2023).

User engagement has been evaluated as low based on the findings. Nevertheless, the benefits of intuitive DT implementation have been identified to promote safety and sustainability (Khajavi *et al.*, 2023). However, resistance among those unfamiliar with digital transformation was stated as a challenge (Wang *et al.*, 2022).

Interoperability and file format issues highlighted could be improved through socio-technical approach, since DT predictive maintenance enhances efficiency by reducing downtime, and a user-centred, co-creation approach enhances service design and functionality (Arsiwala *et al.*, 2023). ST approach through engagements facilitates effective collaboration.

**Engagement (Stakeholders and Supply Chains)** - The successful implementation of DTs extends beyond individual users, necessitating engagement with diverse stakeholders, including suppliers, maintenance teams, and organisational leaders. The study emphasizes critical engagement dynamics. At the technology level, successful DT implementation depends on a structured integration of technology, organisational strategies, and user engagement. Communicating the benefits of DTs and providing robust support mechanisms facilitates adaptation, fostering resilience and innovation within supply chains (Murguia *et al.*, 2024). Moreover, effective communication enhances data-sharing practices and decision-making; however, resistance to digital transformation persists as a barrier that must be addressed through transparent engagement (Cotton *et al.*, 2024).

Change management strategies are vital to overcoming stakeholder resistance challenges (Cotton *et al.*, 2024). Skill development is a pivotal requirement from the findings, ensuring all stakeholders, from facility managers to supply chain operators, possess the technical expertise to operate DT systems efficiently (Atour and Ahmad, 2023). While DTs offer potential cost savings and carbon footprint reductions, a lack of engagement can be disruptive to the transition process if not managed carefully in residential buildings (Cotton *et al.*, 2024).

Collaboration in simple language among engineers, data scientists, and decision-makers fosters cross-disciplinary innovation at the user level (Jedbäck, 2022). However, a lack of clearly defined roles and responsibilities in DT implementation can lead to misalignment and inefficiencies (Jedbäck, 2022). At the process level, aligning social interactions with technical dependencies would prevent system integration failures and productivity disruptions (Atour and Ahmad, 2023; Jedbäck, 2022). Adopting ST approach ensures that DT implementation is not merely a technological upgrade but a holistic transformation that optimises efficiency and stakeholder engagement through equality and ethical considerations.

**Equality and Ethical Considerations** - The study highlights the following critical concerns. Ethical considerations are paramount in DT deployment, particularly regarding data privacy, security, and potential biases (Longo *et al.*, 2020). At the technology level, ensuring data privacy is essential for predictive maintenance applications. Strict data governance policies should be enforced to safeguard individual and organisational data (Murguia *et al.*, 2024). Additionally, designing DT systems with inclusivity in mind prevents disparities in implementation (Longo *et al.*, 2020). Ethical risks such as data misuse and unintended consequences of predictive

algorithms should be proactively addressed to build trust and mitigate harm (Jedbäck, 2022).

Robust data governance frameworks and transparency measures are crucial for ethical DT implementation in support of strategic objectives. Addressing the concerns about AI usage and emotional and well-being behaviours fosters stakeholder confidence, while applying ST approach to big data analytics enhances strategic decision-making (Aseeri and Kang, 2023). Furthermore, integrating ethical principles into DT design and operations ensures that technological advancements align with societal values (Jedbäck, 2022).

Inclusive communication helps address user concerns regarding DT solutions in the built environment. Community engagement and iterative feedback loops enable the refinement of DT interfaces to accommodate diverse user groups, including those with lower digital literacy (Atour and Ahmad, 2023). At the process level, a value-sensitive design approach strikes a balance between technological progress and social expectations. Organisations can foster inclusivity and responsible innovation by engaging communities in discussions about DT deployment (Longo *et al.*, 2020).

A comprehensive approach to exploring ST pillars is essential for successful DT implementation in the UK for predictive maintenance, ensuring an ethical, efficient, and user-centric implementation while optimising energy use, achieving cost savings, and enhancing building conditions. ST approach, which integrates technical solutions with social, cultural, and organisational aspects, is more effective at reducing energy consumption and improving air quality in buildings than traditional digital platforms, promoting collaboration, data management, security, and community engagement.

## **CONCLUSION**

This study provides unique perspectives on implementing predictive DT in maintenance in UK residential buildings, distinguishing itself from previous research. While existing studies primarily focus on technological advancements or commercial buildings, this research highlights the often overlooked human and ethical factors that significantly impact residential energy efficiency and building comfort in the UK. The study identifies critical gaps in predictive maintenance strategies, emphasising the need for more significant consideration of human interaction, impacts, and engagement (stakeholders and supply chains), equality, and ethical considerations.

The researcher found the low implementation of Digital Twins surprising, citing a lack of knowledge and skills, particularly in residential building maintenance. However, reservations regarding AI for ethical reasons were anticipated. Participants emphasized the potential benefits for asset and facility managers in adopting ST approach to implementing DT predictive maintenance, aimed at enhancing energy efficiency, air quality, and reducing maintenance costs. Furthermore, they highlighted its significance for evacuation strategies in high-risk buildings in the UK.

Due to the nuances, the study was limited to residential building maintenance professionals using DT predictive maintenance compared to commercial buildings in the UK. However, the study's strength lies in the qualitative approach with diverse professionals in the public sector's strategic BIM, built asset management industries, and commercial and residential construction management projects, utilising semi-structured interviews with flexible, open-ended questions. Additionally, the credibility of the professional experts interviewed, with an average of 28 years of industry experience, enhances the study's depth and reliability.

Further research is required to develop a structured framework and real-world case studies on ST approach in residential buildings. These will ensure a holistic, human-centred, and efficient predictive maintenance system that optimises energy savings while maintaining building comfort; by adopting ST approach, asset owners, operations and facilities managers, and policymakers can enhance predictive maintenance, improve energy efficiency, and create sustainable, comfortable residential buildings in the UK.

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