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# EXPLORING PATHWAYS FOR COUNTRY-LEVEL BLOCKCHAIN-DRIVEN, FEDERATED, DIGITAL TWINING OF SOCIAL HOUSING

Theodoros Dounas[1], Jonathan R. Scott[2], and Magdalena Blazusiak[2]
[1]Heriot Watt University, Edinburgh, Scotland, U.K
[2]Robert Gordon University, Aberdeen, Scotland, U.K

## Abstract

This paper outlines the development of a Existing Building Digital Twin system for social housing in Scotland. The project focuses on enhancing retrofit planning and execution. Research methodology involved stakeholder workshops, surveys, and case-based reasoning methods. Key findings highlight the need for a decentralised, secure digital system integrating diverse data sources. The paper proposes ten components addressing various aspects of DT development, aiming to create a robust, user-friendly tool for decision-making in retrofit projects, supporting the country's transition to net-zero carbon emissions. The system is expected to offer benefits including improved energy efficiency, cost savings, and enhanced living conditions.

## Introduction

Significantly improving energy use and carbon emissions at the country level requires that issues of functional, building and energy performance be addressed collectively and en-masse within the building stock of a country. Collective retrofits of this kind are a massive financial and physical programme, which requires the coordination of public and private bodies, building owners, stakeholders, and users, construction, architecture and retrofit companies, along with the optimization of the skills and material supply chain. While data driven retrofit approaches are known and have been implemented widely, understanding where and how to strategically apply retrofit techniques at the level of the building stock portfolio, requires the coordination of multiple data sources, financial funding, incentives alignment and collective governance. In part, the collective retrofit of a wide portfolio of buildings, with multiple owners and users, equates to a common pool resource problem. Our paper discusses the possible pathways for creating a country-level system of Digital Twins (DT) that can address the challenge. We describe a study that ascertained how a collection of stakeholders, private and public entities can collaborate to build such a DT system, and what kind of components such a DT system should have.

## Background: Federated Digital Twins

### Digital Twins

A digital twin (DT) in the context of architecture, engineering, and construction (AEC) is defined as a dynamic digital representation of a physical asset, which facilitates the monitoring, simulation, and optimization of its performance throughout its lifecycle. This concept integrates real-time data from the physical counterpart, allowing for enhanced decision-making and operational efficiency. The digital twin serves as a bridge between the physical and digital realms, enabling stakeholders to visualize, analyze, and predict the behavior of structures and systems under various conditions (Moretti et al., 2023; Yang et al., 2024; Rojek et al., 2020). The architecture of digital twins is often characterized by a multi-layered framework that includes data acquisition, data processing, and application layers. The data acquisition layer combines static data with real-time data from sensors in and around the physical asset, while the processing layer utilizes this data to continuously update the digital model. The application layer then leverages this information for various purposes, such as predictive maintenance, performance optimization, and scenario analysis (Steindl et al., 2020; Ferko et al., 2022). This can extend to including the consideration of human behavior and use patterns that could in turn support the occupants in a much more direct manner. This digital architecture not only enhances the operational capabilities of Architecture-Engineering-Construction-Operation projects but also provides the bedrock for the integration of advanced technologies such as artificial intelligence and machine learning, which can further refine the predictive capabilities of digital twins (Steindl et al., 2020; Zhao et al., 2022). In the AECO sector, digital twins are increasingly being adopted to improve project quality and efficiency. They are particularly beneficial in the context of Net zero transition in AECO as they provide a comprehensive framework for managing the complexities of construction projects with the added scope of reducing carbon-equivalent emissions (Papadonikolaki, E, 2024) . Digital twins enable real-time monitoring of construction processes, allowing for immediate adjustments based on performance data, thus reducing delays and enhancing safety (Yang et al., 2024; Sacks et al., 2020; Pan et al., 2023). Despite the promising applications of digital twins in AEC, challenges remain in their implementation. A significant gap exists between theoretical frameworks and practical applications, as many practitioners in the AEC sector have yet to fully understand or define the concept of digital twins (Elyasi et al., 2023). Furthermore, the successful deployment of digital twins requires organizational readiness and the establishment of appropriate data governance frameworks to ensure interoperability and data integrity across various platforms ("Digital Twin Production in the Architecture, Engineering, Construction and Operation Industry: Organizational Attributes and Strategies", 2023; Newrzella et al., 2022, Papadonikolaki, E 2024).

**Federated and Connected Digital Twins**

The concept of federated digital twins (FDTs) expands the application of digital twin technology beyond individual buildings to encompass multiple assets, such as housing portfolios or public buildings owned by public and private bodies. This approach allows for the integration of data from various buildings into a unified digital framework, enabling comprehensive management, monitoring, and optimization of entire portfolios. It essentially develops groups of digital twin aggregates, i.e the digital twin of various collections of physical assets, hence why the federated approach might be needed (Dounas et al, 2022) The federated digital twin orchestrates decision-making capabilities by providing a holistic view of asset performance, resource allocation, and maintenance needs across multiple sites (Khajavi et al., 2019; Shahat et al., 2021). Federated digital twins leverage the principles of interoperability and data sharing, allowing different digital twins of individual buildings to communicate and collaborate. This is particularly beneficial for public sector organizations managing diverse facilities, as it enables them to assess performance metrics, energy consumption, and maintenance schedules collectively. While there are several potential benefits of a federated approach to Digital Twins (enabling proactive maintenance, inefficiencies identification across a portfolio, operational efficiency through the use of artificial intelligence, enablement of strategic planning by allowing for improved governance, and improved lifecycle management), the increased complexity and orchestration of data, incentives and stakeholders is complex (Elfarri et al., 2023). (Steindl et al., 2020; Newrzella et al., 2022, Khajavi et al., 2019; Rasheed et al., 2020.) However, the implementation of federated digital twins presents several challenges. Data governance, standardization, and integration across different systems and platforms are critical for ensuring the accuracy and reliability of the federated model. Organizations must establish clear protocols for data sharing and management to overcome these challenges and fully realize the benefits of federated digital twins (Steindl et al., 2020; Rasheed et al., 2020). Additionally, the need for skilled personnel who can manage and analyze the data generated by these systems is paramount, as the successful deployment of FDTs relies on a robust understanding of both the technology and the operational context (Newrzella et al., 2022).

**The problem: Digital Twins for Building retrofits at the country level - a Common Pool Resource approach.**

The data needed for creating a DT at the country level with a retrofit scope represents a common pool resource problem. Data is spread in repositories in public and private ownership, for example in the Scottish planning system and in legacy repositories of housing associations. The buildings themselves are also under a mixed state of non-excludability with rivalrous consumption. There is fragmented ownership of the data, allowing some of the stakeholders to free-ride, i.e use the publicly available data without contributing value back. At the same time it is only through comprehensive analysis of the aggregated data that the full value emerges, hence one needs multiple parties to contribute data to the data pool, and at the same time curate, maintain and guard the data continuously, giving rise to a common pool of data that needs to be collectively managed, as neither the government alone, the private providers or the housing associations can create or maintain the data alone. Additionally as well the data exists in various formats and legacy containers, some even in physical format. As such for a DT to work at the country level, one needs a data coordination layer, trust and security mechanisms but also incentives structures to ensure that all disparate data pools are provided to the common DT.

**Methodology and Motivation**

The motivation for the study lies within the need to scale building retrofit efforts across Scotland. When examining the DLO we did not simply examine only the data needed for the buildings, i.e for example spatial geometry and physical properties of walls, but also issues of ownership, incentives for retrofit, funding mechanisms, skills and services provision, but also the occupants and users of the assets. Earlier studies have developed a robust methodology that shaped a systems thinking approach to developing a systemic framework for DTs (Papadonikolaki 2024). Our methods follow a similar pattern through four concurrent key tasks (figure 1)

**Understanding Existing Building Portfolio and Stock Databases**

The team assessed current building databases to identify gaps and strengths, focusing on potential for rapid, large-scale data capture to inform broader project goals.

**Stakeholder Workshops**

Three workshops gathered feedback on data capture methodologies from key stakeholders including Local Authorities, Housing Associations, COSLA, Scottish

Building Standards Hub, SFT, and Hub Scotland. These insights refined the project's approach to data integration.

### Digital Twin Framework Development

This task developed an intelligent digital twin framework with learning capabilities. The survey distinguished between a "Building MOT" (observational data for improving performance and reducing emissions) and a "Building Passport" (intelligent data for broader decision-making). The team reviewed existing methods, conducted desk-based analysis of information utility, and assessed the detail required for the database to support expert systems.

### Project Concept De-risking

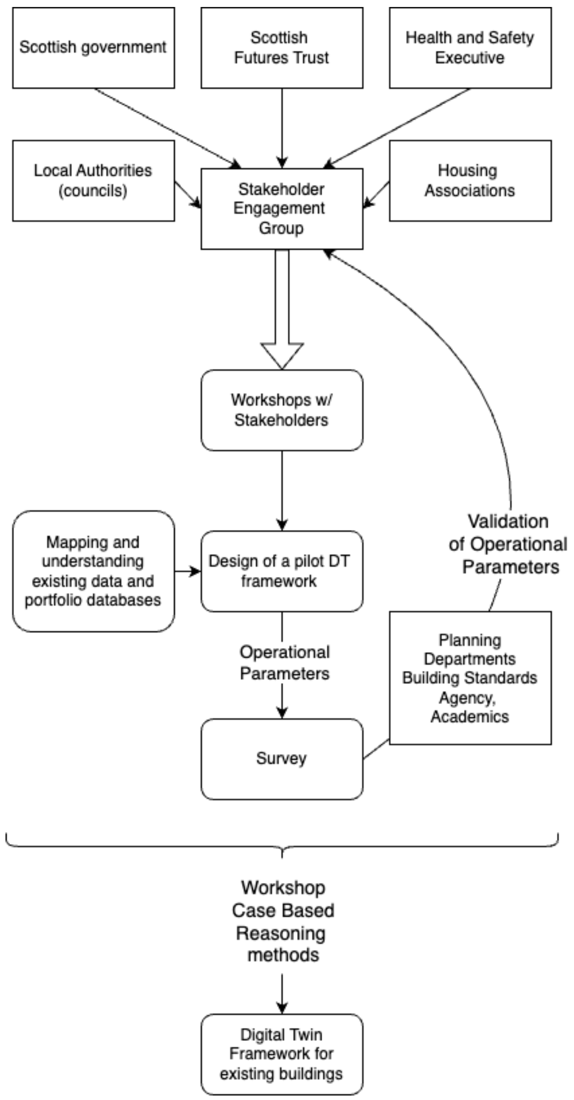


*Figure 1: Methodology*

Using Case-Based Reasoning (Shiva et al 1995), this task explored project feasibility by examining the framework needed for Scotland-wide implementation. One-to-one discussions with academic partners, Local Authorities, and stakeholders assessed confidence in outcomes, potential adoption, and achievable development goals. This structured approach mapped the challenges, opportunities, and requirements for building a robust digital twin framework for Scotland's existing building portfolio, with stakeholder collaboration being fundamental to the findings.

### Currently Available Data and Data Gaps: stakeholder workshops

The development of a comprehensive national existing building digital twin for social housing projects currently draws from various data sources, including Local Authority Development Plans, e-development Scotland backend databases, Energy Saving Trust Home Analytics data, stock condition surveys, and housing association records, Scottish assessors association, Historic Environment Scotland, but also data from utility providers, notwithstanding any remote sensing data that could be orchestrated for this task alone, all of which were reported to provide limited reliability of data, as existing databases were not interoperable. We developed a series of workshops with stakeholders to understand the existing data landscape and the pathways forward to develop a comprehensive collection of data for the DT. Each workshop was centered around a particular output: A building MOT (stemming from the equivalent of basic vehicle check that is performed in the UK) as the basic data set for an asset, a building passport or logbook as the core data needed to create a full retrofit, and a full digital twin as the establishment of a future ready infrastructure for each asset, understanding that the each is the previous stage for the next. While there is currently access to important information such as decarbonization plans, smart meters, air quality data, and weather predictions, the data's reliability and comparability remain concerning, particularly regarding Energy Performance Certificates (EPC) and predicted building performance. The scattered nature of this data across multiple platforms and locations has led to calls for a coordinated, secure database system. Several critical gaps and challenges persist in the current data infrastructure, notably the lack of accurate in-use measurements and dynamic data such as metered energy usage and occupancy patterns. The confidence in existing data is low due to heavy reliance on assumptions rather than physical inspections, and the "performance gap" between predicted and actual building conditions remains a significant issue. To address these challenges, stakeholders advocate for standardized Key Performance Indicators, improved data collection methods including drone surveys and thermal imaging, and the development of interoperable databases that can support both individual property assessments and neighborhood-scale retrofit planning.

### Towards Digital Twins

The stakeholder workshops informed a comprehensive Digital Twin data requirements survey, with respondents primarily from Local Authorities (24%), construction professionals (19%), and Housing Associations (15%). Planning energy efficiency measures (66%), long-term building retrofit planning (59%), and database accessibility (54%) emerged as top priorities, while trigger point identification (37%), skills estimation (36%), and health outcomes (25-39%) received less emphasis. For property data, participants overwhelmingly valued detailed fabric information (93%), performance measurements (85%), and structural details (83%), with building services (75%), orientation (73%), and form factors (64%) also receiving strong support. However, dynamic human-centered data like occupancy patterns (49%) and behavior (36%) scored lower, reflecting workshop discussions about the challenges of accurately capturing, maintaining, and protecting privacy in these data categories. These results reveal a technical focus in digital twin priorities while highlighting the recognized but challenging integration of occupant-related factors that significantly impact retrofit outcomes.

Additionally, participants mentioned information on energy benchmarking contextual information such as fuel type and presence of renewables, pitch and orientation of the roof, energy usage, previous refurbishment and other works, traffic, accessibility.


*Figure 2: Survey Responses to which data should be contained in a DT framework*

Responses on additional property data remained fairly consistent, with only Office for National Statistics data (36%) and third-party climate predictions (39%) selected by fewer than half of participants. This reveals a minor discrepancy with the earlier question about linking to external databases (49%). Condition survey information (81%), accurate drawings (78%), and as-built specifications (75%) were deemed most critical for inclusion. Building Performance Evaluation (68%), known risk factors (66%), Heat Network strategy (66%), local grid capacity (66%), Operations & Maintenance manuals (64%), and maintenance logs (63%) also received strong support from most respondents.

Some participants suggested additional data points like Net Present Value, while others expressed concerns about information overload potentially affecting functionality. Recommendations included focusing on basic static data in the National Existing Building Database while cross-referencing and indexing with other platforms for dynamic data, always linked via Unique Property Reference Numbers. Data consistency across sectors was identified as a potential challenge.

Regarding local spatial context, despite some reservations about data volume, most participants supported including information on gardens (66%), proximity to greenspace (61%), public facilities (59%), health centres (59%), public transport (56%), schools (56%), community assets (54%), and leisure facilities (54%). Landscaping details (47%) were deemed less important, with suggestions to add geological data relevant for ground source heat pumps.

Questions on database location, management, and maintenance revealed tensions, as most respondents preferred a centrally managed system while others suggested a unified approach with common data sharing protocols and secure user identification. There was consensus that a verification process would be necessary for maintaining data reliability and quality when updating the database.

However, the responses were almost equally divided between three answers:

- -Anyone, but with quality approval and verification process (25%)
- -Everyone who uses it ensuring all collected data relevant to the property is logged into the database. This should additionally be subject to verification by relevant data manager (20%)
- -Only qualified and approved professionals or data managers ensuring all collected data relevant to the property is logged into the database (20%)

12% of respondents thought that this should be a responsibility of Centrally based data manager, 8% that is should rather be a locally based data manager, with only 5% suggesting it should be anyone, with possibility for the occupants to interact with the data (5%). No respondents thought that everyone who uses the database should be able to update it, even when ensuring all collected data relevant to the property is logged into the database (0%).

This points away from a centrally managed system and more towards a decentralized, federated system of information where there are multiple tiers of data users, data managers, updaters and locations. Further concerns over privacy of data cause additional tension, as a federated system , potentially using linked data, becomes difficult to secure in terms of the General Data Protection but also in general in terms of cybersecurity. The additional required link to other national databases from the system starts to shape the framework towards an architecture of linked data and blockchain for governance and security purposes.

## Synthesis of a Digital Twins Systems Framework

The tensions and contradictions on the data availability, orchestration and scale needs for the retrofit effort to scale successfully, while making sure that data is kept secure and private within GDPR boundaries, and having a collective orchestration of efforts, points towards addressing the DTS as a common pool resource system. Through the last method of our research journey, we formulated a four-tier approach to the properties of the Digital Twin System Framework: Data coordination layer, the Trust and Security Mechanisms, The Incentive Structures, and the Digital Twin Implementation.

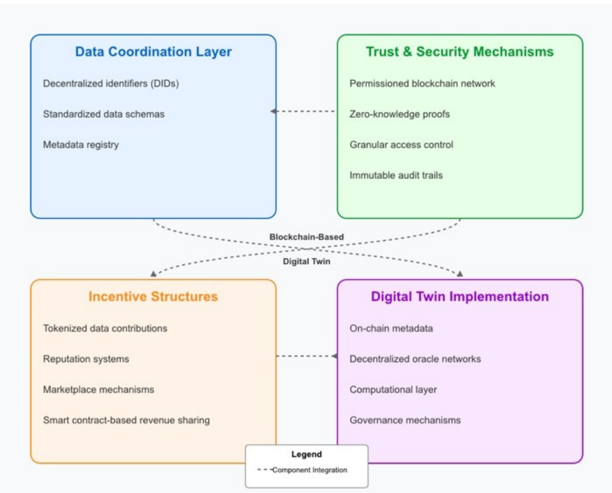


*Figure 3: four tier DT framework*

## Discussion

The objective of the research was to establish the possible framework for a country-level Digital Twin system to scale retrofit efforts.

In terms of data architecture and technologies there are only few that can provide a modern infrastructure towards shaping the DTS as a federated, common pool: namely modern linked data and blockchain technologies. The linked data approach allows for the federated, local development of data pools while linking to wider databases and data, while the blockchain infrastructure can provide supervision-less automation with smart contracts and enhanced privacy in the upkeeping and storage of the data through enhanced encryption. The importance of reliable, cross-pollinating data while safeguarding occupants' privacy was outlined and recognized from the survey responses and workshops participants.

Through the development of the workshops and interviews, the survey and by synthesizing knowledge from literature, we developed a diagram that represents the framework that could be taken forward for Scotland, as a pilot, to develop a full Digital Twin system, with tiers that provide outputs as a Building MOT, a Building Passport or digital logbook, and a fully-fledged Digital Twin that is operated as a federated system.

### From the Components of the Framework to operationalizing it

The workshops provided insights from participants on what kind of work stream would be desirable for the Digital Twins system to develop. These have been highlighted into the figure 4. The DTS framework develops unto of a public blockchain infrastructure, which hosts a treasury for the project, potentially including a fungible token that can be used to fund the country wide retrofits. Connected to this fundamental infrastructure lie distinct components: Computational and data processes (smart contracts, linked data, graph representations in semantic format, and API connections to data pools – web scraping used for immediate legacy formats), Simulation and governance (smart contracts, energy and carbon engines) and a Visualization Interface (dashboards to interact with computing and simulations). On a third tier, processes that deal with supply chain issues, training, and occupants health and wellbeing provide a clear interface to users and stakeholders, i.e building owners, local authorities and housing associations. The development of the DTS framework in terms of its components and its architecture was driven using case-based reasoning, allowing for a varied response in terms of operationalizing the framework. To highlight the multiple pathways to operationalizing the framework, we examine here the Scottish planning system and its e-development Scotland portal. While the portal appears as a single sign-on service for all planning permissions and building warrants, the data associated with each building warrant which is usable for the DTS, lies with each local authority. To provide these data to the data pool of the DTS, each local authority could provide access to their data pool to create a basis for the start of the DTS. Then a web scraping tool could be run to update the data each month, or each authority could create a data push service. The preferred method would need to be selected according to the organizational underpinnings of the final operational architecture of the framework, the organizational and business relationships

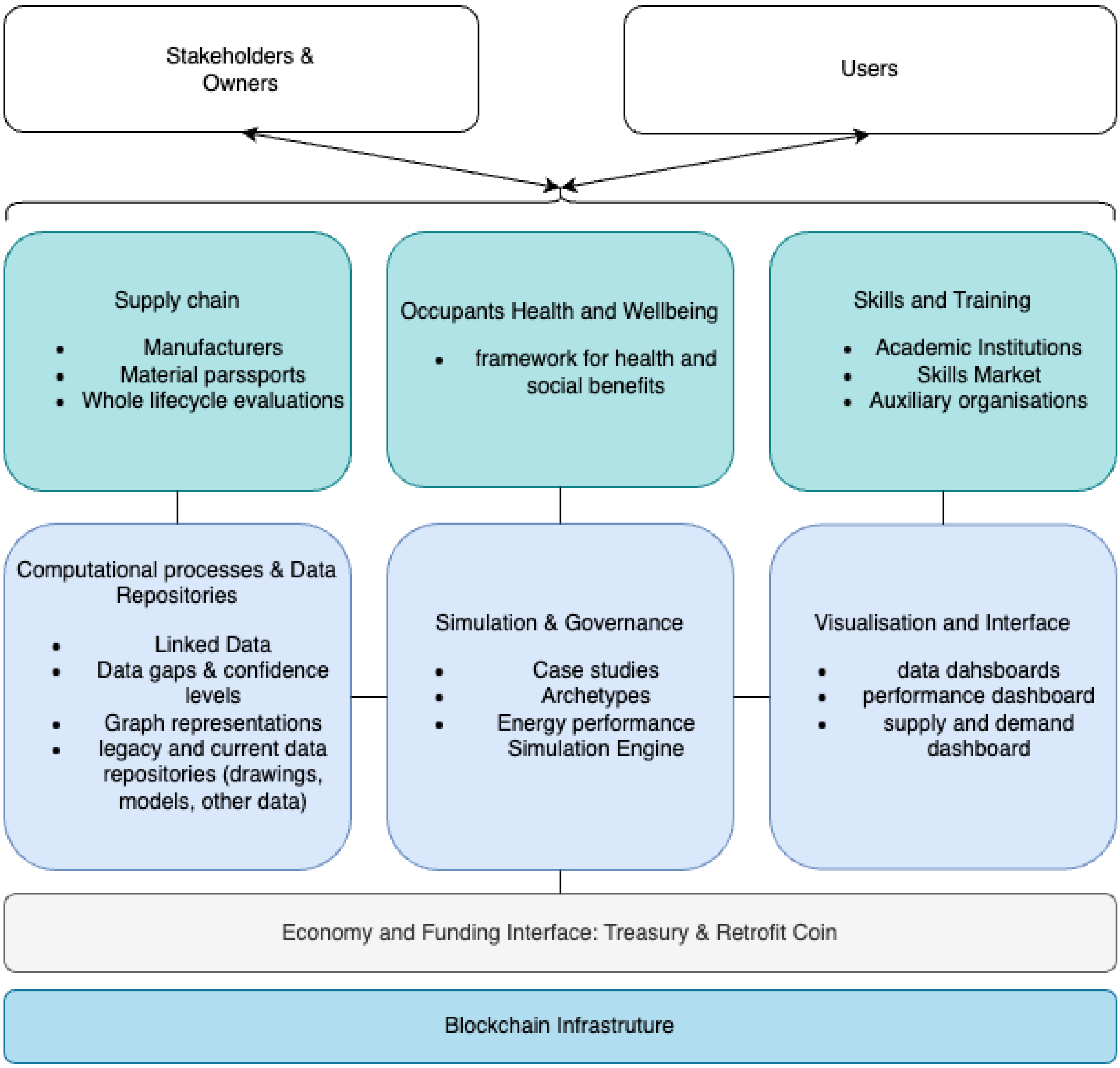


*Figure 4:Digital Twin Framework with a blockchain infrastructure for a country wide retrofit strategy*

developed between the entities on the framework, and of course funding available as each local authority would need to scale up data operations for new data connectors. Beyond these limitations and organizational constraints on how to operationalize the framework, computational limitations on the hardware and software available might drive certain decisions: we developed the framework having in mind a mostly if not wholly open-source software stack and a public blockchain with the use of strong encryption or zero knowledge proofs for certain operations. One additional option that might develop depending on the governance of stakeholders would be the selection of a federated permissioned structure for the blockchain. That would impose constraints on using the blockchain for funding and finance, however it could be paired with more straightforward financial technology.

## Conclusion

Developing a country -level Digital Twin System is difficult, complex and subject to a range of parameters and orchestration of participants and stakeholders. Using a DTS however for scaling the retrofit of large portfolios of buildings can be effective. We have shown, through a qualitative methodology, what type, kind and architecture a Retrofit DTS should have, clearly outlining the focus of a potential infrastructure build up. The use of blockchain technologies allows for a number of features that other technologies do not incorporate: clear collective governance, data resilience, privacy and security, along with data automation through smart contracts. The DTS framework outlines essentially the following development strands:

**Strand 1: Computational and Data Integration** focuses on creating a flexible system capable of integrating diverse data sources while employing advanced technologies like machine learning and blockchain. This foundational element ensures data security, adaptability, and regulatory compliance with frameworks such as GDPR. This includes Data Quality and Confidence Framework proposes a system for evaluating data reliability and identifying improvement areas, crucial for enhancing the overall utility and trustworthiness of the database.

Strand **2: Simulation and governance** establishes a comprehensive data structure capturing both static and dynamic building attributes, ensuring the database accurately reflects the complexity of retrofit projects across different building types.

**Strand 3: Visualisation and Interface Design** aims to create an intuitive, user-friendly platform accessible to various stakeholders, recognising that effective data presentation is crucial for informed decision-making in retrofit projects.

**Strand 4: Supply Chain Development** addresses the critical need for localising supply chains to support retrofit projects throughout Scotland, acknowledging the challenges in meeting demands for both retrofit and new housing standards.

**Strand 5: Skills Enhancement and Training** emphasises addressing the skills gap in the retrofit sector through a dual approach focused on both professional upskilling and raising public awareness.

**Strand 6: Health, Wellbeing and Community Engagement** highlights the broader societal impacts beyond energy efficiency, recognising these factors' importance in government funding allocation while emphasising the need for community involvement in retrofit planning.

As the basis for all strands, the Economic and Blockchain infrastructure: Establishes a data and financing infrastructure using blockchain technology, where both data and finance recurse are treated as a common pool, so that the project becomes resilient and self-sustaining.

In conclusion, these development strands provide a comprehensive roadmap for developing a sophisticated, user-friendly, and adaptive Digital Twin system. By addressing technical, social, and economic factors, this approach sets the foundation for a more efficient, data-driven strategy for social housing retrofit in Scotland, supporting the country's ambitious climate goals and improving residents' quality of life.

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