FUTURE DIRECTIONS IN SPACE-AWARE HOSPITAL DIGITAL TWINS DEVELOPMENT AND IMPLEMENTATION

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Abstract

Hospital facilities are complex systems where the operational efficiency depends on factors such as space, built assets, processes, resources, and logistics. While process-simulation-based improvements have been widely explored in research and practice, few studies investigate how building performance and process efficiency dynamically affect each other. A crucial challenge here is the integration of multi-source data to support cross-domain decision-making capable of informing effective actions at the intersection of Asset, Facilities, Operations Management, and clinical services. Building on the results of the Digital Hospitals project, this paper discusses the latest developments addressing this challenge and analyses the future directions in developing a multi-data-source, process-based Digital Twin for optimal hospital operations. The paper proposes a mid-term research agenda to address key knowledge gaps such as (i) improving the reliability and granularity of integrated indoor and outdoor built environment modelling; (ii) multi-source real-time data communication; (iii) the integration of built asset and clinical equipment monitoring (iv) development of ontology-based data integration strategies; and (iv) testing in operational environment and generalisation. The research agenda sets out the plan to further advance the works in modelling, simulation and control of processes, assets and resources towards a fully functional hospital Digital Twin.

1 Introduction and background

Healthcare facilities are complex systems where service efficiency is closely related to factors like the built environment, resource use, human resources, and supply chain management [1]. The spatial layout, the physical condition of buildings, the condition of equipment, resources and logistics significantly influence the operational process flows, affecting clinical and non-clinical processes [2]. The interdependencies between these factors require advanced analytical and simulation tools to address inefficiencies and ensure high-quality care.

Inefficient hospital layouts adversely affect staff mobility, patient care, and overall workflow. Poorly designed departments and laboratories often lead to congestion and bottlenecks, slowing operations and increasing turnaround times [3]. In addition to layout issues, inadequate space utilisation and suboptimal building design pose further operational challenges. Underused areas waste resources, while overcrowded zones can lead to errors, distractions, and reduced efficiency [4]. These inefficiencies also impact staff well-being, Turnaround Times (TAT), and patient safety. Long walking distances and poorly planned workspaces contribute to fatigue, burnout, and dissatisfaction among staff [4]. Disrupted workflows affect bed assignments, patient transfers, and hospital operations, resulting in care delays and longer waiting times. Delays in bed turnover extend inpatient wait times, negatively affecting patient satisfaction. Additionally, the physical separation between wards and the operating theatre can cause delays in patient transfers [5], [6]. Operations managers face the challenge of optimising limited resources while maintaining service quality and timeliness and often simulation modelling tools such as Discrete Event Simulation (DES) are commonly used to analyse scenarios and support decision-making [6].

Despite extensive research on process simulation and patient safety, few studies dynamically assess how hospital infrastructure affects efficiency. For instance, infrastructure failures like lift breakdowns or access control issues can disrupt operations, decreasing the overall capacity of treating patients effectively and swiftly. To address this challenge Digital Twins (DTs) are viable solutions which enable a real-time, bidirectional link between digital models and physical assets or processes and therefore enhance the decision-making abilities of operations and facilities managers, through the simulation, prediction, and automation of critical systems' performance under varying conditions [7]. Table 1 summarises the main applications of DT-based process improvement in the healthcare sector, which allow us to identity the knowledge gaps, which we address in this paper (see also section 1.3).

1.1 Identification of the remaining knowledge gaps

KG1: While many inefficiencies in healthcare are linked to spatial factors, most DT application focus on isolated changes

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to layout or processes, rather than examining the ongoing interaction between the building's condition and process efficiency.

Table 1: DT domain of application, inefficiencies and delivered benefits. Table adapted from [8].

Domain	Inefficiency	Benefit
Patient flow management	Delays in bed turnover Patient transfer delays	Improved daily/weekly prediction of admissions [9]. Improved management of patient pathways through what-if scenario analysis [[10].
Asset and facilities management	Resource misallocation, Workflow disruptions	Reduced bed turnaround time and automate the notification to the cleaning staff [10]. Reduced energy consumption, facility faults, requested repairs, and enhanced the quality of daily maintenance work [11].
	High staff workload, Resource misallocation	Dynamic asset tracking [12]. Reduced dispensing error and stock-out rates and high staff satisfaction. Reduced time for stock Management [13].
	High staff workload, Workflow disruptions	Improved design and test different intervention strategies which can reduce clinicians' task durations and inform new discharge policy [14].
Portering	Poor space utilisation, Workflow disruptions, High staff workload, and Resource misallocation	Optimised decision variables and determined the best output for each supply chain. Avoid bottlenecks and congestion. Reduced staff Workload [[15].
	Workflow disruptions, Resource Misallocation	Real-time location information of porters, prioritise tasks and manage assignments [16], [17].
Medical equipment management	Resource misallocation	Optimised bedside mechanical ventilation guidance protocols through in-silico simulation and validation. Reduced need for lengthy, resource intensive, high-cost clinical trials [17].

KG2: On the other hand, many existing DTs, both in academia and industry, concentrate individually on processes (e.g., patients' flow, material flows) or physical assets (equipment, built assets or the entire building), with limited attention to the interdependencies and mutual impacts between the two.
KG3: There is a notable lack of research into frameworks that can continuously integrate geometric, topological, semantic, and operational data from various sources, which is an essential requirement for a space-aware process DT. Furthermore, there is limited evidence on how such frameworks and DTs can support decision-making and enhance the efficiency and resilience of core process operations, particularly in response to failures in critical building infrastructure like lifts or access systems.

1.2 Research questions

In this paper we keep exploring a key broad research question *How can information about the layout, built assets and systems be integrated with process simulation models to enable effective analysis and improvement of operations within complex healthcare facilities?*

To study this, in this paper we investigate two sub-questions:
RQ1: *What are the remaining knowledge gaps in enabling such integration?*
RQ2: *What are objectives of a short to mid-term research agenda towards the development of a fully functional DT of hospital facilities?*

1.3 Contribution of this paper

This paper addresses the problem of systematising the future research efforts on space-aware DTs with the aim of solving the inefficiencies of hospital facilities, arising from the complex interdependencies of spaces, built assts, equipment and processes. As summarised in Table 1, current DT applications have primarily targeted isolated operational challenges such as patient flow, asset tracking, or portering. While these studies demonstrate measurable benefits, they also highlight important limitations. First, most solutions optimise either spatial factors or process flows independently, but rarely their ongoing interaction (KG1). Second, applications tend to focus narrowly on processes or physical assets in isolation, without modelling their interdependencies (KG2). Finally, although technical advances in modelling building information, Internet of Things (IoT), and simulation exist, there is little evidence of integrated frameworks that continuously connect heterogeneous data sources to support decision-making in dynamic hospital environments (KG3). Combining the analysis of the literature with the results of the Digital Hospital project, developed in collaboration with a major hospital in the East of England, we propose a mid-term research agenda, to address the remaining knowledge gaps.

2 Methodology

This paper is based on the results of the Digital Hospital project developed in collaboration with the Addenbrooke's Hospital, corroborated with empirical testing in the Histopathology Laboratory and by the analysis of the state of the art.
The Histopathology Laboratory is in fact a disassembly line. The samples are received every day and undergo a set of processing steps as described in [18]. Each step has been empirically observed by the research team in the lab and modelled using a set of techniques within the Business Process Modelling (BPM) approach [19]. The mapping phases comprises both the core process flow (i.e., the case and specimen processing flow) and the information mapping.
Through co-development workshops carried out with the Histopathology operations managers we identified the goal of increasing the throughput, reducing the Turnaround Time (TAT) of the lab, controlling the joint complex effects of the variables impacting workforce; equipment & asset maintenance; and procurement management, while meeting the service level requirements set by the national Royal College of Pathologists (RCPath) [20]. A mixed requirement engineering approach based on the Four Variables Model [21] and Goal-Oriented Requirement Engineering [22] approaches

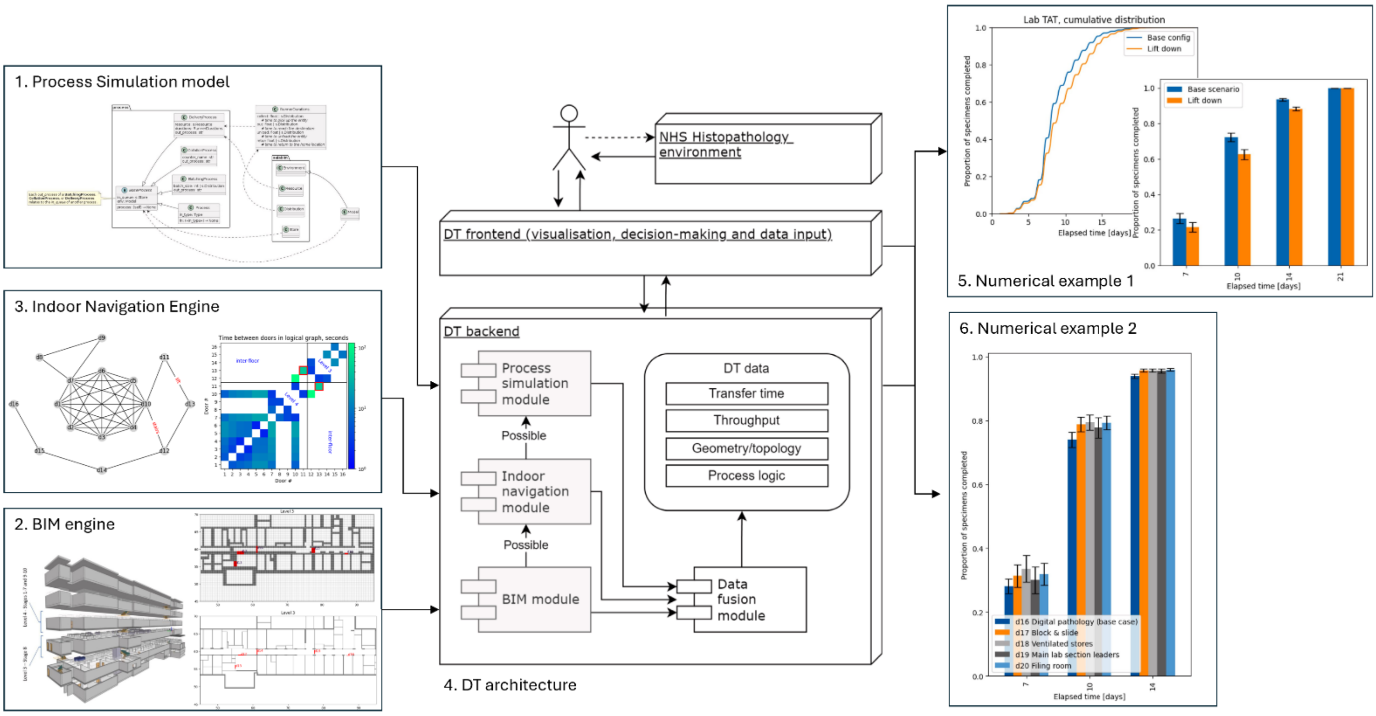

Figure 1: Histopathology laboratory DT overall schema, summarised from [8].

has been used to capture the stakeholders' needs and desires and elicit them into a set of structured requirements which forms the basis for the laboratory DT development, presented in Section 3. The requirement engineering highlighted that in the lab settings the value in DT applications can be achieved both by increasing the monitoring and automation capabilities of the assets, and by enabling better data, process and service interoperability.

The effectiveness of the DT platform has been tested through two numerical examples which have been carried out using real specimen reception and processing data from the Histopathology laboratory, input to the DT architecture described in Figure 1, which leverages open Building Information Modelling (openBIM), DES and shortest path navigation methods to compute the TAT alternative configurations of the laboratory, based on the availability of resources, the performance of the built assts and availability of functional spaces. BIM offers a rich set of process, information management and modelling techniques for buildings and infrastructures. In the UK, the use of BIM is mandatory for all public-funded construction projects [23].

Section 3 describes the results of the Digital Hospitals project (summarised in Figure 1): the development of the DES of the Histopathology Laboratory (section 3.1); the BIM model development of the building hosting the lab (section 3.2); the BIM-DES data integration method (section 3.3); the Histopathology lab DT architecture (section 3.4); and two numerical examples demonstrating the effectiveness of our proposed approach (sections 3.5 and 3.6).

We use these results as argumentative evidence of the benefits and pitfalls for the development of a complete hospital DT platform and to develop a mid-term research agenda which paves the way for future work on studying the features, possibilities and impact of space-aware DTs for hospital management.

3 Results of the Digital Hospitals project

The main goal of the Digital Hospital project was to understand the interdependencies between assets, processes and patients' health in hospitals and solve their inefficiencies impacting on healthcare process delivery. The test bed is the Histopathology Laboratory of the Addenbrooke's Hospital, in Cambridge UK, where DT-related technologies have the aim of solving the inefficiencies causing a decrease of the laboratory throughput – i.e., number of samples processes in given time. After identifying the operational Key Performance Indicators (KPIs) and following a pragmatic evidence-based approach, we identified in the development of a DES model, one of the core features of the Histopathology DT.

3.1 DES model of the Histopathology Lab

The DES model (Figure 1, box 1) was built utilising the Python library salabim (https://www.salabim.org/), which offers built-in statistical tracking for simulation components. While this library provides basic constructs like resources and events, we developed an additional layer to model common process tasks such as batching, collation, and delivery. Each task is encapsulated in a subclass of the base process, enabling modular and manageable code. These processes operate in loops, handling entities through queues and forwarding them along a defined chain. The framework mirrors logic blocks found in graphical DES tools like Arena but benefits from Python's flexibility and easier integration with other systems, such as BIM components.

3.2. BIM model of the Histopathology building

While the DES model in highly effective simulating staffing, equipment, and supply chain variables, a higher resolution of the space and built assets variables is required to model the complex nature of the core Histopathology process. Therefore, we explored the use of open BIM standard Industry Foundation Classes (IFC) 4 ADD2 TC1 [24] to enhance the geometric and built asset features, input for the DES model (Figure 1, box 2). We hypothesized that when a basic and valid BIM model is available, as-built IFC assets' data can be used. To leverage the benefits of using openBIM data (i.e., compliant to the IFC4 schema), both semantic and geometric data is utilised, particularly for modelling space-dependent variables such as task durations influenced by spatial layout and this represents a second core feature of the laboratory DT. To demonstrate this and automate the integration tasks, we utilised the Python-based IfcOpenShell library (https://ifcopenshell.org/).

3.3 BIM-DES data integration for space-aware process simulation

The DES and BIM models were integrated to enhance the simulation capabilities by dynamically incorporating space-dependent specimen transfer times. When the spatial layout of the building chances under the effect of disruptions to the physical assets and spaces, the DES model receives updated information and can be used to build scenario analysis on the best new spatial configuration of the laboratory functions. The bridge between the DES and the BIM model is represented by an indoor navigation engine (Figure 1, box 3): a third core feature. The integration starts with the identification and calculation of the coordinates of the key spatial elements such as doors, walls and columns; then runs the Dijkstra's algorithm on BIM data to calculate the distance and travel time between door pairs, based on a set walking speed for horizontal movement; and concludes with the stage-to-stage travel time calculation associated with consecutive process stages.

3.4 Histopathology laboratory architecture

Adopting a "DT with human-in-the-loop" approach, operations and facilities managers interact with the DT by both supplying data and acting on its outputs. To support this, we developed BIM-DES DT architecture which includes a frontend for decision-making and visualisation, and a modular backend. The three backend modules – BIM, Indoor Navigation, and Process Simulation – operate independently and feed into a data integration module. The BIM module extracts relevant IFC data, the Indoor Navigation module calculates sample transfer times, and the Process Simulation module estimates throughput and turnaround time. This modular and flexible design allows for future expansion, such as integrating IoT or asset maintenance services, without disrupting existing components.

3.5 Numerical example 1: impact of asset failure

This example (Figure 1, box 5) illustrates how a seemingly minor disruption—such as a lift outage— can significantly impact the performance of a Histopathology laboratory, which is organised across two floors of the building (levels 3 and 4). By comparing scenarios with and without lift access, the study shows that increased travel times for transporting fragile glass slides between floors lead to a notable drop in timely specimen report delivery. The lift outage forces staff to use stairs, increasing handling time and requiring batch splitting, which raises runner times by nearly 80%. Despite only a 9.3% increase in average TAT, the knock-on effects—such as higher staff utilisation and delayed tasks—result in a statistically significant decline in service levels, particularly at the 7- and 10-day completion marks (from 73.9% to 62.6% of specimens completed within 10 days). This highlights the sensitivity of lab performance to spatial and operational constraints.

3.6 Numerical example 2: impact of laboratory layout redefinition

This scenario analysis (Figure 1, box 6) demonstrates how relocating the digital scanning room within the Histopathology lab can significantly improve efficiency by reducing travel times, while optimising the available space utilisation. Using the BIM-DES framework, this numerical example evaluates the impact of moving the scanning function from level 3 to a suitable room on level 4. Candidate rooms are identified based on size and suitability using BIM data, and runner times are recalculated using the Indoor Navigation module. The results show that all alternative locations outperform the original setup, with the Block & Slide room yielding the best improvement raising the proportion of specimens completed within 10 days from 73.9% to 78.7%. This supports earlier findings that even small changes in spatial layout can lead to substantial gains in lab performance due to the influence of manual handling tasks on turnaround time.

4 Research agenda

The research agenda builds directly on the findings of the Digital Hospital project presented in Section 3. For instance, the BIM–DES integration framework (Section 3.3) demonstrated how spatial disruptions such as lift failures can be captured in simulations, yet its application was limited to a single laboratory context. Similarly, the modular DT architecture (Section 3.4) showed the feasibility of combining BIM, navigation, and process simulation modules, but raised challenges of interoperability and scalability. The numerical examples (Sections 3.5 and 3.6) further highlighted both the potential and the limitations of current approaches. These insights underpin the future objectives outlined below. Figure 2 illustrates the main objectives of the research agenda, organised as an improvement cycle.

4.1 Integrated indoor and outdoor modelling

As demonstrated by the BIM-DES integration in the Histopathology Lab (Section 3.3), disruptions to lifts or reallocation of rooms directly affected turnaround times. Extending this approach to other departments requires more refined multi-scale modelling. A short-term research objective concerns focusing on consolidating the BIM-DES integration framework introduced in the study. The proposed framework, leveraging openBIM standard and DES, has demonstrated its potential in quantifying the impact of spatial disruptions—such as lift failures or room reassignments—on core hospital processes. Future work concerns generalising this framework beyond the histopathology laboratory to other departments within the hospital, such as radiology, pharmacy, and emergency care.

This will involve on one hand refining the spatial resolution of the simulation model by incorporating additional spatial data, including internal room geometries and fixed equipment layouts. On the other hand, through the generalisation of the framework and its application to other hospital departments, their interdependencies and related functional areas can be studied to identify the impact of the built assets on the clinical processes and solve the resulting inefficiencies. Hospital are complex infrastructures, often organised in multiple pavilions, where the outdoor space and context play a key role. Therefore, the Geographic Information Systems (GIS) can be integrated with BIM tools, to provide a multi-scale model of the hospital complex or campuses. A critical challenge here is the development of an integrated model which allows to structure, access and manipulate built environment information, at different scales and levels of granularity, according to the processes simulated and the decisions to be made.

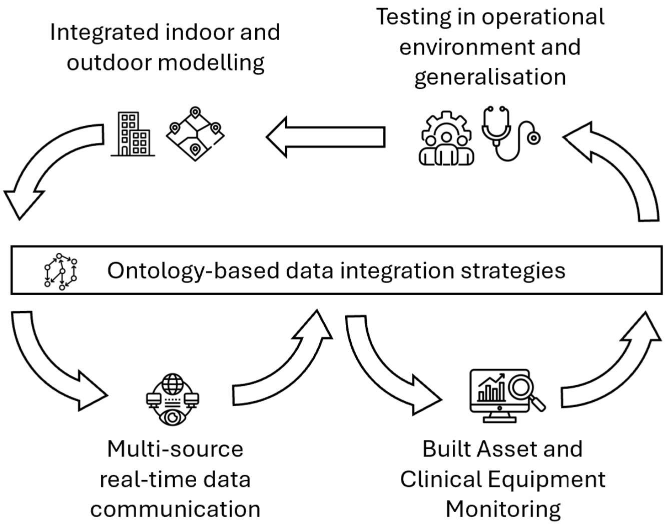

Figure 2: Space-aware hospital DT mid-term (3-5 years) research agenda.

4.2 Multi-source real-time data communication for process monitoring

The current DT prototype (Section 3.4) operated mainly with offline data; extending it to real-time scenarios requires developing robust data pipelines. Therefore, enabling real-time data communication between the physical hospital environment and the DT is another short-term objective. In fact, though the simulation models are a core part of the DTs [25], their dynamic connection with sensing and actuating technology is key to dynamically build scenario analysis, which provide right-time information to the operations and facilities managers. The simulation models can be used to support short-term forecasting by ingesting live data on building and process states at the beginning of each simulation cycle. This will require the development of a robust data serialisation protocol, potentially using formats such as JSON, MessagePack, or HDF5, to store and retrieve simulation states efficiently.

A key technical challenge will be the estimation of residual task durations based on elapsed time, which can be addressed through the implementation of truncated probability distributions and rejection sampling techniques. In parallel, the DT will be extended to support real-time tracking of specimens and assets using barcode scanners, RFID tags, or environmental sensors. This will allow the DT to function not only as a forecasting tool but also as a real-time control system, enhancing operational responsiveness and situational awareness.

4.3 Integration of Built Asset and Clinical Equipment Monitoring

The asset failure scenario (Section 3.5) illustrated how even a single lift failure affects performance. A mid-term objective concerns focusing on expanding the DT's scope to include the dynamic performance monitoring of both built assets and clinical equipment. While the initial implementation considered only a simplified model of asset failure (e.g., a faulty lift), future work will involve the development of a more comprehensive Facilities Management (FM) engine, which can incorporate data from Building Management Systems (BMS), Building Automation Systems (BAS), and Internet of Things (IoT) sensors to assess the condition of rooms, Heating Ventilation and Air Conditioning (HVAC) systems, and other critical infrastructure.

Simultaneously, a closer collaboration with Clinical Engineering teams should be initiated to integrate data on the operational status of diagnostic and therapeutic equipment. This will enable the simulation model to account for disruptions caused by equipment failures, which are currently excluded due to the assumption that staffing is the primary constraint. The integration of this data would support the development of predictive maintenance strategies and enhance the DT's ability to model complex interdependencies between space, assets, and clinical workflows. It is critical here to enable and secure the integration with the legacy IT systems.

4.4 Ontology-based data integration strategies

The modular backend design (Section 3.4) showed the feasibility of component integration but highlighted the need for a semantic layer to ensure interoperability across legacy IT systems supporting the multiple domains involved in hospital operations. On the mid-term horizon, a comprehensive ontology should be developed to federate data from Modelling and Simulation (M&S), Asset Management (AM), FM, IoT and Healthcare systems, currently based on diverse standards which do not align in terms of vocabulary, protocols and formats. For example, while the IFC schema provides a solid foundation for representing spatial process-related information, it lacks sufficient granularity for clinical assets and dynamic process events.

To address the interoperability challenge, a comprehensive ontology should be developed to include all the features of a hospital DT, including geospatial, process, assets (built and clinical), people, patients, staff, resources and supply chain information and should interface with the patients' DTs. Techniques such as Unified Modelling Language (UML), Business Process Model and Notation (BPMN), and Discrete Event System Specification (DEVS) can be used. The resulting interconnected domain knowledge (e.g., modelled as a knowledge graph) will enable the DT reasoning capabilities such as the dynamic compatible room-function assignments, the impact of asset degradation on the lab TAT, and the dynamic sequencing of clinical tasks, based on space availability and quality (supporting a more resilient process management). This semantic layer will also facilitate integration with legacy NHS IT systems and support the development of intelligent decision-support tools.

A critical consideration for ontology-based integration is cybersecurity and privacy. Real-time links between clinical, asset, and facility data may expose sensitive information and vulnerabilities in legacy hospital IT systems. Future work should adopt security-by-design principles (e.g., encryption, authentication, and access control) and align with healthcare standards such as HL7 FHIR (https://www.hl7.org/fhir/) and GDPR. As discussed further in Section 4.5, safeguarding data is a prerequisite for safe deployment of hospital DTs in operational environments.

Testing in operational environment and generalisation

On le the long term, the deployment and evaluation of the fully integrated DT architecture in real-world hospital settings is needed as working demonstrators of DTs in operational environments are still not sufficient. The challenge here is related to security, privacy and the effective integration with legacy operation technologies. Pilot implementations should be conducted in multiple healthcare facilities nationally and abroad, with varying spatial configurations and operational models and the results of the testing should be feedback to the improved integrated built environment modelling and ontology development. The effectiveness of the DT could in this way be assessed through a combination of quantitative performance metrics—such as turnaround times and resource utilisation—and qualitative feedback from end-users.

Scenario analyses could be conducted to evaluate the DT's ability to support strategic planning, such as temporary decamps due to contamination or structural degradation. The results will be used to build a business case for broader adoption of DT technologies in healthcare, highlighting their potential to improve operational efficiency, resilience, and patient outcomes.

Beyond healthcare, the same space-aware DT framework is applicable in other domains where spatial configuration, built assets and process efficiency are tightly coupled. For example, in assembly lines, DTs can link equipment reliability with production flow to minimise downtime. In airports, passenger flows, baggage handling, and security checkpoints depend on both layout and asset availability, much like patient transfers in hospitals. In shipping ports, the coordination of vessel berths, cranes, and container flows mirrors the interdependencies between space, assets, and processes in clinical settings. These parallels demonstrate the broader scalability of the proposed architecture.

5 Conclusions

This paper answers RQ1 by investigating the remaining knowledge gaps in the development of space-aware DTs for hospital operations and discussing them in Section 4. In doing so, a circular research agenda is proposed. The key objectives for achieving a fully developed and deployed DT system are illustrated in Figure 2 and organised into a 3-5 year roadmap, which starts with the clear identification of the modelling requirements of both the process and built environment models. Short-term goals are refining BIM-DES integration and real-time data links; the mid-term goals are enabling asset and equipment monitoring and ontology development; and the long-term objective is the deployment and generalisation (addressing RQ2). The ontology-based data integration strategy sits at the core of this agenda, enabling interoperability across systems, processes, and data domains. Revisiting the knowledge gaps (KG1-3), our findings confirm their relevance: BIM–DES integration addresses KG1 and KG2 by linking spatial and process inefficiencies, while the modular DT architecture begins to tackle KG3 on multi-source integration. In this way, the Digital Hospital project both validates and extends the identified gaps, providing common ground for the next stages of DT research.

To conclude, it is crucial that each research objective is co-developed with key stakeholders and users of the DT, including operations and facilities managers as well as medical professionals. This connection offers a holistic vision for moving space-aware hospital DTs from prototype to operational reality.

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