Digital twin construction with a focus on human twin interfaces

Soman, Ranjith K.; Farghaly, Karim; Mills, Grant; Whyte, Jennifer

DOI
10.1016/j.autcon.2024.105924

Publication date
2025

Document Version
Final published version

Published in
Automation in Construction

Automation in Construction 170 (2025) 105924

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Digital twin construction with a focus on human twin interfaces

Ranjith K. Soman [a,d,*], Karim Farghaly [b], Grant Mills [b], Jennifer Whyte [c,d]

[a] Integral Design and Management, Delft University of Technology, The Netherlands
[b] The Bartlett School of Sustainable Construction, University College London, United Kingdom
[c] John Grill Institute for Project Leadership, The University of Sydney, Australia
[d] Centre for Systems Engineering and Innovation, Imperial College London, London, United Kingdom

ARTICLE INFO

Keywords:
Digital twin construction
Interfaces
Control rooms
Data integration
Human-computer interaction

ABSTRACT

Despite the growing emphasis on digital twins in construction, there is limited understanding of how to enable effective human interaction with these systems, limiting their potential to augment decision-making. This paper investigates the research question: "How can construction control rooms be utilized as digital twin interfaces to enhance the accuracy and efficiency of decision-making in the digital twin construction workflow?". Design science research was used to develop a framework for human-digital twin interfaces, and it was evaluated in a real-world construction project. Findings reveal that control rooms can serve as dynamic interfaces within the digital twin ecosystem, improving coordination efficiency and decision-making accuracy. This finding is significant for practitioners and researchers, as it highlights the role of digital twin interfaces in augmenting decision-making. The paper opens avenues for future studies of human-digital twin interaction and machine learning in construction, such as imitation learning, codifying tacit knowledge, and new HCI paradigms.

1. Introduction

The construction sector is witnessing a transformative shift towards digitization, driven by the need to enhance performance, ensure sustainability, and manage the inherent complexities of modern projects [1–3]. Over the past decade, a notable evolution has been the transition from isolated digital tools to the more integrated framework of digital twins [4]. This framework brings together a myriad of technologies, including Building Information Modelling (BIM), Geographic Information System (GIS), Artificial Intelligence (AI), and real-time data sources like cameras, mobile devices, and sensors [5]. These technologies combine to facilitate the continuous exchange of information between the physical and digital realms. Driving and reflecting on this change, there is a body of research that underscores the potential of construction digital twins in improving decision-making processes, particularly during the production control phase of construction projects [4–12].

While an emerging body of literature advocates using digital twins in production control, many open questions remain [13]. A digital twin is not just a single entity; it is intricately manifested across different lifecycle stages. It essentially comprises three fundamental components: the physical artifact, its corresponding digital representation, and a bidirectional connection that facilitates seamless interactions between the two [14]. The construction domain, however, exhibits a distinct divergence from other sectors in its adoption of this technology. Predominantly, the industry seems to lean more towards developing digital shadows than full-fledged twins [15,16]. A key challenge in implementing fully-fledged digital twins is automating decisions within the digital environment and transmitting these decisions to their physical counterparts without human interventions [17]. As a result, human intervention becomes essential in deploying digital twins within the construction phase. Even with the existing studies illuminating construction processes with digital twin systems [6,18–20], a research gap persists regarding human interaction with these digital counterparts [17,21,22]. Further, concerns related to this interaction in the literature include selecting and installing the right system components, ensuring their integration and interoperability, and maintaining a workforce skilled enough to manage these systems effectively [13].

In the construction literature, there are references to 'big rooms' [23–28] detailing the interaction of humans with construction information. However, these primarily draw from the lean construction domain and do not resonate comprehensively with the Digital Twin Construction (DTC) workflow [19]. DTC is a holistic construction

* Corresponding author at: Integral Design and Management, Delft University of Technology, The Netherlands.
E-mail addresses: r.soman@tudelft.nl (R.K. Soman), karim.farghaly@ucl.ac.uk (K. Farghaly), g.mills@ucl.ac.uk (G. Mills), jennifer.whyte@sydney.edu.au (J. Whyte).

https://doi.org/10.1016/j.autcon.2024.105924
Received 13 November 2023; Received in revised form 2 December 2024; Accepted 6 December 2024
Available online 8 January 2025

approach that uses real-time data from design, supply chain, and site monitoring to effectively manage and close production control loops. Unlike lean construction, which aims to streamline production and reduce waste, DTC combines Building Information Modelling (BIM), lean principles, and AI for a proactive, data-driven management system. It operates on a "Model, Build, Monitor and Interpret, Evaluate, and Improve" cycle within the Plan-Do-Check-Act (PDCA) framework, ensuring continuous improvement by integrating real-time data feedback into every stage of construction [19]. Digital twin interfaces differ from the existing control rooms as they can augment decision-making by presenting relevant data and insights [18,24,28].

Digital twin interfaces are not objects but rather a dynamic environment where a range of stakeholders can communicate through a medium with each other and also the digital counterpart [29]. Crucially, the data obtained from Digital Twins should be visualized in a format suitable for human perception, ensuring that complex information is accessible and actionable [21]. Practitioners and stakeholders can interact with real-time project information, and interfaces should combine visualization techniques and dashboards to present datasets such as drawings and models, photos, Gantt charts, and graphs to inform decision-making [24]. Additionally, digital twin technology enables the analysis and understanding of the process from several viewpoints, corresponding to the stakeholders involved, thus enhancing collaborative decision-making [30]. While the capacity of digital twin interfaces to augment decision-making is recognized, the implications of their dynamic nature—as mediums of stakeholder communication rather than as static entities—require further exploration. Furthermore, the digital technology underpinning the computing and data handling capabilities essential for operating digital twins will only be as effective as our ability to manage it [31]. This necessitates a governance framework that is both transparent and flexible enough to engage users and earn their trust.

To address the concerns, this paper investigates the research question: " *How can construction control rooms be utilized as digital twin interfaces to enhance the accuracy and efficiency of decision-making in the digital twin construction workflow ?*". This leads to two sub-questions: 1) What is the optimal placement of construction control rooms within the DTC workflow to maximize decision-making effectiveness and digital twin knowledge development? and 2) What are the design considerations while utilizing construction control rooms as digital twin interfaces? The study in this paper employs the design science research methodology to address the research question [32] by creating an artifact, 'Human-Digital Twin Interfaces for Digital Twin Construction', and refining it through actual implementation. The scope of the study in this paper is limited to the project's construction phase, chosen due to the presence of a tangible counterpart for progress monitoring and a virtual dimension for managerial collaboration and decision-making. This phase is critical as the cost of change is substantial, and digital twins can enhance decision-making by providing data-driven insights. The remainder of the paper is structured as follows. Section 2 focuses on identifying the prevailing knowledge gap, while the methodology is elucidated in Section 3. The core aim is to devise a framework that assists the industry in effectively integrating human interactions within the digital twin environment using control rooms. This endeavor, detailed in Section 4, is anchored in the unique requirements of the construction sector, the nuances of digital twins, and the dynamic nature of control rooms, drawing from expert workshops, iterative prototyping, and iterative feedback. Section 5 presents a pilot control room reflecting the framework's principles, showcasing its adaptability in a real-world construction context. The feedback from industry stakeholders, crucial for the evaluation of the framework, is discussed in this section. In Section 6, synthesis of our findings and new insights are presented and the limtitions of this work are presented in Section 7. In Section 8, conclusions are presented, encapsulating the primary insights and pointing towards potential future research directions.

2. Digital twins and data-driven construction management

The following section offers an overview of essential concepts relevant to this study. It starts by introducing production control and look-ahead planning in construction, emphasizing the paper's concentration on the construction phase and the significance of information during that stage. The discussion then transitions to the need for situational awareness in production followed by digital twin construction, presenting existing frameworks for its workflow. Finally, the discourse shifts to analyzing digital twin interaction in construction, which serves as the forefront of human-computer interaction for production control. The section wraps up with the point of departure presented in Section 2.5.

2.1. Look ahead planning and role of information management

During the construction phase of a project, the most significant impact of a digital twin would be streamlining the production control. Production control is a concept in project management that aims to steer the project to achieve predefined costs and schedule targets defined during the planning process [33]. While project monitoring focuses on defining financial and schedule targets and monitoring the variance from them (e.g., through earned value, cost variance, and schedule variance), production control has a specific focus on making sure that the project control targets are achieved by steering the projects through the planned path, or figuring out an alternative path when the planned path fails to achieve the targets [23,33]. Production control is critical in lean construction methods, especially the Last Planner System (LPS) [34]. Production control is reported to have increased construction productivity by improving workflow reliability [35,36].

Look-ahead planning is a crucial phase in production control, whereby the forthcoming construction programme is reviewed four to six weeks before execution to communicate issues and identify efficiencies [36,37]. Look-ahead planning was first introduced as a part of the LPS for the production control Field [23] and enabled lean construction's pull scheduling. In contrast with traditional planning, which follows a push-driven approach, look-ahead planning can improve schedule reliability, accuracy and workability [38]. It ensures that all prerequisites are complete and constraints are removed for each work package before the work packages are released to weekly work plans, thus ensuring the flow of the work [33]. The activities planned for the forthcoming weeks are identified from the master plan, followed by a constraint analysis on identified activities to ensure they are ready [37,39]. The activities whose constraints are completely removed and are in a proper sequence are then scheduled for the next six weeks.

Information management has a significant role to play in supporting production control. The synergy between BIM and production control has been explored [40]. Their review suggests that the BIM functionalities (such as collaboration in construction using 4D BIM, rapid generation and evaluation of construction plan alternatives, and object-based communication in BIM) support production control through digital management of the construction process. Further, existing literature has identified capabilities required to support the last planner system to support the production control [18,41–43] (see Table 1).

Several tools have been developed to support production control in construction. For example, KanBIM, a prototype using BIM to support planning, negotiation, and commitment, has shown promising results to visualize the status of the different work packages [43]. KanBIM was later developed into a VisiLean, a commercial solution. Similarly, researchers have worked on cloud-based BIM to improve collaboration among project participants, focusing on communicating constraints [44–46]. Also, Song et al. [47] see detailed BIM models generating daily work orders (Matching resource availability with the workload and preparing a list of actions to make the work ready) in the look-ahead planning process. These work orders can help automatically generate activity assignments from a resource-loaded BIM model with embedded

Table 1
Capability requirement for IT systems to aid production control.

Capability	Source
1. Support for physical collaboration of Last Planner during the planning	[18]
2. Schedule and cost tracking with great frequency	[18]
3. Visualization of the construction process and its status	[40,43]
4. Visualization of the construction product and work methods	[40]
5. Support for planning, negotiation, commitment, and status feedback	[40]
6. Implementation of pull flow control	[40]
7. Maintenance of workflow and plan stability	[40]
8. Formalization of production experiments for continuous process improvement	[40]
9. Reviewing commitments from the previous week and making commitments for the next week, i.e., allowing for creating a weekly plan.	[41]
10. Review and establish restrictions for each activity, specifying the person responsible and the date and the causes of non-compliance.	[41]
11. Create or allow to enter a list of tasks in an intermediate plan and the global plan of the project.	[41]
12. Allows to propose and control corrective actions to the causes of non-compliance.	[41]
13. Consolidate historical records of restrictions and causes of non-compliance affecting the project.	[41]
14. Restrict the progress of tasks with restrictions and/or their inclusion in short-term periods.	[41]
15. Standardization of the planning and control process	[42]
16. Use of indicators to assess compliance with planning	[42]
17. Critical analysis of information	[42]
18. Using an easy-to-understand and transparent master plan	[42]
19. Analysis and systematic removal of constraints	[42]

planning information. In addition, there have been efforts to support look-ahead planning using ADC technologies and BIM [48–50].

2.2. Situational awareness in construction production control

When projects get more complex, it is challenging to do constraint checks and create Look Ahead Schedules manually [37,51], resulting in errors [52,53]. Prior research has developed linked data-based approaches to codify complex constraints and then used automated methods to check for constraint violations [54]. Studies on situational awareness (SA) in construction management, particularly regarding production control, have demonstrated its potential to help in such situations. Martinez [55] demonstrates a positive correlation between production planners' SA and workflow quality, and Halttula [56] shows that digital awareness systems can support takt production and enhance task productivity. However it needs real-time situational data to empower workers [57], and a systematic understanding of SA levels, measurements, and influencing factors [58]. Additionally, Lappalainen (2021) identifies deficiencies in current SA systems, noting that merely collecting and presenting data is insufficient [59]. To qualify as a true SA system, it must also incorporate the second and third levels of SA: understanding the data and projecting future states based on it. Digital twins in the construction phase can significantly improve situational awareness for production control. Halttula [56] and Eckhart [60] highlight their role in boosting productivity and providing a comprehensive project overview. Other studies emphasize their simulation, real-time monitoring, and quality control applications [8–10,61].

However, strategies must be developed to interact and manage constraints in a user-friendly environment to support decision-making during the look-ahead planning stage. In addition, most of the developed tools are an all-in-one solution and require users to completely change their workflows and hardware and software platforms to use these closed systems. This is against the recommendations proposed in Hartmann [62], where it was suggested that new technologies co-exist with existing workflows for better adoption. The importance of these more open systems for production control needs further investigation.

2.3. Digital twin construction (DTC)

Digital Twin Construction (DTC) introduces an integrated method in the construction sector by harnessing "digital twins" for data-centric management and oversight of physical structures. Central to DTC is the Plan-Do-Check-Act (PDCA) cycle, which promotes continuous enhancement and ensures each construction phase is fine-tuned using real-time feedback. [19] This approach fosters a proactive construction process, with each phase evolving based on prior experiences. The DTC model spans several dimensions: the tangible and digital, the end product and the ongoing process, and the alignment between intended and actual progress. The real construction site and its digital counterpart have a constant data flow. The model also emphasizes the synergy between design plans and actual construction activities. Due to the intricate nature of these dimensions, a comprehensive "system of systems" approach is vital, ensuring all DTC elements cohesively drive a construction process that's both agile and attuned to real-world complexities [19].

Within this expansive framework, construction projects are part of a larger ecosystem, encompassing the wider built environment and local economic structures [63]. The interactions among digital twins, representing anything from construction machinery to overarching infrastructure, are crucial. Humans orchestrate these interactions, ensure effective communication, and address data reliability concerns. Construction endeavors demand extensive collaboration among many stakeholders, such as designers, consultants, and contractors [64]. While tools like DTC streamline data sharing and insights, human expertise remains indispensable for informed decision-making. Even as DTC offers a data-focused construction management approach, humans are its linchpin, steering its functions.

Effective collaboration between humans and Digital Twins (DTs) hinges on clear role delineation. This concept ties back to the distribution of tasks among humans, computers, and robots, and their integration with Cyber Physical Systems [65]. DTs wear multiple hats, from data gatherers to decision-makers [17]. Prior research highlights four pivotal roles for a digital twin: as an Observer, it collects and presents data akin to human sensory perception, exemplified by using sensors to gauge soil conditions; as an Analyst, it processes raw data, leveraging advancements in artificial intelligence, such as determining soil's bearing capacity post-assessment; in the Decision Maker role, it offers informed solutions, like suggesting crane path alterations if soil conditions are suboptimal; and as an Action Executor, it enacts decisions, potentially aiding in tasks like remote crane control and recognizing that a digital twin might encompass one or several of these roles is crucial, with humans filling any gaps. Concerning autonomy levels, they range from No Automation, where humans dominate, through Routine Support and Routine Autonomy, where the digital twin offers varying degrees of assistance or independence in standard tasks, to Non-routine Support and Non-routine Autonomy, where the digital twin aids in or autonomously handles complex tasks, signifying a shift towards data-driven organizational decisions and showcasing the immense potential of evolving technology. The automation extent for each can be at different levels, transitioning from manual operations to complete automation [17]. Humans, conversely, complement DTs by acting on their analyses, ensuring alignment with broader goals, and sometimes taking over data-related tasks, capitalizing on their unique expertise. A solid interface between digital twins and humans is essential to harness this collaborative potential.

2.4. Digital twin interaction in construction

Prior research has developed frameworks to enable real-time information flow between the construction site and construction digital twins for effective decision-making [7,44]. Building on these frameworks, researchers have developed collaborative visualization environments such as control rooms to visualize and interact with real-time

Table 2
Evolution of control rooms in the construction sector for production control.

Paper	Summary	Limitation
The CIFE iRoom Fischer et al. (2002) [27]	The CIFE iRoom featured three large boards acting as screens: the first displayed the 4D model view, the central panel showed the Microsoft Project schedule as a Gantt chart, and the third screen displayed the system's 'room controller', providing a graphical user interface for drag-and-drop application and data management across the room.	The work does not integrate process data with risk management, pre-construction document control workflow, and real-time site updates. No risk resource documents real time connection
Field - Kuo et al. (2011) [72]	Proposed a multi-system with four advanced screens for construction information visualization. This system included features for controlling maneuverer and extracting information, aimed at improving the management and coordination of experts working on a project.	
Digital display room McHugh et al. (2018) [28,73]	Focused on weekly on-site production control meetings with four interactive displays: one for the construction schedule, a second for a federated BIM model in 3D, and the third and fourth screens for necessary site drawings and other materials. The sequence and arrangement of screens mirrored the planning session flow, aiding in visualization, control, and reporting of production status.	The work does not connect with risk management and resource requirements
BeaM! Schimanski et al. 2021) [68]	A software prototype for BIM-Lean integration using an Industry Foundation Classes (IFC) structure. This environment advanced the last planner by integrating and visualizing 3D models, phase planning, and look-ahead datasets.	The work does not integrate process data with risk management, pre-construction document control workflow, and real-time site updates.
CCR Ezzedine et al. (2023) [74]	Introduced the Construction Control Room (CCR) concept, inspired by military operation rooms, for coordinating, supervising, and controlling live construction projects. The CCR included large screens for monitoring live data streams, a digital dashboard for comprehensive project data view, and dedicated personnel for monitoring progress. It was implemented on the Beirut reconstruction project.	The work does not integrate document management and risk management datasets.

construction information for effective production management [18,28]. A range of studies have explored the use of big rooms in construction for production control. Temel [66] and Majava [67] both highlight the importance of the big room concept in improving coordination, communication, and visual control among project stakeholders. Schimanski [68] discusses integrating BIM and Lean Construction methods in big-room settings, emphasizing the need for functional requirements and the potential for value co-creation. Dave [69] proposes a product-centric system for production control, while Farghaly [24] and Tezel [70] explore the use of real-time data visualization and IT-based visual management in big rooms. Boton [71] underscores the role of big rooms in BIM projects, particularly in integrating different disciplines and improving information sharing. These studies collectively highlight the potential of big rooms in enhancing production control in construction.

The NASA mission operations control room is a well-known example of a large-scale collaborative data display, with multiple real-time data streams available to engineers. Inspired by this example, the construction industry has adapted the concept and started implementing production control rooms to display and monitor the progress of construction sites. Despite how the control room looks, it is defined by what it does [75]. Several control rooms have been developed and implemented in construction sites in the last two decades, such as CIFE iroom Field [18], construction dashboard system Field [49], and BeaM! [18]. The shape, size, and space hosting the construction production control room have changed and become more advanced. The evolution of control room architectures over the years are shown in Table 2. Limitations, such as the lack of integration of process data with risk management, pre-construction document control workflows, and real-time site updates in the current studies, may limit situational awareness for effective production control in construction detailed in section 2.2. However, there are opportunities to learn and develop construction production control predictability.

2.5. Point of departure

There is a noticeable gap in the existing body of literature regarding the integration and situating of control rooms as human-digital twin interfaces within the digital twin construction workflow to improve situational awareness for production control. While studies emphasize the productivity benefits of digital situational awareness systems [56,60] and highlight applications in real-time monitoring and quality control [8,10–13], the focus on control rooms is limited. Other studies illustrate advancements in construction control rooms [28,74], but these studies do not fully integrate digital twin concepts or human-machine interaction.

The concept of human interaction with Digital Twins (DTs) is explored through various studies emphasizing the need for innovative interfaces. Palmer (2023) proposes a "symbiotic interface" for DTs to enhance human collaboration [76], while Dingli (2019) details HCI components in Intelligent Digital Twin systems [77]. Löcklin (2021) discusses a Human-centered Digital Twin (H-DT) architecture for bi-directional information flow in production [78], and Wilhelm (2021) provides a human-centered classification of DTs, highlighting current scenarios and future research directions [79].

These studies highlight the need for deeper exploration into human-digital Twin (DT) interactions, highlighting a broader research gap. This lack of integration in existing studies (Table 3) presents a significant opportunity for research to explore how control rooms can function as dynamic interfaces within the digital twin ecosystem, enhancing decision-making and situational awareness in construction management. Addressing this gap could lead to improved production control by leveraging real-time, data-driven insights and fostering better human-machine collaboration.

Table 3
Need for a study on digital twin interface.

Focus	Point of Departure
Digital situational awareness systems [56,60]	Limited focus on integrating control rooms with digital twin interfaces for improved situational awareness.
Applications of digital twins in construction [8,10–13]	Do not fully integrate digital twin concepts with human-twin interaction.
Construction control rooms [28,74]	Lack integration of control rooms with digital twin ecosystems and human-machine interaction.

3. Research methodology

This paper on the integration of control rooms within digital twin systems as dynamic communication environments for stakeholders was steered by the Design Science Research (DSR) paradigm, drawing inspiration from foundational work by Simon [80]. Simon's perspective emphasizes a pragmatic approach, focusing on crafting innovative artifacts to tackle real-world challenges. This methodology is especially apt for information systems (IS) research, given its engagement with two core aspects: the debated central role of IT artifacts [81–83] and the aspiration for professional relevance in IS studies [83,84]. With its roots in engineering and the sciences of the artificial, as highlighted by Simon (1996), the DSR paradigm inherently adopts a problem-solving approach. This methodological choice was further validated by its widespread adoption in numerous construction informatics research endeavors, underscoring its relevance and applicability to the study.

Design science research intertwines design and behavioral sciences to tackle complex IT application challenges through three interlinked cycles: Relevance, Rigor, and Design. The Relevance Cycle roots research in practical contexts, setting benchmarks for requirements and evaluation, questioning the artifact's environmental impact and measurable improvements. These findings are then cycled back into the practical setting for real-world validation. The Rigor Cycle builds the research on a solid foundation of existing knowledge, carefully applying theories and methods to develop and assess artifacts. At the heart of this methodology, the Design Cycle iteratively refines the artifacts through construction and evaluation.

The Relevance, Design, and Rigor cycles are pivotal in formulating the framework, ensuring an evidence-based approach. The Rigor Cycle deeply roots the framework in scholarly and practical domains, as depicted in Fig. 1. A literature review (Section 2) forms the academic foundation, while industry insights provide a real-world context. This is further enhanced by *end-user requirement* studies, ensuring the framework meets genuine industry demands. The study's environment for the Relevance Cycle was a live urban redevelopment project, where a control room was set up through a partnership between industry and academia, funded by the UK government, as elaborated in Section 5. The Rigor Cycle guarantees methodological robustness, drawing from literature on look-ahead planning, the significance of digital twins, and the incorporation of digital twin systems in construction. This academic probe ensures the framework's relevance and foundation on existing knowledge.

The Design Cycle encompassed the iterative development of the digital twin interface framework, informed by feedback from both the Relevance and Rigor cycles. Initially, the digital twin interface was integrated into the DTC workflow to determine its roles within this context based on end-user requirements and results of the literature review. This led to the first iteration of the Human-Digital Twin Interface framework, which was continuously tested through various stages. First, *end-user requirements* were gathered and analyzed over five months through observations of meetings and interviews to determine the placement of the interface in the digital twin workflow and determine the functional requirements of the interface (see Sections 4.1 and 5.1, Fig. 2 and Table 4). Subsequently, *data integration* involved examining existing data and software tools to identify implicit connections (Sections 4.2 and 5.2). *Predictive analytics and visualization* were then developed through co-creation workshops with end users to make sure human-twin teaming is possible to improve situational awareness (Sections 4.3 and 5.3), incorporating input from the Rigor and Relevance cycles. Each step included workshops with end users to discuss and refine outputs.[1] The developed interface was implemented in the project workflow and observed for approximately five months, with iterative modifications based on user feedback gathered from seven workshops during the implementation study (Section 5.4, Fig. 2, and Table 4). The final output of this detailed research is presented in Section 4, with the design cycle described in Section 5.

The digital twin interface design cycle was performed in the construction of an urban redevelopment project. This ambitious project involves the construction of a striking cube-shaped edifice hovering over a three-story podium, culminating in a structure that spans ground plus 18 stories. Below this, a new four-story basement will house back-of-house operations, plant machinery, and retail spaces. The project's intricacy is further amplified by the involvement of numerous stakeholders, including four design consultants, a primary contractor, and

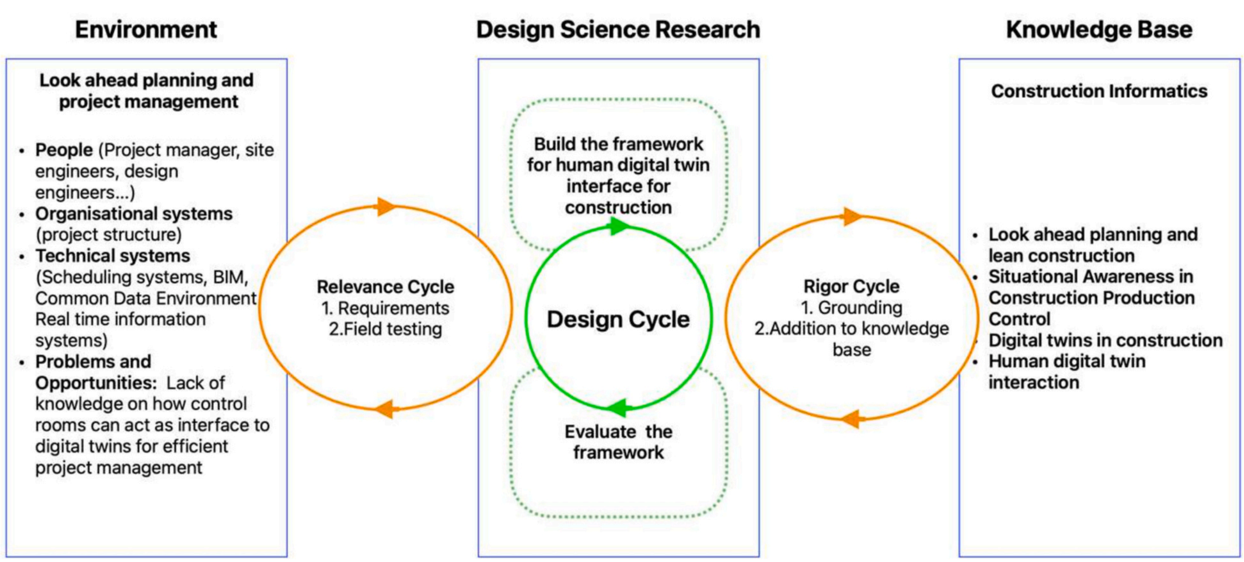

Fig. 1. Design science research cycle for the development of a framework for human digital twin interface for construction.

[1] To conduct the data collection, ethics approval was granted by University College London's Research Ethics Committee and is filed as UCL 19083/001: AEC Production Control Room.

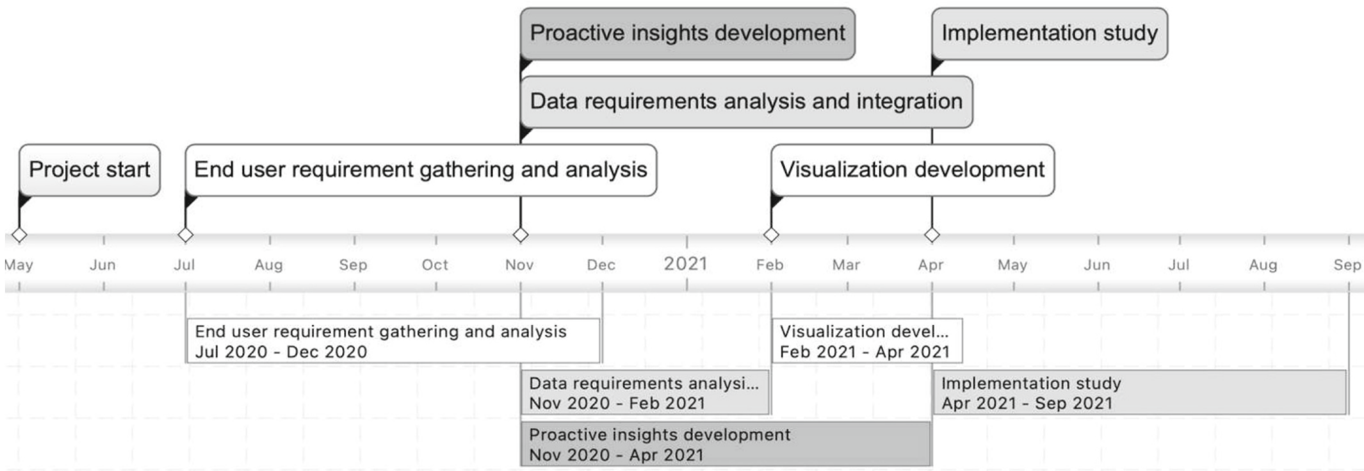

Fig. 2. Project activities and associated timelines.

Table 4
Data collection records.

Data Source	Count	~Time
Look-ahead-planning-meetings - Researchers were silent observers of the planning meetings attended by end-users of the platform. End users include project director, package managers, sub-contractors, document controllers, planners, and digital engineers. Researchers observed the nature of discussions, interactions between end-users, interaction between end-users and construction data sets, decision making process, and look-ahead planning process.	9	9 h
Interviews with end-users - End-users of the control room were interviewed to understand their current work process, datasets they interact with to support their work process, how they would interact with the control room, what features that they would like to have in a control room and why they would want them. End-users included Project manager, package manager, planners, digital engineers, and subcontractors	8	12 h
Documents and software tool access - The researchers had access to different documents, datasets, software tools, common data environment and workflows used for production control. This access was used to map the capabilities of different tools and how they interacted with each other.	7	12 months
Meetings with end-users involved in co-creation - Problem owners and end-user representatives associated with digital engineering (BIM manager and document controllers) to discuss the evolution of requirements, data integration, and visualization development. These meetings were used to refine the developments with feedback from the practice.	20	20 h
Meetings with problem owners - These are the meetings with main contractor's innovation team, research teams from two major universities, three start-up companies, and the UK's national innovation agency where the researchers discussed the various outputs such as end user requirements, data integration, predictive analytics, and visualization. The procedure of planning, acting, observing, and reflecting were followed for each task.	25	50 h
Workshops on site - These were the workshops where problem owners and end-users met and discussed the outputs of each research steps to refine them. Feedback from the end users to improve them. These workshops also served as a venue to train and the end-users to use the different aspects of the control room.	3	9 h
ROI Workshop - A workshop was held with four project teams and platform providers' representative. Direct quotes from members of the project team might support ongoing discussion on how a return on investment was formally stated.	7	3 h

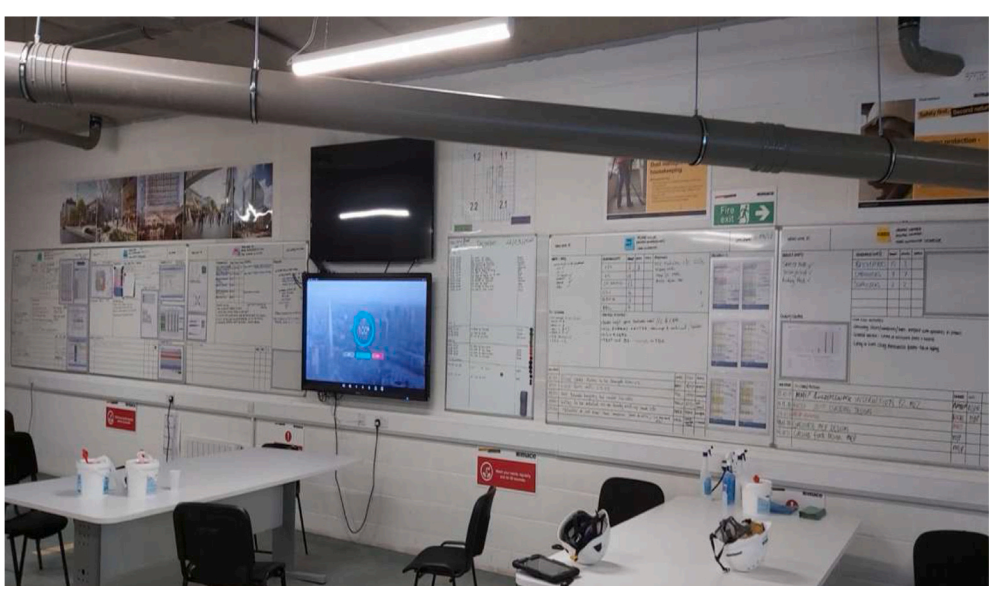

Fig. 3. Existing control room.

over 20 subcontractors. Furthermore, this project was located in central London, adjacent to a major railway station and surrounded by busy roads and tube lines. This made the delivery of materials and the operation of heavy equipment challenging, requiring extensive coordination. Given the project's multifaceted nature, with various production control information generated daily with many interdependencies, it presented an ideal setting for the control room's implementation. Fig. 3 represents the existing control room where the data was recorded on whiteboards, resulting in zero traceability and fragmented information.

4. Human-digital twin interfaces for digital twin construction

To seamlessly integrate human interactions within the digital twin environment using a control room, it's imperative to distinguish between Digital Twin Construction (DTC) and prevailing construction management practices. The salient distinction is that DTC is inherently data centric. Further, there is a need to understand the role a digital twin plays during digital twin construction. Previous research indicates that digital twins can assume various roles: (1) Observer, (2) Analyst, (3) Decision Maker, and (4) Action Executor [17]. In construction project management, especially during look-ahead planning, the digital twin typically serves as an Observer, Analyst, and Decision Maker. The role of Action Executor is less common since construction largely depends on human intervention to translate decisions into actions, given the current limited automation in the field. However, this dynamic might evolve in the future.

Moreover, these roles manifest with varying degrees of autonomy, from no automation to complete autonomy. Within look-ahead planning, the digital twin's role can vary. For highly intricate decisions with scarce data, there is minimal automation. Yet, the digital twin offers non-routine support for scheduling and resource management tasks. Therefore, digital twin construction would fall between areas highlighted in blue in Fig. 4. This placement informs the design considerations for the digital twin interface.

To accurately conceptualize a digital twin interface for construction, it's essential to differentiate between data, information, and knowledge. These distinctions are pivotal as they shape our comprehension of the semantics and the inherent uncertainty within various facets of DTC workflows [19]. Decision-making within the DTC workflow encompasses two primary data sets: real-time data from the ongoing project represented by the digital twin and historical digital twin data, which informs design knowledge. Once interpreted, the monitored data from the live project provides the project status information (PSI). When contextualized within a broader project framework, this information, upon inference, yields the Project Status Knowledge (PSK). Subsequently, merging the PSI with anticipated plans results in formulating the Project Intent Knowledge and outlining plans. In look-ahead planning, this pertains to identifying project activities with removed constraints, ready for execution. This knowledge is then transformed into Project Intent Information (PII). In conventional construction practices, managers are tasked with collating project status information, interpreting it, and amalgamating it with intent knowledge to derive the PII. Analogous to DTC, they leverage their past experiences from other projects, akin to data from historical digital twins.

The interaction between managers and the digital twin is paramount in a future where computer-based insights through DTC enhance human decision-making. The best position for the control room interface in the DTC workflow process proposed by Sacks et al. [15] would be right after we've fully understood the current project status (PSK phase) but before we start planning the following steps (Project Intent Knowledge stage) (See Fig. 5). This stage is pivotal because it's where we consider the past, present, and future to make decisions. Here, the digital twin plays a crucial role, providing managers and engineers with valuable insights and simulations to make informed choices.

Building upon the insights into the Digital Twin Construction (DTC) workflow and its interaction with conventional construction practices, it becomes evident that we must first position the digital twin within the broader construction management processes to craft interfaces within

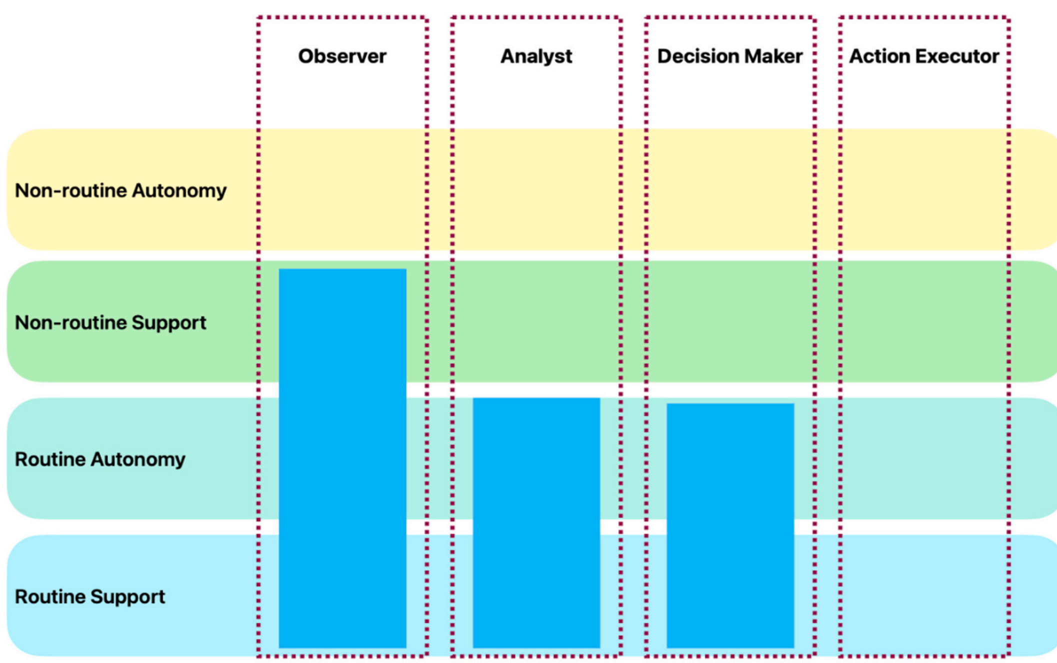

Fig. 4. Roles that digital twin plays in digital twin construction and levels of autonomy adapted from [17] -represented as blue bars. DT would support data collection and observations in non-routine and routine situations, perform routine data analysis and decision making autonomously for routine situation, but not perform any actions. Humans would handle data analysis, and decision making in non-routine situations. Actions in all situations would be performed by humans. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

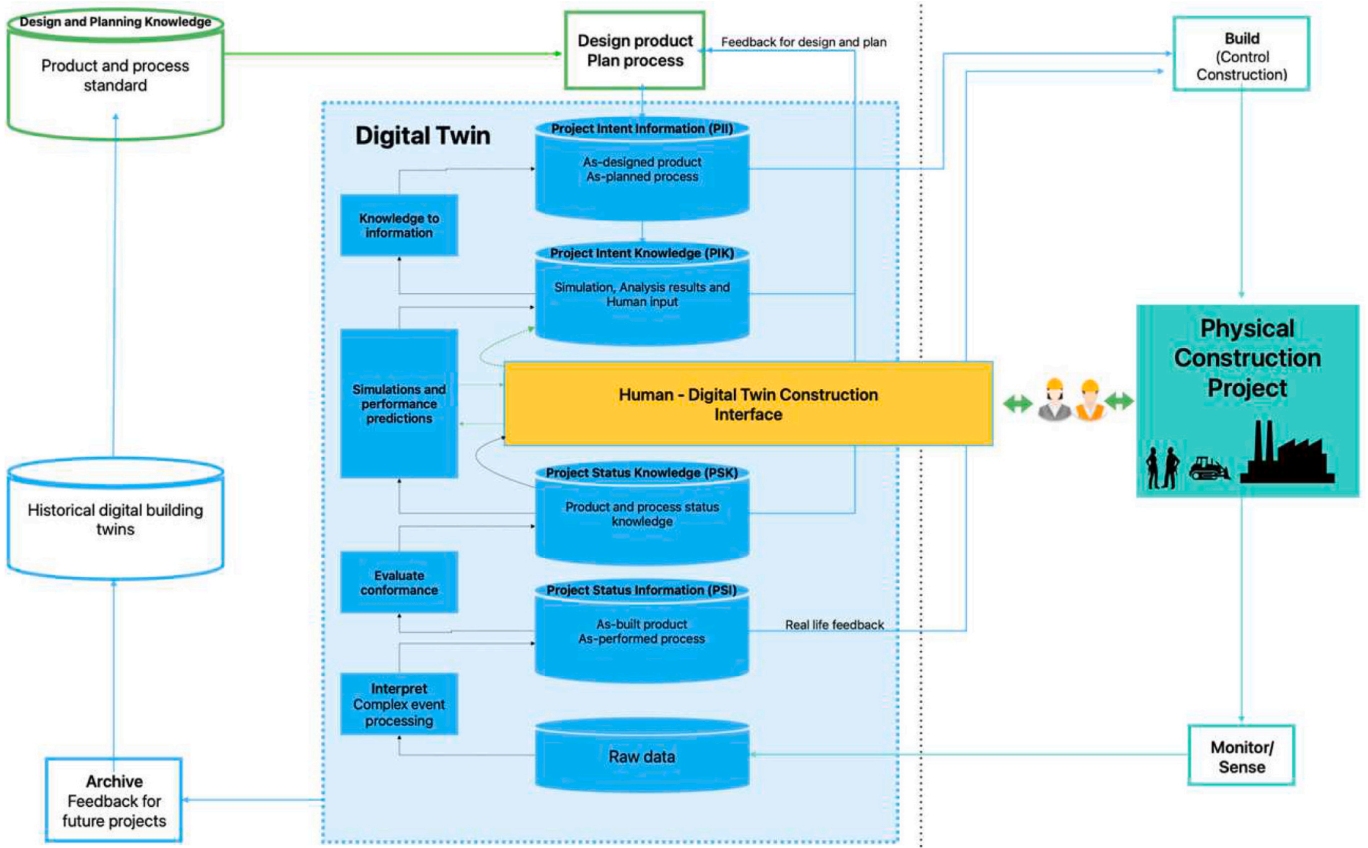

Fig. 5. Digital twin interface within digital twin construction from [19].

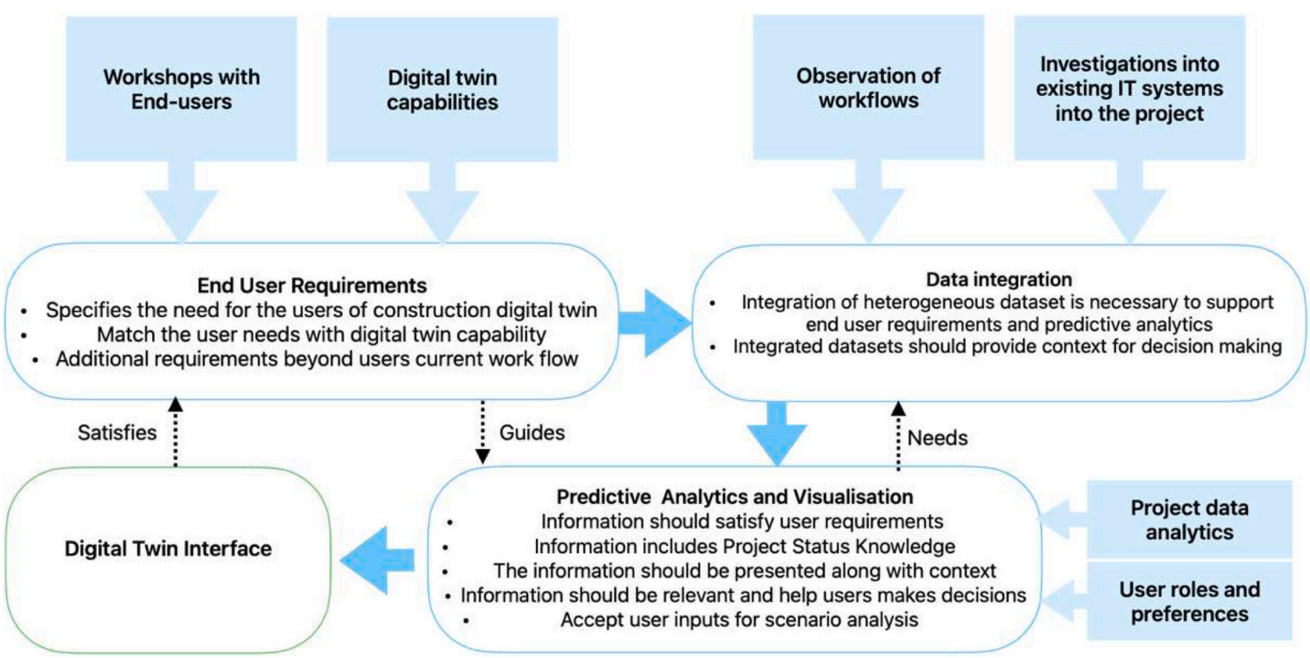

Fig. 6. Digital Twin Interface Design Workflow.

the DTC workflow. This positioning necessitates that the development of user interfaces be rooted in user requirements. Catering to these requirements often calls for integrating diverse data sources and formulating analytics tailored to support these needs. Equally significant is the role of visualization. Effective visualization techniques foster user engagement and facilitate meaningful interactions with the digital twin. To examine these critical facets more deeply, the subsequent subsections will discuss design considerations (See Fig. 6) for digital twins' interfaces based on the above.

4.1. End-user requirements

Adopting a systematic requirements engineering approach to develop a robust digital twin interface tailored for the construction sector is essential [22,85]. This cyclic methodology starts with defining and documenting the requirements of the digital twin interface. Researchers must then immerse themselves in the contextual environment where the interface will operate, ensuring the requirements are relevant and practical. The process continues with requirement induction, where initial requirements are gathered, followed by their evaluation to assess feasibility. Detailed specifications and documentation are crucial for clarity and future reference. The cycle concludes with validation and verification stages, ensuring that the requirements are accurate and complete, all while being managed and overseen for smooth transitions and problem resolution. Researchers may use one of the established requirements analysis methods, such as 'goal and scenario-based domain requirement analysis' [86]. Here, a 'goal' is defined as an objective a stakeholder aims to achieve in the future, gathered during the initial stages by attending look-ahead planning meetings and conducting interviews with the control room's end-users. A 'scenario', on the other hand, is understood as a set of planned interactions among various agents within certain limits.

A combination of observational and interview methods is used for effective requirement gathering. Researchers can gain insights into potential stakeholders, their needs, and existing workflows by attending relevant meetings, such as those focused on look-ahead planning in construction. Complementing this, semi-structured interviews with these stakeholders can further refine the requirements list. It is vital that researchers not solely rely on end-users but also introduce potential capabilities of the digital twin interface based on their expertise. Once gathered, these requirements are categorized into functional, detailing what the interface should do, and non-functional, describing how it should operate. Non-functional requirements can be further broken down into constraints, usability, security, efficiency, functionality, reliability, and maintainability [87]. For instance, constraint requirements might dictate using a consistent technology stack to ensure scalability and reduce rework. Usability requirements emphasize user-friendly operation and clear outputs, while security requirements focus on safeguarding confidential data. Efficiency and functionality requirements address the interface's performance and specific features. Lastly, reliability ensures the interface functions under given conditions, and maintainability ensures its adaptability to new technologies and platforms. To ensure user adoption and effectiveness, emphasizing efficiency and usability is crucial, especially in non-functional requirements. Feedback mechanisms, like workshops, can further refine and validate these requirements, setting the stage for the interface's practical implementation.

4.2. Data integration

For the construction project's look-ahead planning, accurate data structures are paramount, ensuring clarity and preventing errors in interpretation. Developing a digital twin encompasses many data and integration considerations [88]. However, it is crucial to consider user-specific interface development requirements. These requirements outline the unique scenarios where users might utilize the digital twin. Data management is pivotal, the connecting 'thread' for various application scenario components [89]. The digital thread concept is significant, facilitating end-to-end connectivity and interoperability. It seamlessly links real-world entities with their digital counterparts, integrating communication networks, design algorithms, and essential visualizations throughout the design, construction, and operational phases [89]. A thorough data integration approach, tailored to user-defined application scenarios for interface development, is essential to realize this.

Within the AEC sector, five primary strategies for data integration emerge Schema, service, ontology, process, and system [90]. Schema-based methods, such as the Industry Foundation Classes (IFC), are crucial in achieving interoperability within BIM systems [91]. In contrast, service-based approaches typically utilize Application Programming Interfaces (APIs) for data extraction and subsequent integration. Notably, ontology-based methods are often the most effective for integrating data within digital twins [92–94]. When formulating ontologies, researchers should adhere to two guiding principles: first, to leverage and expand upon existing ontologies, capitalizing on the embedded knowledge, and second, to emphasize the development of modular ontologies. These modular designs streamline the mapping and merging processes and bolster adaptability across various applications. Given the increasing number of ontologies in the AEC domain, each catering to different functions such as the production control Field [68,69], digital twin information management Field [17,65], safety Field [70], etc., it's vital to approach data integration with one of the strategies above, ensuring optimal results.

4.3. Predictive analytics, simulations, and interactive visualization

The primary aim of the interface within digital twin construction is to enhance the decision-making capabilities of construction managers by harnessing the computational strength of the digital twin. Look-ahead planning stands out as a pivotal stage in construction planning and control, where the construction agenda for the upcoming six weeks is formulated. Interfaces in digital twins are primarily used in this stage. During this phase, it is essential to confirm that all prerequisites for each work package are met and that any potential constraint violations are addressed before integrating them into weekly work plans [37]. These interfaces should be equipped with advanced analytics to assist managers in making informed decisions. Previous studies have pinpointed tasks such as the constraint verification Field [43], generation of look-ahead schedules Field [71], and risk reduction [13]. Constraints, like the relationships between activities or the logical ties between tasks, resources, and on-site conditions, can be discerned from consolidated datasets in digital twins. This allows for a deeper understanding of underlying issues and the ability to anticipate potential delays. The presence of constraint violations can indicate the likelihood of an activity taking place as scheduled. For instance, an activity with numerous constraint violations has a reduced chance of occurring on its intended date, which could delay any succeeding activities. Therefore, by analyzing constraint violations, one can forecast the confidence levels associated with the scheduled tasks within a specific timeframe.

Developing an interactive visualization for a digital twin interface requires a harmonious blend of principles from human-computer interaction (HCI), digital twin construction, and user requirements section 4.1.

First, the interface should be designed such that it can be placed between Project Status Knowledge and Project Intent Knowledge stages [19], so that users can make informed, computationally augmented decisions. The interface should provide visualizations of project status information, simulation results, performance predictions, and elements of project intent knowledge derived from existing data. Interactivity is paramount, allowing users to probe deeper into the data and understand its context. Additionally, the digital twin should offer a section to display raw data, such as photographs, weather forecasts, delivery schedules, and document submission timelines, providing a comprehensive context for decision-making. Real-time simulations, activated by human input and interactions with the digital twin, further enhance its utility.

Secondly, visualization of the interface should be tailored to meet the specific needs of its users described in Section 4.1. This means the workflows essential for fulfilling user requirements should be delineated in the interactive visualization development. The design should be intuitive, guiding users seamlessly through the processes they need to complete, ensuring that the interface serves its functional purpose and offers a user-friendly experience.

Table 5
Example of design consideration for digital twin interface for DTC.

End user Requirement	User profiles	Project Director, Project Manager, Subcontractors, Trade Contractors, Safety Manager, Risk Manager, Procurement Manager, Site Manager, Temporary Works Engineer, Design Engineers, Quality Control Manager, Financial Controller, Environmental Manager, Stakeholders, Logistics Manager, Legal Advisor
	User roles	Decision Making, Data Extraction, Data Input, Data Input, Data Analysis, Scenario Analysis, Data Extraction, Data Input, Data Input, Data Input, Data Analysis, Data Analysis, Data Analysis, Decision Making, Data Analysis, Data Extraction
	Requirement examples	Weather Display, Risk Register, Model Display, Photo Review, Schedule Monitoring, 3WLA Presentation, Work Milestones, Risk Location, Snag Presentation, Activity Zones, Activity Deliveries, Action Recording, 3WLA Sync, Work Integration
Data integration	Data types	IFC, Revit files, MS Project, Primavera P6, XLSX, CSV, Excel, Navisworks, Synchro, JPEG, PNG, PDFs, DWG, Database files
	Data integration methods	Schema, service, ontology, process, and system
Predictive analytics	Data analytics methods	Descriptive Analytics, Diagnostic Analytics, Predictive Analytics, Prescriptive Analytics, Exploratory Data Analysis, Data Mining, Text Analytics, Time Series Analysis, Statistical Analysis, Cluster Analysis, Sentiment Analysis, Anomaly Detection, Association Rule Learning, Regression Analysis, Classification Analysis, Forecasting, Data Visualization, Correlation Analysis, Trend Analysis, Simulation Modelling, Decision Trees, Neural Networks
	Predictive analytics examples	Performance Forecasting, Progress Tracking, Task Scheduling, Resource Allocation, Safety Incident Prediction, Risk Assessment, Supply Chain Optimization, Design Feasibility Analysis, Cost Prediction, Environmental Impact Prediction, Performance Dashboards, Logistics Optimization
Visualization	Project Director	Project performance metrics, Cost and time overruns, Key milestones, High-level risk indicators
	Project Manager	Project schedule, Task progress, Resource allocation, Upcoming deadlines
	Subcontractors	Task-specific progress, Assigned tasks, Upcoming deadlines, Resource needs
	Trade Contractors	Trade-specific task progress, Resource allocation, Material usage, Upcoming schedules
	Safety Manager	Safety incident reports, Real-time safety conditions, Safety compliance status, Risk areas
	Risk Manager	Identified risks, Risk mitigation status, Impact predictions, Risk assessment trends
	Procurement Manager	Material delivery schedules, Inventory levels, Supplier performance, Procurement costs
	Site Manager	Daily site activities, Worker performance, Resource usage, Task progress
	Temporary Works Engineer	Temporary structure status, Structural integrity reports, Simulation results, Safety checks
	Design Engineers	Design specifications, Change requests, Design validation status, Integration with construction progress
	Quality Control Manager	Quality inspection results, Compliance status, Quality issues, Resolution actions
	Financial Controller	Project budget, Expenditure tracking, Cost overruns, Financial forecasts
	Environmental Manager	Environmental impact assessments, Compliance status, Sustainability metrics, Environmental risk areas
	Stakeholders	Overall project progress, Key performance indicators, Milestones, High-level financials
	Logistics Manager	Material transportation status, Delivery schedules, Storage utilization, Logistics efficiency

Thirdly, the cornerstone of any digital interface is its usability and end-user accessibility. In digital twin interfaces, the interactive visualization element serves as the primary conduit for user interaction. Therefore, it's imperative to incorporate user-centered design methods to ensure data quality and mitigate biases. The design should consider the dynamic relationship between the physical and digital realms, emphasizing the value creation by making real-world entities more accessible. The interface should also be context-sensitive, adapting dynamically to changes in the modelled entity or its environment. This requires a deep understanding of the digital twin's context during its design phase and operation. Furthermore, the data used for the digital twin, its creation, and its purpose should be carefully evaluated, ensuring that the interface is inclusive and does not inadvertently exclude any stakeholders [22,85]. Other factors must be considered, such as accessibility, usability, control room location, time required to access the control room, and how it can effectively support various goals and scenarios.

Creating an effective digital twin interface is a confluence of HCI principles, strategic positioning within the digital twin construction framework, and a keen understanding of user requirements. It is to be noted that some of the requirements in the above three points might be overlapping and some could even be considered as a subset of the other. By intertwining these elements, one can craft an interface that facilitates efficient decision-making and ensures a seamless and intuitive user experience. Examples of end user requirements, data integration, predictive analytics and interactive visualization are given in Table 5.

5. Implementing and refining the framework (design cycle)

This section describes the implementation of the framework/artifact described in the prior section in a construction project. The feedback from the implementation was used to refine the artifact.

5.1. End user requirements

End user requirements were gathered using the 'goal and scenario-based domain requirement analysis' proposed by Kim et al., 2006 [86]. Goals, in this context, refer to the aspirations and objectives of stakeholders, particularly those relating to the future operational efficacy of the construction site control room. These were thoroughly gathered during the preliminary stages of the research through various methods, including participatory observation in look-ahead planning meetings and interviews with the end users of the control room. The scenarios envisioned as specific, purpose-driven interactions among multiple agents within a defined context were extracted from the data integration and refined through interactive workshops conducted on the construction site. These workshops facilitated a deeper understanding of the practical scenarios and allowed for identifying a broader range of use cases. These use cases, subsets of the main goal, provide a comprehensive view of the production control processes in the construction site environment. The interdependence between goals and scenarios was further examined and validated in the Return on Investment (ROI) workshops, where the synergy between the identified scenarios and the overarching goals was critically assessed.

The research team employed a combination of observations and interviews to determine the initial requirements. They actively participated in the demonstration project's weekly "look-ahead planning" meetings, where the control room's utility was most evident. This engagement helped them identify which stakeholders would use the control room, understand their specific needs, and grasp the workflows these projects followed. Additionally, they conducted semi-structured interviews, posing questions to various stakeholders about their expectations from the control room. While these end-users outlined their requirements based on their experiences and current process limitations, the research team supplemented these with insights from their observations and expertise regarding the control room's potential

Table 6
Summary of the functional requirements of the production control room.

No.	Requirement	Why	Information insight	Priority
1	Weather for the coming two weeks is displayed on the screen	To identify its effect on the following week construction activities	Information	Must
2	The risk register is shown on the screen.	To track the actions and responses of the different stakeholders	Information	Must
3	The 3D and 4D models are displayed on the screen and should be not only visualized but also queried.	To understand location workloads and dependencies and improve the sequence	Insight	Must
4	The photos of completed tasks are reviewed on the screen.	To review the real-time progress	Information	Must
5	Delivery schedules are monitored and displayed.	To understand logistics required and rearrange the site storage areas to fit the purpose	Insight	Must
6	The 3 Week Look Ahead (3WLA) for each subcontractor is presented effectively on the screen.	To understand each package status in the workflow	Information	Must
7	The work packages and milestones are connected and displayed together on the screen.	To link the different work packages with the main milestones to predict any delays and find solutions to reduce the risk.	Insight	Must
8	The risk register for all subcontractors is displayed in relation to their locations.	To see how the risks will affect the construction activities.	Insight	Must
9	The incomplete tasks (snag) and root causes are highlighted and well-presented on the screen.	To control the construction activities and learn from previous data	Insight	Must
10	The construction activities are linked to the associated zones.	To understand the workplace sequence	Insight	Must
11	The construction activities are linked to the associated deliveries.	To understand the relation between delivers and the construction activities requiring these delivers.	Insight	Must
12	The capability to record actions based on the meetings held using the control room.	To share with other stakeholders and document actions	Information	Must
13	The 3WLAs are synchronized to the master plan.	To review planned vs. actual	Information	Should
14	The work packages of the different subcontractors are integrated and presented as a whole.	To know what changed and where it occurred and how it will affect others	Insight	Should
15	The risk register can be updated outside the control room.	To have real-time data in the control room	Information	Could
16	The different data sources can be integrated, queried, and presented as a single source of truth.	To review and query any data required from various sources	Information	Could

capabilities.

Table 6 provides a detailed breakdown of the functional requirements proposed for the production control room, the rationale behind each choice, whether it offers insight or merely visualizes information, and its priority level. A system's functional requirement defines what the system or its components are designed to achieve. Interviews revealed that datasets influencing project completion time, such as weather forecasts, three-week look-ahead schedules, site deliveries, on-site photos, and critical milestones, are crucial. During the look-ahead planning meetings, the team's observations corroborated this, where discussions predominantly revolved around schedules, potential risks, and delays. Another set of requirements highlighted the importance of visualizing the relationships between activities, 3D models, work zones, and deliveries. This is essential to comprehend the sequential ownership of work zones, prevent trade conflicts, and eliminate delays. The final requirements set emphasized visualizing the risks associated with trades, activities, and their root causes. Notably, some criteria introduced by the research team were innovations the end-users had yet to consider possible. This underscores the importance of blending methodologies to capture known and previously unconsidered user needs. After identifying these requirements, they were reviewed with the project's primary stakeholders and validated with the end users.

5.2. Data integration

Informed by end-user requirements and observations of software tools and construction workflows, it became evident that each requirement needed the integration of specific datasets to derive insights. The integrations required were categorized into five types: data extraction, exchange, integration (encompassing semantic enrichment and alignment), capture standardization, and governance.

- Data extraction pertains to the challenges of accessing specific platforms to retrieve information via Application Programming Interfaces (APIs).
- Data exchange concerns the format in which data will be shared, necessitating agreements with end-users.
- Data integration focuses on the semantics, assessing whether they are mature, enriched, and structured for seamless integration with other datasets, irrespective of format.
- Capture standardization, vital for ensuring consistency and building trust, is essential for aspects like the three-week look-ahead collected from various subcontractors.
- Semantic enrichment addresses datasets that lack sufficient data for integration. In contrast, semantic alignment deals with datasets that, although containing the necessary data for integration, face challenges connecting with other datasets due to naming conventions or consistency issues.
- Lastly, data governance ensures that datasets managed by the main contractor maintain their credibility.

Fig. 7 visually represents the six primary datasets and their interrelations needed to fulfil specific functional requirements, as outlined in Table 7. For example, the second requirement necessitates the integration of process data (like activities from the 3-week look-ahead), risk data (such as risk registers submitted by trades/sub-contractors), and documents typically managed in document control systems. This integration demands consistent naming conventions and semantic enrichment for datasets, such as work packages, zones, and subcontractors responsible for these activities and addressing the identified risks. Some requirements focused on a single aspect, but achieving integration was challenging due to differences in syntactic interoperability, such as format and information breakdown structure. After defining the data integration requirements, various integration approaches were explored, with ontology-based data integration adopted for this study.

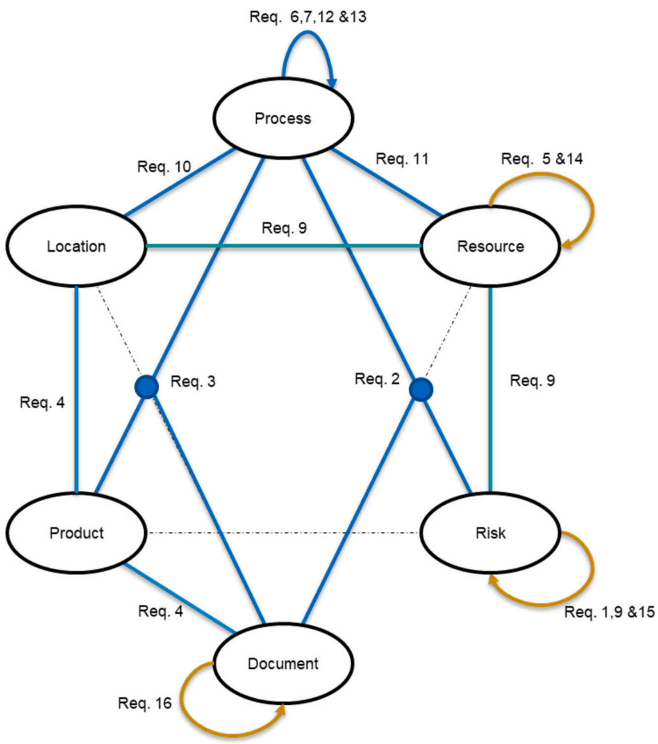

Fig. 7. The six primary datasets and required integration for the end-user's requirements.

The ontology was tailored to the dataset of the chosen case study and its specific requirements. Fig. 8 showcases the three primary datasets: those from the document control platform (in green), the resource platform (in orange), and the schedule dataset (in blue), along with their integration. The ontology development process, beyond the scope of this paper, is detailed in [64,65]. The developed ontology can be obtained from [95]. The subsequent section describes the application of this ontology for predictive analysis. Finally, data governance is related to that dataset managed through the main contractor to ensure their credibility.

5.3. Predictive analytics, simulations, and interactive visualization

Integrated datasets link activities to locations, documents, and milestones. However, more than merely integration does not need to highlight issues or root causes. It is essential to infer constraints, such as precedence and logical relationships between activities, resources, and site conditions, from the dataset to understand root causes and anticipate delays. Constraint violations can influence the likelihood of an activity occurring as planned. Activities with more violations are less likely to proceed on schedule, potentially delaying subsequent activities. These likelihoods of activities can be quantified as task confidence levels. One must infer constraint relationships from the semantically enriched dataset to determine the task confidence level. The number of constraints, delays, and confidence levels of preceding activities influence the task confidence level for an activity. This level can guide managers during planning meetings. A low confidence signals potential issues, prompting managers to investigate and address constraint violations. Task confidence in construction projects can be calculated using a mathematical model considering various factors and constraints. Here is a breakdown of the coefficients and variables in the equation:

1. Constraint violations (N): This represents the total number of violations across different categories. These violations can be identified using Soman et al. [54].It's calculated as

Table 7
Table showing the datasets to be integrated.

Requirement	Datasets to be integrated	Current issues
Weather for the coming two weeks is displayed on the screen	Risk (external datasets)	Data extraction and exchange
The risk register is shown on the screen.	Risk (internal datasets)	Data integration (Semantic enrichment)
The 3D and 4D models are displayed on the screen and should be not only visualized but also queried.	Process, Product	Data integration (Semantic alignment)
The photos of completed tasks are reviewed on the screen.	Process	Data storage (Real-time data)
Delivery schedules are monitored and displayed.	Resources	Data integration (Semantic enrichment)
The 3 Week Look Ahead (3WLA) for each subcontractor is presented effectively on the screen.	Process	Data standardization
The work packages and milestones are connected and displayed together on the screen.	Process	Data extraction and exchange
The risk register for all subcontractors is displayed in relation to their locations.	Location, risk	Data integration (Semantic enrichment)
The incomplete tasks (snag) and root causes are highlighted and well-presented on the screen.	Process	Data governance
The construction activities are linked to the associated zones.	Process, Location	Data integration (Semantic alignment)
The construction activities are linked to the associated deliveries.	Resources, Process	Data integration (Semantic enrichment)
The capability to record actions based on the meetings held using the control room.	Process	Data capture standardization
The 3WLAs are synchronized to the master plan.	Process	Data integration (Semantic alignment)
The work packages of the different subcontractors are integrated and presented as a whole.	Resources, Process	Data integration (Semantic alignment)
The risk register can be updated outside the control room.	Risk	Data capture standardization
The different data sources can be integrated, queried, and presented as a single source of truth.	Document	Data access, extraction, and exchange

$$N = N_{ZC} + N_{MI} + N_{LC}$$

- Zone Clashes (N_ZC): These are potential delays in the activity due to clashes in zones. The higher the number of zone clashes, the lower the task confidence level.
- Missing Information (N_MI): This represents the absence of essential data. A higher number of missing information instances will result in a lower task confidence level.
- Logical Clashes (N_LC): These arise from logical constraint violations, such as a mismatch between a crane's operating requirement and the predicted weather.

2. Delay Factor (D): This factor represents the proportion of delay to the number of days until the start date of the concerned activity. It's calculated as:

$$D = \frac{\text{Amount of delay}}{\text{Number of days until the start date of concerned activity}}$$

Where the amount of delay is the weighted sum of delays from various sources, such as delays in the submission of necessary documents, delays in the completion of previous activities, delays in the procurement etc.

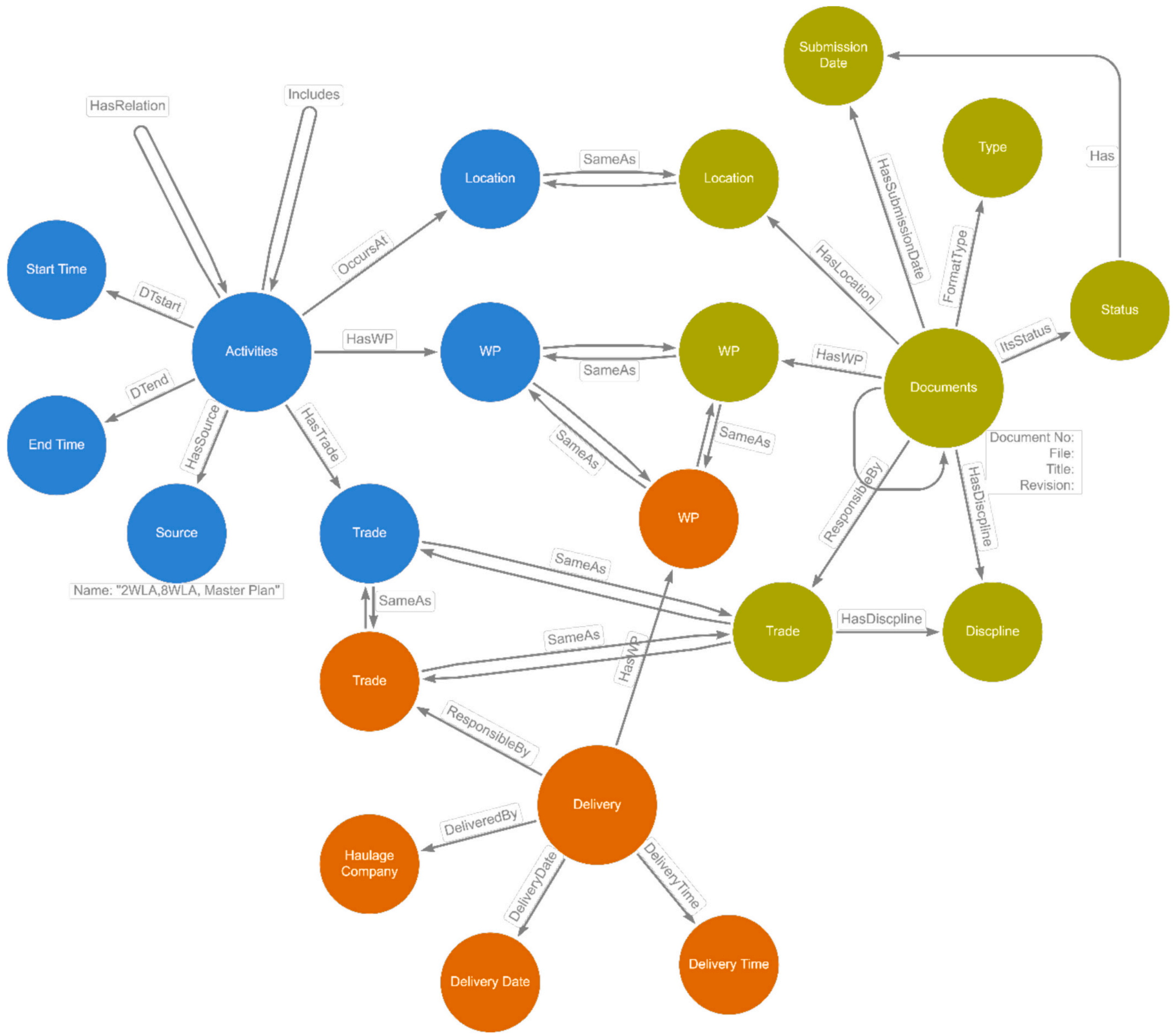

Fig. 8. Relationship between the different sources of datasets that will be presented in the production control room.

3. Penalty Function (P(N)): This function assigns a penalty based on the number of constraint violations:

$$P(N) = \begin{cases} 0 & \text{if } N = 0 \\ 0.5 & \text{if } N = 1 \\ 1.5 & \text{if } N > 2 \end{cases}$$

The penalty increases with the number of violations, reflecting the reduced confidence in task completion.

Finally, the Task Confidence Level (TCL) is a function that combines the delay factor and the penalty from constraint violations to provide a measure between 0 and 1 (represented as varying colors in the Gantt chart of the control room, indicating the confidence in task completion:

$$TCL = \frac{1}{1 + e^{-(3 - D + P(N))}}$$

This equation provides a comprehensive measure of task confidence by considering various constraints and delays in construction projects.

The development of the interactive visualization for the digital twin interface was deeply rooted in principles from Human-Computer Interaction (HCI), Digital Twin Construction (DTC), and User Requirements. From an HCI perspective, the cornerstone of the digital interface was its usability and accessibility. The screen layout for the control room was crafted to emphasize value creation by making real-world entities more accessible. Feedback from end-users refined the design, ensuring inclusivity. The final design, showcased in Fig. 9, featured three large touch screens optimized for collaborative visualization and equipped with multi-touch capability, allowing for seamless data interaction.

From a DTC standpoint, the interface was strategically positioned between the Project Status Knowledge and Project Intent Knowledge stages. This ensured that users could make informed decisions augmented by computational insights. The control room, by default, displayed a comprehensive context for decision-making, making it a true digital twin interface for the construction site. When considering User Requirements, the design was tailored to meet specific user needs. The control room was developed to be intuitive, guiding users seamlessly

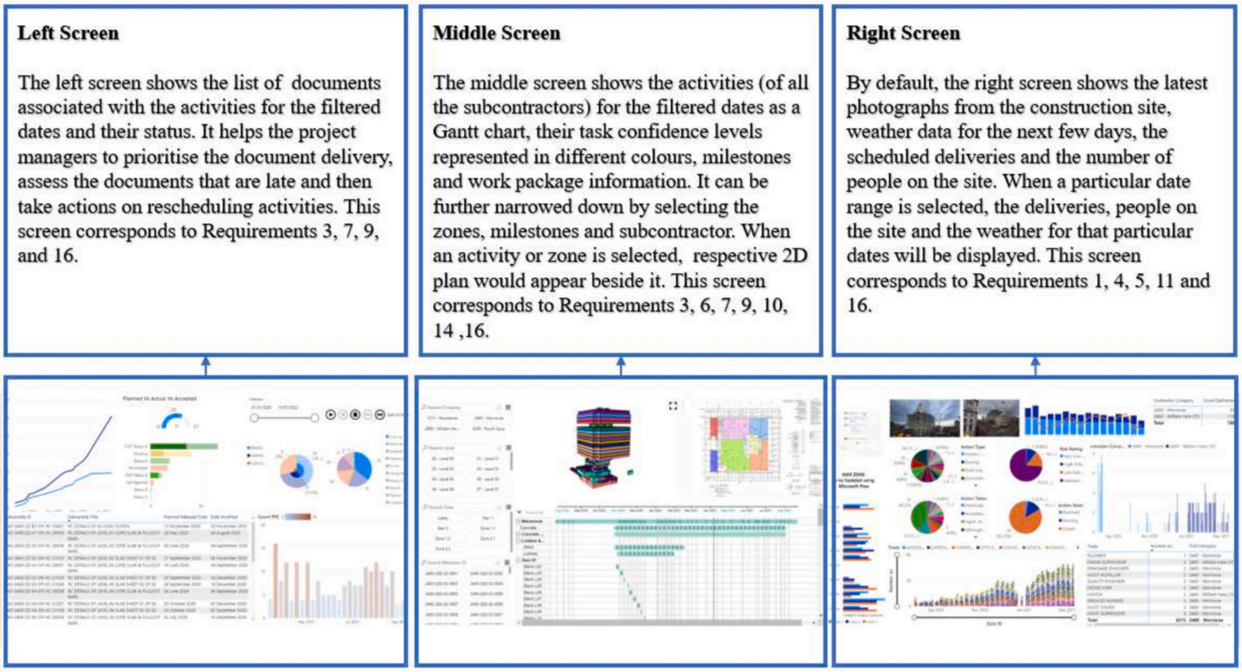

Fig. 9. Collaborative visualization using three large touch screens.

through essential workflows. Users could select specific date ranges to assist in look-ahead planning, revealing several information from task confidence levels to weather data. This user-centric approach ensured a functional and user-friendly experience, satisfying all delineated requirements. The final implementation of the control room as an interface to the construction digital twin is presented in Fig. 10.

5.4. Framework validation

The validation of the framework for Human-Digital Twin Interfaces tailored for Digital Twin Construction was done by creating a control room designed explicitly for look-ahead planning in construction, providing insights for the framework. The control room acted as an interface to the digital twin. The role of the digital twin in this paper was to observe the data from the construction through real-time information from the site, such as weather data, number of people on the site, etc. Here, it can report routine and non-routine situations. Further, it also acted as an analyst by analyzing the documents and relating them to whether they were submitted on time, delayed, or not submitted, informing whether the activities could be planned or not. Here, the digital twin can only provide routine support as there is no intelligence behind the model to provide non-routine support. With this support and analysis, the digital twin provides the project managers insights about the project status – PSK. Using this, the project managers can make decisions on scheduling activities, managing trade, and managing workspaces, which would be the project intent knowledge, later converted to project intent information. This conversion process was manual.

The implementation, evaluated through Return of Investments (ROI) interviews, unveiled multifaceted benefits. Digitization streamlined the

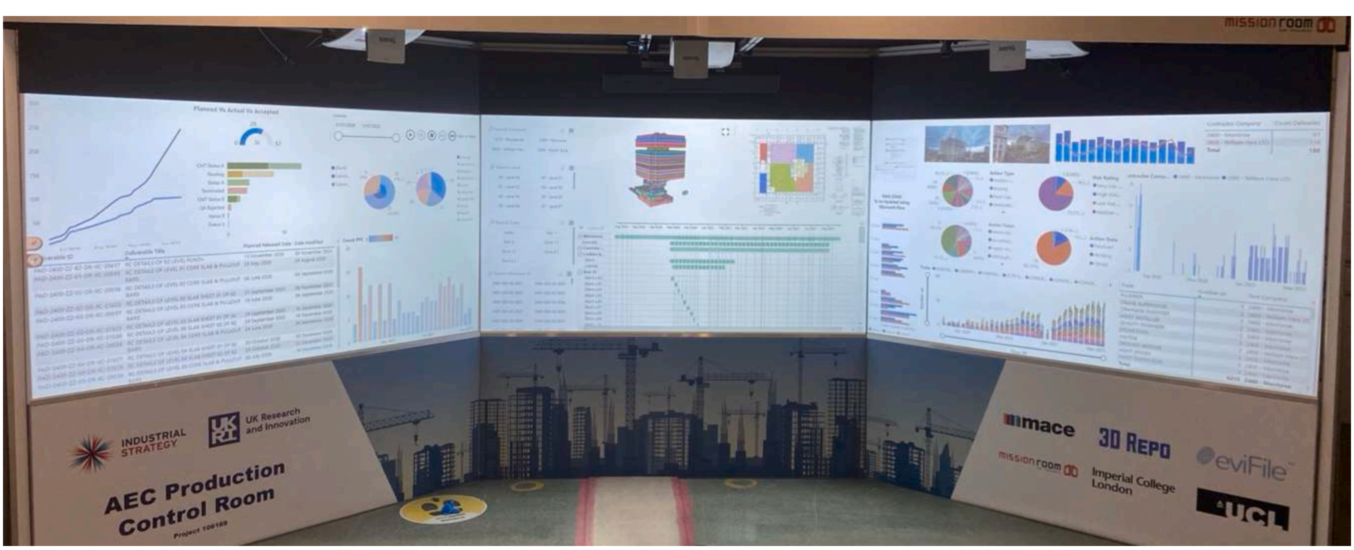

Fig. 10. Control room as an interface to the construction digital twin.

preconstruction and construction phases, saving the information manager 5 h weekly. Enhanced data integration reduced the Board's weekly look-ahead planning and production control updates from 45 min to 10, facilitating deeper discussions on subcontractor labor and potential risks. The efficiency of these meetings increased, with twenty packages now being addressed in a single 45-min session, compared to the previous 8-h span over four sessions. Accessible dashboards provided subcontractors with transparent progress comparisons and delay reasons. Automated data generation replaced the earlier reliance on the Project Director's commentary, ensuring consistent project reporting. Additionally, the system's predictive capabilities highlighted unfeasible plans and flagged irrelevant reporting.

Although resulting in benefits, the implementation faced multiple challenges, primarily centered around data integration and exchange. One significant issue was the inconsistent format of the 3-week look-ahead spreadsheets submitted by subcontractors. The research team introduced a web interface with dropdown lists to address this, ensuring submission uniformity. Another challenge was the regular data extraction from platforms like Data scope, Aconex, and Lobster Pictures. To streamline this, the control room's APIs were developed for automatic data extraction and updates. Inconsistencies in naming conventions across platforms, such as subcontractor abbreviations versus full names, further complicated integration. To resolve this, alignment tables were created in the control room's backend to ensure consistent relationships between datasets. Additionally, subcontractor resistance to change necessitated multiple workshops and training sessions. Many of these challenges are not purely technical but socio-technical, underscoring the importance of considering both aspects when developing a digital twin interface.

6. Discussion

The research presented in this paper addresses the question, *"How can construction control rooms be utilized as digital twin interfaces to enhance the accuracy and efficiency of decision-making in the digital twin construction workflow?""* by employing a design science research methodology. The findings showcase control rooms as flexible digital twin interfaces tailored to industry stakeholders' unique requirements and communication needs. The paper delineates the role of a digital twin in construction, spanning from an observer to a decision-maker, with autonomy levels ranging from none to routine autonomy, as framed within the model proposed in [17]. This is in line with Wilhelm's [79] recommendation of a digital twin workflow involving human operators interacting with both digital and physical objects, underscoring the need for a comprehensive classification that includes the operator. Moreover, the interface is strategically positioned between the project status knowledge and project intent knowledge in the digital twin construction workflow outlined in Fig. 5. The paper also introduces and evaluates design considerations for developing digital twins. To validate the effectiveness of these positioning, the digital twin interface was implemented on a construction project, and the increasing coordination efficiency during look-ahead meetings was recorded and identified through an ROI workshop. The success in implementation is evidenced through the improved coordination efficiency (Section 5.4). The improved coordination efficiency in terms of more work package coordination per 45-min session, reduction in time for planning and control updates and reduction in the workload of the information manager demonstrates that the decision-making accuracy and efficiency are improved. Through the implementation of predictive analytics within production control by identifying task confidence levels, this paper demonstrates how digital twins can incorporate the second and third levels of situational awareness (SA): understanding the data and projecting future states based on it, as recommended by [59]. This strengthens the existing studies' claims that digital twins can boost productivity by providing a comprehensive overview [56,60].

This paper is in congruence with the current state of the art in human interaction with digital twins. DT interface design should prioritize customisation, flexibility, and significant user involvement through End User Design, with a focus on fostering human-AI teaming [22]. The findings of this paper align with [22] conclusions by emphasizing end-user requirements as the foundation of interface design and incorporating predictive analytics for look-ahead planning, enabling DT to assist project managers in creating conflict-free schedules. The implementation of data integration and predictive analytics has shown to reduce the cognitive load of project managers by enabling them to effectively perceive complex interrelationships between tasks, trades, locations, documents, and real-time site data. This aligns with Palmer's [76] recommendation for a symbiotic interface through ecological interface design. This interface transforms the DT in DTC into a human-centered digital twin, enhancing the capabilities of project managers through data integration and simulations, and serves as a common interface, as recommended by [96].

It is also important to note that digital twin interface design should address its stakeholders' unique requirements and communication needs. Researchers or developers must separate between stakeholder requests for feasible digital twin features and unrealistic ones when gathering these requirements. Moreover, there might be beneficial features unbeknownst to stakeholders, necessitating researchers to propose such requirements and subsequently gather feedback. This process demands researchers to possess both digital proficiency and domain knowledge in construction. During data integration, mere observation of the data often proved insufficient for seamless integration. However, when datasets were examined within the project's workflow processes, intersections between these datasets became evident, offering integration nodes and foundational concepts for ontology development. Thus, it's crucial to contextualize data within construction processes to achieve effective integration. Another essential consideration is that the interface design should harmonise with existing workflows to ensure high-quality data collection vital for digital twin construction. This observation is in agreement with [62].

Within the workflow of digital twin construction, there is an embedded mechanism for the digital twin to evolve with each cycle. The incorporation of a digital twin interface facilitates the capture of human decisions. Crucially, these decisions about the project's status, knowledge, and plans are documented. This system can translate tacit construction knowledge into a machine-readable format. Consequently, the digital twin serves as a transactive memory system (See Fig. 11), archiving the collective project knowledge for potential reuse in subsequent projects [97]. The interaction with Digital Twins acts as a Human/Social System (Individuals, teams and organizations) to Software and Information Systems transactions, and these transactions can result in a shared transactive system that people working with digital twins develop for encoding, storing, and retrieving information about different construction project management [98].Moreover, this data can pave the way for developing autonomous systems through the imitation learning [99], a technique successfully employed in sectors like automotive for autonomous driving, where systems learn from human actions and the sensed environment. The stored data, encompassing project status knowledge and human decisions, can also be harnessed to formulate algorithm policies, such as reinforcement learning, especially in intricate construction settings where policy development is challenging [100]. Therefore, integrating a digital twin interface into the digital construction workflow unveils many new innovative research avenues, from knowledge management to advanced machine learning techniques like imitation and reinforcement learning in construction.

Contemporary literature emphasizes the development of DT that are autonomous and adaptive for production scheduling across various sectors [78]. Despite these advancements, it remains evident that DT systems will continue to rely significantly on the integration of human and computational efforts for the foreseeable future [17]. This reliance underscores the necessity of incorporating human interaction within DT frameworks, which is pivotal for managing the complexities of such

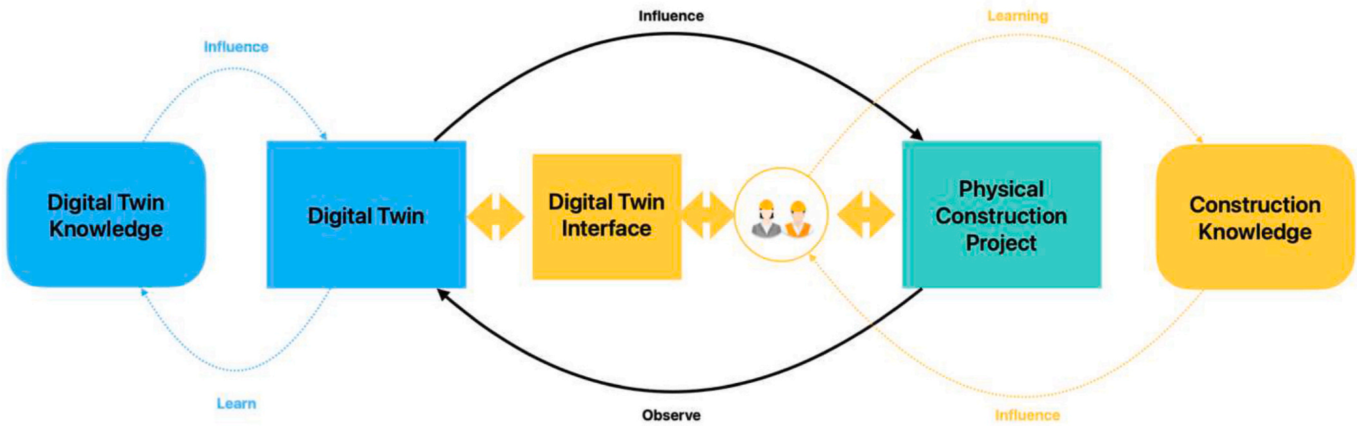

Fig. 11. Digital twin as a collective project knowledge.

systems effectively [13]. Our paper underscores the critical importance of co-creation with users for the successful execution and implementation of DT systems. This approach is congruent with the roles identified by [17] and adheres to the human-related characteristics suggested by [78]. According to these guidelines, the data layer of DT systems should prioritize human factors, prompting our methodology to begin with the collection of both existing data and functional requirements directly from users before development initiates. Subsequently, the design of the virtual layer is explicitly focused on the skills of the workforce, leading to the creation of diverse dashboards and data representations tailored to the specific needs and roles of the users. This user-centric design philosophy not only facilitates a more intuitive interaction with the DT system but also emphasizes the importance of convenience in the DT interface over the visual quality [101]. We have found that enhancing the practical usability of these systems, based on non-functional requirements derived from user interviews, significantly improves the manageability and effectiveness of digital twin technologies in real-world applications. Moreover, this focus on practical usability contrasts starkly with the complexities of more traditional systems like 4D models, where data integration issues and the requirement for extensive navigational skills can severely hinder effective system management. By simplifying the user interface and aligning it more closely with user needs, our DT framework helps to overcome these barriers, making the technology more accessible and beneficial for everyday operational needs. This strategic emphasis on user-friendly design and operational efficiency is essential for the broader adoption and success of digital twin technologies in the construction sector and beyond.

7. Limitations

While this paper has addressed the research questions, there are inherent limitations that are opening new avenues for future research. As a pioneering work on novel digital twin-human interfaces in the DTC workflow, our paper primarily focused on an urban redevelopment case, drawing inspiration from literature on big rooms and lean construction. However, the question of generalizability to different types of construction projects remains, aligning with the ongoing debate on generalizability in DSR research. Although we proposed a generalized digital twin interface framework, its testing was confined to site-based physical touchscreen control rooms. Potential interfaces, such as web-based, mobile app-based, and VR-AR, offer opportunities for further testing, validation, and design cycle refinement, but these are beyond the scope of the current paper. The generalized framework we presented can serve as a foundation for exploring these possibilities. While the importance of UI/UX in facilitating smooth human-computer interactions was acknowledged, these components were not empirically evaluated during the project's execution phase. Moreover, the paper employed a design science research approach to gauge impact, utilizing a Return on Investment (ROI) workshop for qualitative feedback. This approach yielded insights into the system's effectiveness primarily from user experiences, lacking a quantitative or statistical analysis of its performance. Within the limitations of this study, specific elements of Human-Data Interaction, such as legibility, agency and negotiability, and data ownership, were not comprehensively explored, presenting opportunities for subsequent research.

8. Conclusions

This paper contributes to the understanding of human interaction integration in digital twin construction, emphasizing the pivotal role of control rooms as adaptable digital twin interfaces. These interfaces, designed to meet the unique demands of industry stakeholders, encompass a spectrum of roles for digital twins, from observation to decision-making, each with its own degree of autonomy. This paper also placed the digital twin interface within the PSK and PIK stages in the digital twin workflow. It also provides the design consideration for digital twin interfaces in terms of considering user requirements study, data integration, predictive analytics simulation, and visualization. A salient aspect of the paper is the discernment between feasible and unattainable stakeholder requests while spotlighting potential features that could benefit immensely. As the digital twin evolves with each iteration, the interface plays a crucial role in capturing and documenting human decisions, effectively converting implicit construction knowledge into a format that machines can comprehend. This process not only preserves the collective wisdom of a project but also paves the way for the application of cutting-edge machine-learning techniques in the construction domain.

Using an implementation study, this paper highlights the transformative impact of digitizing construction production control as flexible digital twin interfaces. By pinpointing 16 end-user requirements and advocating an ontology-based data integration approach in the implementation, the paper paves the way for enhanced construction management. The introduced control room optimizes planning and decision-making across all levels, promising cost savings, reduced rework, and timely project completion. This approach is currently being applied in a significant urban redevelopment project in the UK. Furthermore, SMEs in construction visualization are utilizing these findings to develop expansive touchscreen visualizations for construction sites. The paper also aids construction software vendors in refining their ecosystems, emphasizing the importance of integration and actionable insights.

The findings from this paper reveal that control rooms can serve as effective digital twin interfaces, significantly enhancing decision-making accuracy and efficiency in construction workflows. This outcome highlights the often-overlooked importance of human interaction within digital twin systems, demonstrating that control rooms do more than visualize data; they promote collaborative decision-making and situational awareness. This knowledge is vital for both researchers and practitioners in the construction sector. For researchers, it opens new pathways to investigate human-digital twin interactions, emphasizing the necessity for user-centric interfaces that integrate various data sources. For practitioners, the paper offers actionable guidance on utilizing digital twin interfaces to optimize project management, minimize rework, and boost overall efficiency. Construction managers and stakeholders stand to gain from adopting control rooms as digital twin interfaces, as they provide an interactive platform that enhances decision-making and improves project outcomes.

This paper makes a contribution to the literature by clarifying the role of digital twins in digitally enabled production control, particularly within the context of construction. It holds great importance for researchers in artificial intelligence, lean construction, digital twins, visualization, and sustainability. The deployment of the digital twin interface generates vast amounts of contextualized structured data, which machine-learning researchers can use as a dynamic test bed for training models that forecast risks, scheduling, and cost performance in future projects. Insights from this paper enable academics in lean construction to leverage the digital twin interface to implement, assess, and quantify lean theories of production control in a digital environment. By ensuring decision traceability, the interface links every decision to relevant datasets. Scholars focused on construction domain ontologies can build on these findings to integrate construction process datasets with other relevant datasets, facilitating the development of real-time digital twins. Additionally, the paper highlights how collaborative visualization environments can serve as gateways to enriched digital twins. Visualization experts can apply advanced extended reality techniques to enhance the digital twin interface, allowing for seamless participation from both physical and remote participants during look-ahead planning sessions. Lastly, those researching sustainable construction can expand on the interface to incorporate sustainability and circularity metrics within predictive analytics and simulations, enabling thorough assessments of sustainability impacts in production control.

CRediT authorship contribution statement

Ranjith K. Soman: Writing – review & editing, Writing – original draft, Software, Project administration, Methodology, Funding acquisition, Conceptualization. **Karim Farghaly:** Writing – review & editing, Software, Investigation, Conceptualization. **Grant Mills:** Investigation, Funding acquisition, Formal analysis. **Jennifer Whyte:** Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT in order to proofread and improve readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take (s) full responsibility for the content of the publication.

Declaration of competing interest

Ranjith K. Soman reports financial support was provided by Innovate UK. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgment

This work is a part of ongoing project that has been kindly sponsored by Innovate UK grants AEC Production Control Rooms No. 106169.

References

[1] N. Murtagh, L. Scott, J. Fan, Sustainable and resilient construction: current status and future challenges, J. Clean. Prod. 268 (2020) 122264, https://doi.org/10.1016/j.jclepro.2020.122264.

[2] J.L. Blanco, D. Rockhill, A. Sanghvi, A. Torres. Accelerating growth in construction technology | McKinsey, McKinsey, 2023. https://www.mckinsey.com/industries/private-equity-and-principal-investors/our-insights/from-start-up-to-scale-up-accelerating-growth-in-construction-technology (accessed October 1, 2023).

[3] M.J. Ribeirinho, J. Mischke, G. Strube, E. Sjodin, J. Biorck, T. Anderson, J. L. Blanco, R. Palter, D. Rockhill, How Disruption Is Reshaping Construction | McKinsey. https://www.mckinsey.com/capabilities/operations/our-insights/the-next-normal-in-construction-how-disruption-is-reshaping-the-worlds-largest-ecosystem, 2020.

[4] W. AlBalkhy, D. Karmaoui, L. Ducoulombier, Z. Lafhaj, T. Linner, Digital twins in the built environment: definition, applications, and challenges, Autom. Constr. 162 (2024), https://doi.org/10.1016/j.autcon.2024.105368.

[5] B.G. Hwang, J. Ngo, P.W.Y. Her, Integrated digital delivery: implementation status and project performance in the Singapore construction industry, J. Clean. Prod. 262 (2020) 121396, https://doi.org/10.1016/j.jclepro.2020.121396.

[6] C. Boje, A. Guerriero, S. Kubicki, Y. Rezgui, Towards a semantic construction digital twin: directions for future research, Autom. Constr. 114 (2020) 103179, https://doi.org/10.1016/j.autcon.2020.103179.

[7] R. Sacks, M. Girolami, I. Brilakis, Building information modelling, artificial intelligence and construction tech, Dev. Built. Environ. (2020) 100011, https://doi.org/10.1016/j.dibe.2020.100011.

[8] V.V. Tuhaise, J.H.M. Tah, F.H. Abanda, Technologies for digital twin applications in construction, Autom. Constr. 152 (2023) 104931, https://doi.org/10.1016/j.autcon.2023.104931.

[9] G.S. Saini, A. Fallah, P. Ashok, E. Van Oort, Digital twins for real-time scenario analysis during well construction operations, Energies 15 (2022) 6584, https://doi.org/10.3390/en15186584.

[10] D.Y. Jahagirdar, R.M. Leicht, Applications of digital twins for the construction process, in: Computing in Civil Engineering 2023, American Society of Civil Engineers, Corvallis, Oregon, 2024, pp. 357–363, https://doi.org/10.1061/9780784485231.043.

[11] S. Su, R.Y. Zhong, Y. Jiang, J. Song, Y. Fu, H. Cao, Digital twin and its potential applications in construction industry: state-of-art review and a conceptual framework, Adv. Eng. Inform. 57 (2023) 102030, https://doi.org/10.1016/j.aei.2023.102030.

[12] W. Long, Z. Bao, K. Chen, S. Thomas Ng, I. Yahaya Wuni, Developing an integrative framework for digital twin applications in the building construction industry: a systematic literature review, Adv. Eng. Inform. 59 (2024) 102346, https://doi.org/10.1016/j.aei.2023.102346.

[13] E. Altan, Z. Işık, Digital twins in lean construction: a neutrosophic AHP – BOCR analysis approach, Eng. Constr. Archit. Manag. (2023), https://doi.org/10.1108/ECAM-11-2022-1115 ahead-of-print.

[14] M.W. Grieves, Digital twins: Past, present, and future, in: N. Crespi, A.T. Drobot, R. Minerva (Eds.), The Digital Twin, Springer International Publishing, Cham, 2023, pp. 97–121, https://doi.org/10.1007/978-3-031-21343-4_4.

[15] D.-G.J. Opoku, S. Perera, R. Osei-Kyei, M. Rashidi, Digital twin application in the construction industry: a literature review, J. Build. Eng. 40 (2021) 102726, https://doi.org/10.1016/j.jobe.2021.102726.

[16] M. El Jazzar, M. Piskernik, H. Nassereddine, Digital twin in construction: An empirical analysis, in: EG-ICE 2020 Workshop on Intelligent Computing in Engineering, Proceedings, 2020, pp. 501–510, https://doi.org/10.14279/depositonce-9977.

[17] A. Agrawal, R. Thiel, P. Jain, V. Singh, M. Fischer, Digital twin: where do humans fit in? Autom. Constr. 148 (2023) 104749 https://doi.org/10.1016/j.autcon.2023.104749.

[18] C.P. Schimanski, G. Pasetti Monizza, C. Marcher, D.T. Matt, Development of a BIM-based production planning and control system for lean construction through advancement and integration of existing management techniques, Front. Eng. Manag. 8 (2021) 429–441, https://doi.org/10.1007/s42524-020-0105-5.

[19] R. Sacks, I. Brilakis, E. Pikas, H.S. Xie, M. Girolami, Construction with digital twin information systems, Data Centric Eng. 1 (2020) e14, https://doi.org/10.1017/dce.2020.16.

[20] Y. Wang, Z. Wu, Model construction of planning and scheduling system based on digital twin, Int. J. Adv. Manuf. Technol. 109 (2020) 2189–2203, https://doi.org/10.1007/s00170-020-05779-9.

[21] Y. Palazhchenko, V. Shendryk, S. Shendryk, Digital twins data visualization methods. Problems of human interaction: A review, in: I. Karabegovic, A. Kovačević, S. Mandzuka (Eds.), New Technologies, Development and

Application VI, Springer Nature, Switzerland, Cham, 2023, pp. 478–485, https://doi.org/10.1007/978-3-031-31066-9_53.
[22] B.R. Barricelli, D. Fogli, Digital twins in human-computer interaction: a systematic review, Int. J. Hum. Comp. Interact. 0 (2022) 1–19, https://doi.org/10.1080/10447318.2022.2118189.
[23] B. Dave, R. Sacks, Production control systems for construction at the nexus of lean and BIM, in: Lean Construction: Core Concepts and New Frontiers, Routledge, New York, 2020, pp. 54–83 (ISBN: 9780429203732).
[24] K. Farghaly, R.K. Soman, J. Whyte, Visualizing real-time information through a construction production control room, in: 2021 European Conference on Computing in Construction, 2021, pp. 415–422, https://doi.org/10.35490/EC3.2021.169.
[25] C.P. Schimanski, G. Pasetti Monizza, C. Marcher, D.T. Matt, Development of a BIM-based production planning and control system for lean construction through advancement and integration of existing management techniques, Front. Eng. Manag. 8 (2021) 429–441, https://doi.org/10.1007/s42524-020-0105-5.
[26] C. Boje, V. Bolshakova, A. Guerriero, S. Kubicki, G. Halin, Ontology assisted collaboration sessions on 4D BIM, in: Creative Construction Conference 2019, Budapest, Hungary, 2019. https://hal.archives-ouvertes.fr/hal-02555769 (accessed January 9, 2023).
[27] M. Fischer, M. Stone, K. Liston, J. Kunz, V. Singhal, Multi-stakeholder collaboration: The CIFE iRoom, in: Proceedings CIB W78 Conference, Citeseer, 2002, pp. 6–13. ISBN 87-90078-34-9.
[28] K. McHugh, B. Dave, R. Craig, Integrated lean and BIM processes for modularised construction - A case study, in: 27th Annual Conference of the International Group for Lean Construction, IGLC 2019, The International Group for Lean Construction, 2019, pp. 227–238, https://doi.org/10.24928/2019/0252.
[29] B. Hookway, Interface, MIT Press, 2014. ISBN: 9780262322638.
[30] L. Skoury, S. Treml, N. Opgenorth, F. Amtsberg, H.J. Wagner, A. Menges, T. Wortmann, Towards data-informed co-design in digital fabrication, Autom. Constr. 158 (2024) 105229, https://doi.org/10.1016/j.autcon.2023.105229.
[31] P. Bauer, T. Hoefler, B. Stevens, W. Hazeleger, Digital twins of earth and the computing challenge of human interaction, Nat. Comput. Sci. 4 (2024) 154–157, https://doi.org/10.1038/s43588-024-00599-3.
[32] A. Hevner, S. Chatterjee, Design science research in information systems, in: Design Research in Information Systems, Springer US, Boston, MA, 2010, pp. 9–22, https://doi.org/10.1007/978-1-4419-5653-8_2.
[33] G. Ballard, I. Tommelein, 2020 Current Process Benchmark for the Last Planner (R) System of Project Planning and Control. https://escholarship.org/uc/item/5t90q8q9, 2021 accessed October 25, 2022.
[34] H.G. Ballard, The Last Planner System of Production Control, PhD Thesis, https://etheses.bham.ac.uk/id/eprint/4789/1/Ballard00PhD.pdf, 2000.
[35] S.-S. Liu, C.-J. Wang, Resource-constrained construction project scheduling model for profit maximization considering cash flow, Autom. Constr. 17 (2008) 966–974, https://doi.org/10.1016/j.autcon.2008.04.006.
[36] R. Sacks, S. Korb, R. Barak, G. Geva, Building Lean, Building BIM: Improving Construction the Tidhar Way, Routledge, 2017. ISBN-10: 1315300486.
[37] F.R. Hamzeh, E. Zankoul, C. Rouhana, How can 'tasks made ready' during lookahead planning impact reliable workflow and project duration? Constr. Manag. Econ. 33 (2015) 243–258, https://doi.org/10.1080/01446193.2015.1047878.
[38] A. Mossman, Last Planner®: 5 + 1 Crucial & Collaborative Conversations for Predictable Design & Construction Delivery. http://bit.ly/LPS-5cc, 2013.
[39] Z.-Z. Hu, X.-Y. Zhang, H.-W. Wang, M. Kassem, Improving interoperability between architectural and structural design models: an industry foundation classes-based approach with web-based tools, Autom. Constr. 66 (2016) 29–42, https://doi.org/10.1016/j.autcon.2016.02.001.
[40] R. Sacks, M. Radosavljevic, R. Barak, Requirements for building information modeling based lean production management systems for construction, Autom. Constr. 19 (2010) 641–655, https://doi.org/10.1016/j.autcon.2010.02.010.
[41] M. Cortés, R. Herrera, F. Muñoz, B. La Rivera, Key requirements of an IT tool based on last planner systemRevista Ingeniería de Construcción. https://www.scielo.cl/pdf/ric/v35n2/en_0718-5073-ric-35-02-126.pdf.
[42] C.I. Lagos, Contribution of information technologies to last planner system implementation, in: Proceedings for the 25th Annual Conference of the International Group of Lean Construction, 2017. https://www.academia.edu/45687533/Contribution_of_Information_Technologies_to_Last_Planner_System_Implementation. accessed October 25, 2022.
[43] R. Sacks, R. Barak, B. Belaciano, U. Gurevich, E. Pikas, KanBIM workflow management system: prototype implementation and field testing, Lean Construct. J. 2013 (2013) 19–35. https://www.leanconstruction.org/media/docs/lcj/2013/LCJ_12_004.pdf.
[44] B. Dave, O. Seppänen, Ralf-Uwe Modrich, Modeling information flows between last planner and location based management system, in: Proceedings of the 24th Annual Conference of the International Group for Lean Construction, 2016. https://research.aalto.fi/files/7207101/Dave_et_al._2016_Modeling_Information_Flows_Between_Last_Planner_and_Location_Based_Management_System.pdf.
[45] J. Matthews, P.E.D.D. Love, S. Heinemann, R. Chandler, C. Rumsey, O. Olatunj, Real time progress management: re-engineering processes for cloud-based BIM in construction, Autom. Constr. 58 (2015) 38–47, https://doi.org/10.1016/j.autcon.2015.07.004.
[46] A. Redmond, A. Hore, M. Alshawi, R. West, Exploring how information exchanges can be enhanced through cloud BIM, Autom. Constr. 24 (2012) 175–183, https://doi.org/10.1016/j.autcon.2012.02.003.
[47] M.H. Song, M. Fischer, P. Theis, Field study on the connection between BIM and daily work orders, J. Constr. Eng. Manag. 143 (2017) 6016007, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001267.
[48] A. Dimitrov, M. Golparvar-Fard, Vision-based material recognition for automated monitoring of construction progress and generating building information modeling from unordered site image collections, Adv. Eng. Inform. 28 (2014) 37–49, https://doi.org/10.1016/j.aei.2013.11.002.
[49] M. Pazhoohesh, C. Zhang, Automated construction progress monitoring using thermal images and Wireless Sensor Networks, in: Proceedings, Annual Conference - Canadian Society for Civil Engineering, 2015, pp. 593–602, https://doi.org/10.13140/RG.2.1.1540.3365.
[50] R.K. Soman, B. Raphael, K. Varghese, A system identification methodology to monitor construction activities using structural responses, Autom. Constr. 75 (2017) 79–90, https://doi.org/10.1016/j.autcon.2016.12.006.
[51] A.O. AlSehaimi, P. Tzortzopoulos, L. Koskela, Last planner system: Experiences from pilot implementation in the Middle East, in: 17th Annual Conference of the International Group for Lean Construction IGLC 17, Taipei, 2009. http://usir.salford.ac.uk/id/eprint/9545/1/2009_Last_planner_sys_exps_from_pilot_implementation_in_middle_east.pdf.
[52] S. Lindhard, S. Wandahl, Scheduling of large, complex, and constrained construction projects - an exploration of LPS application, Int. J. Project Organisation Manag. 6 (2014) 237, https://doi.org/10.1504/IJPOM.2014.065258.
[53] A. Nieto-Morote, F. Ruz-Vila, Last planner control system applied to a chemical plant construction, J. Constr. Eng. Manag. 138 (2012) 287–293, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000415.
[54] R.K. Soman, M. Molina-Solana, J.K. Whyte, Linked-data based constraint-checking (LDCC) to support look-ahead planning in construction, Autom. Constr. 120 (2020) 103369, https://doi.org/10.1016/j.autcon.2020.103369.
[55] J.G. Martinez, T. Yeung, R. Sacks, Y. Shahaf, L.-O. Sharoni, Situational awareness in construction using a serious game, J. Constr. Eng. Manag. 149 (2023) 04022183, https://doi.org/10.1061/JCEMD4.COENG-12521.
[56] H.P.I. Halttula, O. Seppänen, Situational awareness in construction projects using takt production, in: Proceedings 30th Annual Conference of the International Group for Lean Construction (IGLC). Edmonton, Canada, 27–29 Jul 2022, International Group for Lean Construction (IGLC), 2022, pp. 164–174, https://doi.org/10.24928/2022/0119.
[57] C. Görsch, O. Seppänen, A. Peltokorpi, R. Lavikka, Construction workers' situational awareness – an overlooked perspective, in: 28th Annual Conference of the International Group for Lean Construction (IGLC), International Group for Lean Construction (IGLC), 2020, pp. 937–948, https://doi.org/10.24928/2020/0022.
[58] C.-Y. Cheng, B. Esmaeili, Situation awareness study in the construction industry: A systematic review, in: Construction Research Congress 2024, American Society of Civil Engineers, Des Moines, Iowa, 2024, pp. 843–853, https://doi.org/10.1061/9780784485293.084.
[59] E.M. Lappalainen, O. Seppänen, A. Peltokorpi, V. Singh, Transformation of construction project management toward situational awareness, Eng. Constr. Archit. Manag. 28 (2021) 2199–2221, https://doi.org/10.1108/ECAM-12-2020-1053.
[60] M. Eckhart, A. Ekelhart, E. Weippl, Enhancing cyber situational awareness for cyber-physical systems through digital twins, in: 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), IEEE, Zaragoza, Spain, 2019, pp. 1222–1225, https://doi.org/10.1109/ETFA.2019.8869197.
[61] T. Yeung, J. Martinez, L. Sharoni, R. Sacks, The role of simulation in digital twin construction, in: Proceedings of the 29th EG-ICE International Workshop on Intelligent Computing in Engineering, EG-ICE, 2022, pp. 248–258, https://doi.org/10.7146/aul.455.c215.
[62] T. Hartmann, A Grassroots Model of Decision Support System Implications by Construction Project Teams, PhD Thesis, Stanford University, 2008, https://stacks.stanford.edu/file/druid:gv950qy3147/WP108.pdf.
[63] M. Bosch-Rekveldt, Y. Jongkind, H. Mooi, H. Bakker, A. Verbraeck, Grasping project complexity in large engineering projects: the TOE (technical, organizational and environmental) framework, Int. J. Proj. Manag. 29 (2011) 728–739, https://doi.org/10.1016/j.ijproman.2010.07.008.
[64] M.R. Nezami, M.L.C. de Bruijne, M.J.C.M. Hertogh, H.L.M. Bakker, Collaboration and data sharing in inter-organizational infrastructure construction projects, Sustainability 14 (2022) 16835, https://doi.org/10.3390/su142416835.
[65] M. Jirgl, Z. Bradac, P. Fiedler, Human-in-the-loop issue in context of the cyber-physical systems, IFAC-PapersOnLine 51 (2018) 225–230, https://doi.org/10.1016/j.ifacol.2018.07.158.
[66] Karadeniz Technical University, B.A. Temel, H.B. Başağa, M.U. Temel, G. K. Yılmaz, M.M. Nasery, Big room concept in project management and control, J. Construct. Engi. Manage. Innov. 2 (2019) 204–214, https://doi.org/10.31462/jcemi.2019.04204214.
[67] J. Majava, H. Haapasalo, K. Aaltonen, Elaborating factors affecting visual control in a big room, Constr. Innov. 19 (2019) 34–47, https://doi.org/10.1108/CI-06-2018-0048.
[68] C.P. Schimanski, N.L. Pradhan, D. Chaltsev, G. Pasetti Monizza, D.T. Matt, Integrating BIM with lean construction approach: functional requirements and production management software, Autom. Constr. 132 (2021) 103969, https://doi.org/10.1016/j.autcon.2021.103969.
[69] B. Dave, S. Kubler, E. Pikas, J. Holmström, V. Singh, K. Främling, L. Koskela, A. Peltokorpi, Intelligent products: Shifting the production control logic in construction (with lean and BIM), in: Proceedings of the 23rd Annual Conference

of the International Group for Lean Construction, 2015. https://www.semanticscholar.org/paper/Intelligent-products%3A-Shifting-the-production-logic-Dave-Kubler/fe8faad3a6affa8c4828098fad300f7a5cb7c5a3. accessed July 3, 2024.
[70] A. Tezel, Z. Aziz, From conventional to IT based visual management: a conceptual discussion for lean construction, J. Informa. Techn. Construct. 22 (2017) 220–246.
[71] C. Boton, D. Forgues, Practices and processes in BIM projects: an exploratory case study, Adv. Civ. Eng. 2018 (2018) 1–12, https://doi.org/10.1155/2018/7259659.
[72] C.H. Kuo, M.H. Tsai, S.C. Kang, A framework of information visualization for multi-system construction, in: Automation in Construction, Elsevier, 2011, pp. 247–262, https://doi.org/10.1016/j.autcon.2010.10.003.
[73] K. McHugh, B. Dave, L. Koskela, On the role of lean in digital construction, in: M. Bolpagni, R. Gavina, D. Ribeiro (Eds.), Industry 4.0 for the Built Environment, Springer International Publishing, Cham, 2022, pp. 207–226, https://doi.org/10.1007/978-3-030-82430-3_9.
[74] A. Ezzeddine, L. Shehab, I. Srour, W. Power, E. Zankoul, E. Freiha, CCC_implementing the construction control room on a fast-paced project: the case study of the Beirut port explosion, Int. J. Constr. Manag. 23 (2023) 745–755, https://doi.org/10.1080/15623599.2021.1925395.
[75] A. Brazier, Operations: A control room is only a component in a complex system, in: Article of AB Risk Limited Managing Risks of Control Room Operations, 2010. https://www.slideshare.net/slideshow/2010-ibc-managing-risks-of-control-room-operations/61712461#5. accessed July 3, 2024.
[76] C. Palmer, Y.M. Goh, E.-M. Hubbard, R. Grant, R. Houghton, The need for a symbiotic Interface for a digital twin, in: P. Koomsap, A. Cooper, J. Stjepandić (Eds.), Advances in Transdisciplinary Engineering, IOS Press, 2023, https://doi.org/10.3233/ATDE230685.
[77] A. Dingli, F. Haddod, Interacting with intelligent digital twins, in: A. Marcus, W. Wang (Eds.), Design, User Experience, and Usability. User Experience in Advanced Technological Environments, Springer International Publishing, Cham, 2019, pp. 3–15, https://doi.org/10.1007/978-3-030-23541-3_1.
[78] C. Franciosi, S. Miranda, C.R. Veneroso, S. Riemma, Investigating human factors integration into DT-based joint production and maintenance scheduling, in: E. Alfnes, A. Romsdal, J.O. Strandhagen, G. von Cieminski, D. Romero (Eds.), Advances in Production Management Systems. Production Management Systems for Responsible Manufacturing, Service, and Logistics Futures, Springer, Nature Switzerland, Cham, 2023, pp. 633–648, https://doi.org/10.1007/978-3-031-43662-8_45.
[79] J. Wilhelm, C. Petzoldt, T. Beinke, M. Freitag, Review of digital twin-based interaction in smart manufacturing: enabling cyber-physical Systems for Human-Machine Interaction, Int. J. Comput. Integr. Manuf. 34 (2021) 1031–1048, https://doi.org/10.1080/0951192X.2021.1963482.
[80] H.A. Simon, The Sciences of the Artificial, 3rd ed., MIT Press, Cambridge, Mass, 1996. ISBN: 9780262691918.
[81] R. Weber, Toward a theory of artifacts: a paradigmatic base for information systems research, J. Inf. Syst. 1 (1987). ISSN 0888-7985.
[82] W.J. Orlikowski, C.S. Iacono, Research commentary: desperately seeking the "IT" in IT research—a call to theorizing the IT artifact, Inf. Syst. Res. 12 (2001) 121–134, https://doi.org/10.1287/isre.12.2.121.9700.
[83] I. Benbasat, R.W. Zmud, The identity crisis within the IS discipline: defining and communicating the Discipline's Core properties, MIS Q. 27 (2003) 183–194, https://doi.org/10.2307/30036527.
[84] H.K. Klein, Crisis in the IS field? A critical reflection on the state of the discipline, J. Assoc. Inf. Syst. 4 (2003), https://doi.org/10.17705/1jais.00037.
[85] F. Vainionpää, M. Kinnula, A. Kinnula, K. Kuutti, S. Hosio, HCI and digital twins – a critical look: a literature review, in: Proceedings of the 25th International Academic Mindtrek Conference, ACM, Tampere Finland, 2022, pp. 75–88, https://doi.org/10.1145/3569219.3569376.
[86] J. Kim, M. Kim, S. Park, Goal and scenario based domain requirements analysis environment, J. Syst. Softw. 79 (2006) 926–938, https://doi.org/10.1016/j.jss.2005.06.046.
[87] A. Rashwan, O. Ormandjieva, R. Witte, Ontology-based classification of non-functional requirements in software specifications: a new corpus and svm-based classifier, in: 2013 IEEE 37th Annual Computer Software and Applications Conference, IEEE, 2013, pp. 381–386, https://doi.org/10.1109/COMPSAC.2013.64.
[88] A. Borrmann, J. Schlenger, N. Bus, R. Sacks, AEC digital twin data - why structure matters, in: Advances in Information Technology in Civil and Building Engineering. ICCCBE 2022, Lecture Notes in Civil Engineering, vol. 357, Springer, Cham, 2023, https://doi.org/10.1007/978-3-031-35399-4_46.
[89] T. Margaria, S. Ryan, Data and data Management in the Context of digital twins, in: N. Crespi, A.T. Drobot, R. Minerva (Eds.), The Digital Twin, Springer International Publishing, Cham, 2023, pp. 253–278, https://doi.org/10.1007/978-3-031-21343-4_10.
[90] T.W. Kang, C.H. Hong, A study on software architecture for effective BIM/GIS-based facility management data integration, Autom. Constr. 54 (2015) 25–38, https://doi.org/10.1016/j.autcon.2015.03.019.
[91] R. Vieira, P. Carreira, P. Domingues, A.A. Costa, Supporting building automation systems in BIM/IFC: reviewing the existing information gap, Eng. Constr. Archit. Manag. 27 (2020) 1357–1375, https://doi.org/10.1108/ECAM-07-2018-0294.
[92] J. Schlenger, T. Yeung, S. Vilgertshofer, J. Martinez, R. Sacks, A. Borrmann, A comprehensive data schema for digital twin construction, in: Proceedings of the 29th EG-ICE International Workshop on Intelligent Computing in Engineering, EG-ICE, 2022, pp. 34–44, https://doi.org/10.7146/aul.455.c194.
[93] J. Akroyd, S. Mosbach, A. Bhave, M. Kraft, Universal digital twin - a dynamic knowledge graph, Data Centric Eng. 2 (2021) e14, https://doi.org/10.1017/dce.2021.10.
[94] K. Farghaly, R.K. Soman, J. Whyte, The evolution of ontology in AEC: a two-decade synthesis, application domains, and future directions, J. Ind. Inf. Integr. 36 (2023) 100519, https://doi.org/10.1016/j.jii.2023.100519.
[95] K. Farghaly, R. Soman, J. Whyte, cSite ontology for production control of construction sites, Autom. Constr. 158 (2024) 105224, https://doi.org/10.1016/j.autcon.2023.105224.
[96] A. Löcklin, T. Jung, N. Jazdi, T. Ruppert, M. Weyrich, Architecture of a human-digital twin as common Interface for operator 4.0 applications, Procedia CIRP 104 (2021) 458–463, https://doi.org/10.1016/j.procir.2021.11.077.
[97] Y. Yao, E.A. Patterson, R.J. Taylor, The influence of digital technologies on knowledge Management in Engineering: a systematic literature review, IEEE Trans. Knowl. Data Eng. (2023) 1–15, https://doi.org/10.1109/TKDE.2023.3285952.
[98] V. Singh, S. Mirzaeifar, Assessing transactions of distributed knowledge resources in modern construction projects – a transactive memory approach, Autom. Constr. 120 (2020) 103386, https://doi.org/10.1016/j.autcon.2020.103386.
[99] A. Hussein, M.M. Gaber, E. Elyan, C. Jayne, Imitation learning: a survey of learning methods, ACM Comput. Surv. 50 (2017), https://doi.org/10.1145/3054912, 21:1–21:35.
[100] J. Ho, S. Ermon, Generative adversarial imitation learning, in: Advances in Neural Information Processing Systems, Curran Associates, Inc., 2016, in: https://proceedings.neurips.cc/paper_files/paper/2016/hash/cc7e2b878868cbae992d1fb743995d8f-Abstract.html. accessed September 21, 2023.
[101] N. Slob, W. Hurst, R. van de Zedde, B. Tekinerdogan, Virtual reality-based digital twins for greenhouses: a focus on human interaction, Comput. Electron. Agric. 208 (2023) 107815, https://doi.org/10.1016/j.compag.2023.107815.