2025 European Conference on Computing in Construction

CIB W78 Conference on IT in Construction

Porto, Portugal
July 14-17, 2025

CONVERGENCE OF DIGITAL TWIN AND HUMAN-DATA INTERACTION: ADVANCING CUSTOMER EXPERIENCE IN THE BUILT ENVIRONMENT

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Abstract

Digital Twin (DT) demonstrates opportunities to advance Human-Data Interaction. Previous studies documented DT applications in manufacturing and construction industries to improve accuracy and efficiency. While these findings showcased DT's benefits as a product or process, they lack connection with humans, users of DTs. This paper is the first to explore the potential of transitioning DT into Twin System (TS) to address Customer Experience (CX) challenges in the built environment. A literature review and focus group discussion were conducted to develop a 3-layered TS framework with 26 applications. The conceptualisations extend DT from a technology-focused aspect to a human-centric design.

Introduction

Transitioning from Industry 4.0 to Industry 5.0, there is a paradigm shift from a data-driven society to a human-centric community. Apart from exploiting the benefits spurred by digital transformation, establishing harmonious relationships between humans and technologies (e.g. machines, computers and data) to create a resilient and sustainable society is a key theme of Industry 5.0 (Fontes *et al.*, 2024; Huang *et al.*, 2022). In modern society, individuals spend over 90% of their everyday lives inside buildings. Thus, constructing, designing and operating buildings for a comfortable living environment is pivotal (Zhang *et al.*, 2024). Technological innovations in Industry 4.0, for instance, Building Information Modelling (BIM), revolutionised the planning and construction processes. Visualising the multiple sources of data in the computerised models fosters stronger collaborations among stakeholders (Li *et al.*, 2024). Leveraging data is thus the key.

Human-Data Interaction (HDI) is an emerging field to study processes and systems which support the ethical collection and use of personal data. Nonetheless, data without context are "noises", collecting, archiving and analysing the multi-faceted sources of data is a difficult job in the fragmented construction industry (Agrawal *et al.*, 2023). The evolution of BIM to Digital Twin (DT) enables near real-time monitoring of building data. Twin System expands the conventional understanding of DTs by integrating several disconnected DTs into a structured system, enabling more precise predictive and adaptive decision-making (Pärn et al., 2024). In the context of Industry 5.0, where human-centric design is prioritised, Twin Systems can serve as intelligent interfaces that respond to human behaviour, ensuring that buildings and services adapt to real-time customer needs. This shift moves DTs beyond mere efficiency improvements to foster experiential, adaptive, and resilient environments. In the hospitality sector, a Twin System could not only monitor environmental conditions but also anticipate customer needs, personalise experiences, and optimise resource allocation to enhance satisfaction and operational efficiency.

Existing research elaborated on some deficiencies in construction management resulting from a solely technology-oriented approach. For instance, the mismatch of occupants' desires and building designs (thermal comfort, lighting, wall decorations) has led to a significant increase in facility management costs and users' dissatisfaction with buildings (AlFaris *et al.*, 2016; Li *et al.*, 2017). There is a gap in DT capabilities in the built environment to cater to building users' needs on top of measuring building performance dynamically. It is therefore necessary to investigate how to input users' data, experiences and feedback into buildings' life cycle management in a systemic way.

This paper aims to explore the co-creation of values for a human-centric built environment by both humans and data inside a Digital Twin System at a hotel setting. The research investigates the following questions:

- RQ1: How does DT drive HDI in CX use cases?
- RQ2: What CX data are required for DT of buildings?
- RQ3: What barriers will hinder DT application in HDI for improving CX?

Firstly, the concepts of HDI, CX and DT are reviewed from the literature. Next, a research methodology is presented, followed by findings and discussion. Finally, the conclusion summarises the value of research in this study to intertwine DT and HDI in alleviating the CX challenges. The paper contributes to the body of knowledge in Digital Twin and its potential to extend to Twin System. In particular, DT applications in a hotel, which require a higher degree of CX in the built environment, are explored. This research's novelty lies in 2 major paradigm shifts: (1) expanding DT into a Twin System that connects several DTs systematically and (2) transitioning traditional technical-oriented DT design in Industry 4.0 to a human-centric DT design in Industry 5.0. The research findings demonstrate how HDI is applied in DT, which is important to guide future research in designing and constructing DTs. It is also timely to reflect on the interactions of humans and technologies, enabling upcoming research to explore DT as a Twin System that incorporates general customers' feedback on top of conventional building designs, which are advised only by architectural, engineering and construction (AEC) experts.

Literature Review

Human Data Interaction (HDI)

HDI emerges as a research area to examine the relationships between humans and data. HDI evolved from human-computer interaction (HCI), which focuses on hardware computer devices. Elmqvist (2013) elaborated HDI as an *"anytime, anywhere sensemaking performed on a plethora of networked digital devices"*. Promising technologies like artificial intelligence, machine learning, and big data analytics are built upon the massive amount of connected data to assist analysis and decision-making across industries. In order to leverage the existing data for designing a human-centric society, Mortier et al. (2014) proposed 3 overriding HDI principles:

- **Legibility***: human to understand the data*
- **Agency***: human to take actions inside the data systems (e.g. change or modify the data collection and inference processes)*
- **Negotiability***: humans to update and change their preferences of data usage over time or based on different contexts*

As data evolve and contexts change, HDI should be dynamic to keep abreast of the latest data available and personal needs, such that customers can re-evaluate their decisions.

Customer Experience (CX) Challenges

Bolton (2018) conceptualised CX into 3 chief categories: **(1) Physical complexity; (2) Digital density; (3) Social presence.** Firstly, **physical complexity** focuses on the interactions between customers and the physical environments through sensory systems, such as colourful and attractive visual billboards in advertisements, upbeat music in shopping malls and the face-to-face interactions between consumers and service providers' employees (Lemon and Verhoef, 2016). Secondly, **digital density** is rooted in the sharing of data between customers and companies to design personalised products and services. Finally, **social presence** relates to the interactions among various customers and between employees and customers to build social branding for the company. There is a gap about how to combine all 3 of the categories into a single platform that enables service providers to tailor their customers' experience.

Customer Experience (CX) Challenges in the Built Environment

There is growing research exploring how to design buildings to maximise occupants' satisfaction. Abbott (1955) discussed in his book about the customers' choice of quality: *"what people really desire are not products but satisfying experiences"*. For example, a typical Heating, Ventilation and Air Conditioning (HVAC) system usually contributes up to 30-40% of the electricity consumption of the building (González-Torres *et al.*, 2022); however, according to a survey conducted with over 34,000 participants, only 39% of the respondents were satisfied with the thermal comfort provided by HVAC (Li *et al.*, 2017). It is thereby crucial to understand what elements are significant to tackling the CX challenges in the buildings. To combat the 3 CX challenges mentioned above, Bolton (2018) suggested incorporating cutting-edge technologies such as DT, big data analytics and wearable equipment to first collect data from customers, uncover insights into their needs, and then devise personalised services accordingly.

From Digital Twin to Twin Systems

In the past decade, Digital Twin (DT) has been the center of discussion to drive Industry 4.0 for efficient manufacturing. DT is a digital representation of the physical environment with dynamic updates of data between the 2 (physical and digital) dimensions. There has been wide adoption of DT technologies in the automobile, aircraft and healthcare industries. (Grieves and Vickers, 2017; Sacks *et al.*, 2020). However, the adoption of DT in the built environment is still not as popular as its counterparts. One possible reason is that in buildings, whether it is a campus or a cinema, there is a higher degree of interaction between the physical assets and humans. For example, when designing cars and airplanes, the focus is primarily on fluid dynamics and mechanical engineering. Conversely, in buildings, although tangible factors such as structural integrity and fire safety are essential, intangible interactions between buildings and occupants are pivotal to retaining customers. Currently, most of the CX challenges are not yet resolved by solely relying on data (AI, machine learning) and technologies (BIM, VR and LiDAR).

Prior research findings related to DT are generally positive in boosting productivity, reducing errors and predicting future scenarios in manufacturing, aviation and construction industries. Very recently, research trends of DT have started to grow in the cognitive layer to include humanistic elements on top of the traditional focus on hardcore technologies. There is potential to further incorporate HDI principles when designing DT, by blending psychology and cognitive science to enhance building and customer interactions and personalised experience. In light of Industry 5.0's human-centric design initiative, El Saddik (2018) has proposed a DT with heterogeneous social media to improve the well-being, social connection and quality of life for users. To engage users' feedback, Ren et al. (2024) presented a highly personalised design of the automobile by leveraging a human digital twin (HDT).

In the built environment, Nochta and Oti-Sarpong (2024) introduced the concept of participative planning by embedding citizens' opinions into DT to assist smart city development. Pärn et al. (2024) introduced *"Twin System"* as a new concept in which several standalone DTs are connected into a single DT system. This is a critical step to improve building designs and advance CX. For example, DTs of HVAC systems, façades, and humans are able to communicate with each other within the Twin System to expand DT functionalities. Depending on the users' requirements, AEC professionals can twin a variety of systems and products, and the resulting DTs will form a Twin System themselves to interact within the ecosystem. This innovatively opens doors to new HDI possibilities. Calvetti et al. (2023) developed a conceptual framework with 7 levels of DT for incremental interaction between HDI and DT. Nonetheless, there are limited studies of HDI from the perspective of users. It suggested further research on understanding and evaluating end users' orientation about HDI.

This research aims to explore the use of DT as a system to facilitate HDI for tackling CX challenges in a hotel setting. For this research paper, the evolution of DT into Twin System is particularly vital in the hospitality industry, where guest experience is influenced by both physical space and service quality. For instance, if a guest frequently orders room service at a specific time, the system can proactively suggest or prepare their preferred meal. Similarly, digital concierge services could evolve based on prior engagements, personalising recommendations based on previous stays. The advantage of a Twin System lies in its ability to connect not just the physical hotel environment but also digital service ecosystems, integrating booking systems, smart room controls, and guest feedback mechanisms into a cohesive, responsive framework.

Methodology

In an attempt to answer the 3 research questions, this study conducted a literature review of recent papers about DT use cases. Papers were selected from 2018 onwards, based on keyword search of "digital twin", "human-data interaction", "occupancy comfort", "human-centric design" and "customer experience" from ScienceDirect. At first, 124 publications were obtained. All titles and abstracts were carefully reviewed, and some duplicated papers were removed. Papers were only selected if they were related to hospitality and the built environment fields. 9 final papers were filtered according to their relevance and significance (Table 1). A 3-layered DT framework was developed with 26 use cases and focus group discussions.

Table 1: Literature review of use-case analysis

No.	Literature
1	(Muschkiet *et al.*, 2022)
2	(Bolton, 2018)
3	(Tahmasebinia *et al.*, 2023)
4	(Chen *et al.*, 2021)
5	(Singh *et al.*, 2023)
6	(Figueiredo *et al.*, 2024)
7	(Yeom *et al.*, 2024)
8	(Ohueri *et al.*, 2024)
9	(Ren *et al.*, 2024)

To verify the findings from the literature review, a focus group discussion was conducted (November 2024) at a 4-star hotel in London that has been operating for over 10 years. An expert panel with 5 hotel staff of different expertise was formed, as shown in Table 2. All participants have at least 5 years of working experience in the built environment to ensure that they are familiar with hotel management. The focus group method was selected to gain deep qualitative insights from industry professionals regarding CX challenges and DT implementation barriers (Verma and Chandra, 2018). The participants were chosen based on their expertise in hospitality management and building operations, ensuring a comprehensive understanding of both technical and customer experience aspects. However, potential biases exist, as familiarity with DT varied among participants. To validate our framework, findings were cross-referenced with real-world case studies of smart hotels and benchmarked against existing DT models in retail and healthcare. Future research should incorporate quantitative assessments to measure the impact of DT on guest satisfaction and operational efficiency. Previous research has stressed the importance of qualitative data from industry practitioners to narrow gaps between research findings and business applications (Chan and Hawkins, 2012).

Table 2: Focus group participants' background.

No	Job Title	Educational Level	Working Experience in the hospitality industry (year)
1	Senior Vice President of Global Sales and Revenue	University	20-30
2	Development Manager	University	20-30
3	Area Chief Engineer	University	20-30

4	Cluster Maintenance Manager	University	10-20
5	Engineering/ Maintenance Coordinator	Secondary school	5-10

This hotel was selected given the following 3 rationales. Firstly, from the building design perspective, hotels are differentiated from other building types, such as schools, hospitals, industrial facilities, and offices, which have luxurious architectural elements and aesthetic features. (Heide *et al.*, 2007). Secondly, from the customer service perspective, hotels require a higher level of customer support services, and their employees are trained extensively to curate top-notch guest experiences (Yang *et al.*, 2021). Finally, from a geographical perspective, the selected hotel is situated in London, which is a metropolis, with an over 90% occupancy rate. The data collected from this case represented a large sample size of customers for insightful evaluation. It should be noted that the hotel being investigated does not have a DT model. This will be an intriguing exploration of DT's capability to address some of the problems currently hindering hotel operational and customer management teams' work.

Findings and Discussion

3 final dimensions with 26 use cases were synthesised and identified in *Table 3*.

- **Building dimension: building design**

From the literature, all findings suggested that DT is capable of **real-time data monitoring of building operational energy efficiency**. The collection of the physical asset data, such as air quality, carbon dioxide density, temperature, and relative humidity, were frequently reported as critical benchmarks to enhance human health, i.e. alleviating the CX challenges due to physical complexity. From the empirical data collected from the hotel, there were no IoT sensors or real-time analysis of the hotel situation. All staff responded that a DT platform for real-time HDI will be helpful in managing customers' satisfaction levels. In particular, the HDI can be separated into 2 areas: (1) Human (hotel facility management staff)-Data (real-time performance data of different building services systems)-Interaction; (2) Human (hotel visitors and customers)-Data (real-time room and lobby data)-Interaction. Another benefit of incorporating HDI in DT for buildings is the possibility of predictive maintenance. Forecasting in advance the failure probability of facilities and scheduling regular maintenance to avoid peak traveling seasons based on occupancy, asset service life and monthly operational data will be particularly advantageous to successful CX. The last application of DT for improving HDI is to heighten security control of the physical environment, like installing CCTV cameras.

- **Virtual dimensions: digital model & data**

The second category discovered is the virtual dimension, which can be further broken down into the **digital model** layer and **data** layer. Regarding the **digital model** layer, the most cited application of DT for avoiding undesirable CX is **what-if scenario simulations: emergency and accidents**. By injecting data from previous failures, such as water burst, electricity supply interruptions and fire accidents into DT, the HDI enables built environment professionals to envision designs with careful considerations in advance. As from the focus group discussion, most of the respondents agreed that carrying out regular what-if scenarios training will be conducive to raising staff's awareness of ad-hoc and unforeseen accidents. The **digital model** is also highlighted as a platform in DT to support other online services. For example, hotel customers could make their choice of room, bed and visiting more conveniently through visualising the digital representation before arrival. In DT's virtual space, apart from the digital model, the **data** layer was also conceptualised for analytics and seamless communication. Data collected from IoT sensors will be fed into the 3D model of the building for various purposes, such as the evaluation of building energy efficiency performances, which is pivotal when applying for WELL certifications (Taha and Elabd, 2020). DT will not only be beneficial to drive sustainable developments in the built environment, but also spillover the merits brought about by WELL's certification to strengthen building users' overall wellness. This is in line with Industry 5.0's overarching goal to co-create a human-centric, sustainable and resilient society. By leveraging data, foresight insights are derived. The more versatile HDI is, the higher the quality of CX is attained.

- **People dimension: customer engagement**

Considering the last dimension about people, it has the closest relationship to CX. From the literature and focus group findings, **simulating customer experience** within DT plays a key role in strengthening HDI. Data from customers, such as their historical travelling and dietary records, are golden data thread for companies to profoundly understand individual consumers' choices. Acosta et al. (2016) elaborated an approach to aggregate multi-source data (historical electrical consumption, heat gain and loss, and centralised air conditioning system data) to improve building users' thermal comfort. The accuracy and precision will be highly upgraded when data are fed into DT instead. Flyvbjerg et al. (2005) explained the inherent bias in models and forecasting techniques in traffic data analysis. A dynamic update of data inside DT realises real-time analysis and maintains a bidirectional feedback loop. This is particularly critical since future data predictions can learn from their previous records instead of probabilistic estimation and forecasting algorithms. On top of the shift from providing standardised services to customised services, another future direction is to consolidate customers of similar demographics (e.g. age group and gender) for behaviour analysis. For our context, the personal information collected from building users will be the main driving force to design personalised services, which are fundamental to handling the social presence CX challenge as above-mentioned.

The findings synthesised from the 9 selected papers and the focus group discussion were presented in a conceptual framework in Figure 1, which intends to answer RQ1 about the use cases of DT for addressing CX challenges. 3 separate domains: (1) Building dimension of building design; (2) Virtual dimension of digital model and data; and (3) People dimension of customer engagements were labelled. Within each of the realms, HDI requirements were detailed, showcasing what types of data are the most important to drive HDI in DT, hence answering RQ2 of this study. To answer RQ3, 2 major barriers were identified when deploying DT for HDI in CX.

- **Personal privacy**

A bulky amount of data collection is the prerequisite to constructing personalised customisation in buildings. Referring to the 3 pillars of HDI, *legibility, agency, and negotiability,* the importance of users' willingness to share their data is most critical. When developing digital platforms, such as DT, reluctance from users to share their personal information may be one of the challenges. The European General Data Protection Regulation (GDPR) provided guidance for software developers and enterprises on the ethical use of data from their consumers, echoing the 3 HDI principles (Voigt and von dem Bussche, 2017).

- **Cybersecurity**

Another challenge of HDI in DT relates to cybersecurity of the data and systems. Pärn et al. (2024) highlighted the vulnerabilities of DT to hackers' malicious attacks. Given the highly connected nature of DT's 3 key components and external database, cybersecurity is a critical infrastructure to protect both the customers and companies. Standardised cybersecurity assessment should be conducted in advance of the DT full deployment.

Limitations and Future Directions

The proposed framework captured the latest trends of DT developments in the building and construction industries. Yet, the findings above are limited to:

- The literature review part of this study is constrained by the 9 selected papers. Future research should include a systematic review of the literature regarding "human-centric digital twin", "human-data interaction in buildings" and "customer experience challenges in the built environment".
- The empirical investigation of HDI in DT is limited to only 1 focus group discussion with hotel representatives. The qualitative data collected were subject to participants' personal backgrounds and working experiences. In the future, several rounds of focus group discussions or Delphi surveys can be carried out.
- In this study, only a hotel is selected given its building structure complexity and top-notch service quality levels. Another future direction is to compare the different customer experience needs in different building types.

Conclusions

In conclusion, digital transformation has transcended technologies and society from a data-driven Industry 4.0 to a human-centric Industry 5.0 landscape. This paper reviewed key Human-Data Interaction (HDI) concepts related to the built environment. Prevalent Customer Experience (CX) challenges were investigated from the literature. This study highlights the potential of Digital Twins in addressing CX challenges in the built environment. However, to achieve true adaptability and predictive intelligence, Twin Systems offers a more comprehensive approach. By enabling bidirectional data flows and dynamic feedback loops, Twin Systems transform digital hospitality from a passive monitoring system into an interactive, self-optimising experience. This paradigm shift ensures that guest preferences are continuously learned, service delivery is predictive rather than reactive, and operational efficiencies are maximised without compromising comfort. As the hospitality industry advances toward Industry 5.0, integrating Twin Systems will be key to crafting responsive, intelligent, and human-centric environments. Future research should explore implementation frameworks that bridge the gap between digital infrastructure and human experience, ensuring that hospitality spaces evolve in real-time to meet the ever-changing needs of guests. Twin Systems was identified as a critical tool for enhancing customer experience in buildings. Followed by a case study in a UK hotel, findings from 9 papers and 1 focus group discussion are summarised to develop a digital twin framework with 3 dimensions and 26 use cases to tackle customer experience challenges. 2 potential threats to the framework are discussed. Digital twin acts as a melting pot for the vast amount of data collected from buildings and humans to drive well-informed and human-centric building management decisions. Grounded by previous research about the technicalities of DT system design and data collection, the framework developed in this study presents a novel exploration of building design to incorporate the people layer in DT, which is pivotal to enhancing HDI and CX. The findings of the paper unveil a practical approach to drive digital transformation in the hospitality and built environment sectors by merging both human data and digital technologies.

Table 3: Digital twin applications for enhancing customer experience in buildings (Literature from Table 1)

	Literature								
	1	2	3	4	5	6	7	8	9
1. Physical dimension: building design and management									
1.1 Real-time data monitoring of building operational energy efficiency	X	X	X	X	X	X	X	X	X
1.2 Predictive maintenance of building		X	X			X	X	X	X
1.3 Physical security systems for building security and safety	X		X			X	X		
2. Virtual dimension (digital model): virtual representation and online services									
2.1 Virtual spatial measurement	X		X	X	X	X		X	X
2.2 What-if scenarios simulations: emergency and accidents	X	X	X	X	X	X		X	
2.3 Virtual prototyping for building design and engineering simulations	X	X	X	X	X	X	X	X	
2.4 Virtual training for employees to familiarise with the physical building	X	X					X		
2.5 Remote building visiting and monitoring		X	X	X	X				X
2.6 Virtual resort and building room tour	X	X		X	X				
2.7 e-Concierge	X				X				
2.8 VR immersive building experience	X	X			X		X		X
2.9 Blockchain transaction and e-payment	X	X				X			
2.10 3D visualisation of building geometry				X	X		X		X
2. Virtual dimension (data): analytics and seamless communication									
2.11 IoT sensors for dynamic information exchange between building services systems	X	X	X	X	X	X		X	
2.12 Big data analytics for building operation efficiency	X	X	X		X			X	
2.13 Resource management: food, water, energy efficiency, carbon footprint		X	X	X	X	X	X	X	
2.14 AI algorithm for building design and monitoring	X	X	X		X	X		X	X
2.15 Dashboard display for real-time data analysis	X	X			X			X	
2.16 Machine and Deep Learning for building customer experience optimisation	X	X	X		X	X		X	X
3. People dimension: customer engagement									
3.1 Simulate customer experience	X	X	X		X		X	X	X
3.2 Recommender system	X	X			X				X
3.3 Predict future customer behaviour			X		X		X	X	X
3.4 Personalised marketing services	X	X			X		X		
3.5 Analytics of service reviews	X								X
3.6 Monitor customer needs and satisfaction	X						X	X	
3.7 Customers' active participation in product design		X			X		X		X

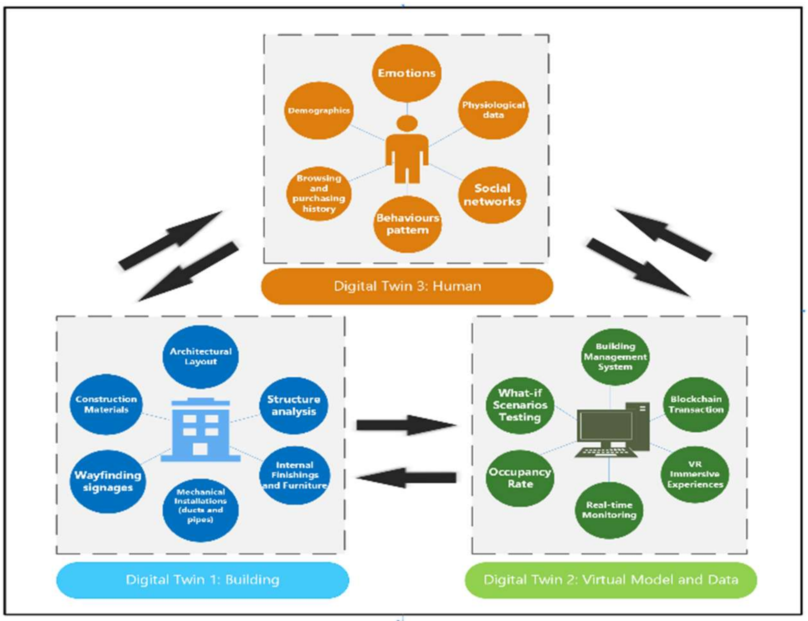

Figure 1: Conceptual framework of digital twin system for human-data interaction in the built environment

Acknowledgements

The authors acknowledge industry partners who participated in the focus group discussion to give invaluable insights. The authors also acknowledge the funding received from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101079961 (AEGIR project).

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