

# LEVERAGING DIGITAL TWINS TOWARDS AN OCCUPANT-CENTRIC BUILT ENVIRONMENT: A REVIEW

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## Abstract

One of the main purposes of building design and development is to enhance the experiences and activities of occupants. Traditionally, the longitudinal collection of occupant data has presented challenges. In this context, the emerging paradigm of Digital Twins (DTs) offers a promising solution. This systematic review investigates recent advancements in DT applications within the Architecture, Engineering, Construction and Operations (AECO) sector, focused on the integration and utilisation of real-time occupant data. Our findings categorize the types of data collected and the varying degrees of occupant involvement in these processes. The review also identifies the primary challenges encountered in data collection and integration, emphasising the need for balancing ethical and privacy concerns. Additionally, the paper explores the potential of DTs in enriching occupant-centric applications, highlighting their role in optimising building performance, enhancing comfort, and improving maintenance and safety. This review not only sheds light on the current state of occupant data in DT applications but also explores opportunities for leveraging occupant data to create more responsive and efficient built environments.

## Introduction

The fundamental purpose of the built environment is to support and structure the activities and tasks of its occupants. Historically, understanding the impact of buildings on occupants has predominantly been the domain of Post-Occupancy Evaluations (POE). Initiated in the 1960s and 1970s, POEs have aimed to optimise and fine-tune building performance to better support occupants and inform the design of future structures (Preiser and Nasar, 2008). This field later expanded to include energy performance evaluations, significantly influenced by research in the 1990s and early 2000s (Leaman and Bordass, 2001). Despite significant contributions of POE to our current understanding of occupant comfort and general building performance, data collected from users has usually been limited to qualitative studies (i.e. focus groups) and one-off satisfaction surveys. As such, legacy challenges like the performance gap, the discrepancy between designed performance and actual performance persist, largely

driven by occupant behaviour and usage patterns (Far *et al.*, 2022).

In recent years, the concept of Digital Twins (DTs) has emerged as a novel paradigm in built environment research. Evolving from advancements in Building Information Modelling (BIM), smart building technologies, and developments on Internet of Things (IoT) sensors, DTs offer the potential to enhance building performance through real-time data collection, granular control of building systems, and advanced operational intelligence via automation and improved simulation methods (Building Smart International, 2020). If the objective remains to design buildings that meet user needs, the role of DTs in understanding and refining performance for occupants could be substantial.

Although several systematic reviews have investigated DT applications in the built environment within recent years (Long *et al.*, 2024), there has been limited focus on the specific challenges and opportunities related to integrating occupant data into DTs. This paper aims to examine how recent published research has addressed the incorporation of occupant data. Thus, the paper aims to analyse the selected articles to determine the purposes for which the identified DT applications are being developed, as well as to identify the various methods and types of occupant data that are integrated in the identified DTs.

## Defining DTs

While the concept of Digital Twins (DTs) originated decades ago, primarily in the manufacturing context (Tao *et al.*, 2019), its evolution in the built environment has been significantly influenced by advancements in smart buildings, the Internet of Things (IoT), enhanced sensing technologies, and the development of semantically rich digital models within Building Information Modelling (BIM). Additionally, recent reviews (Long *et al.*, 2024) have shown an exponential growth in interest regarding DT applications in built environment research. Studies such as Shahzad *et al.* (2022) have highlighted a lack of common understanding among various stakeholders in the AECO sector, leading to challenges in establishing a universally accepted definition of a DT. For the purposes of this paper, a DT is defined as “(...) a digital representation of a physical asset. Linked to each other, the physical and digital twin regularly exchange data

throughout the Plan Build Operate Decommission lifecycle and use phase. Technologies like AI, machine learning (ML), sensors, and IoT allow for dynamic data gathering and right-time data exchange to take place” (Building Smart International, 2020 p.2).

This definition encompasses the widely accepted view of DTs as digital replicas of physical assets, further enriched with data collected in real-time. However, to ensure consistent criteria for the article inclusion criteria used in this review, the constituents of a DT will be further defined. Drawing from the manufacturing sector, particularly the work of Tao *et al.* (2019) five layers have been identified as integral to a DT. Massafra *et al.* (2023) adapted these elements to the context of building-related DTs (Figure 1). These five constituents or layers include:

- Physical Asset: The building, equipped with IoT sensors.
- Virtual Asset: A digital representation of the building, typically a semantically rich Asset Information Model (AIM).
- Connections: The information and flows and connections that link the virtual and physical layers, as well as the other layers.
- Data: Integration of all data collected from both digital and physical asset layers to create a comprehensive and accurate information set.
- Services/Actuator: These facilitate the application of data to meet the needs of DT users. For instance, visualisation, system control, "what-if" scenario simulations etc.

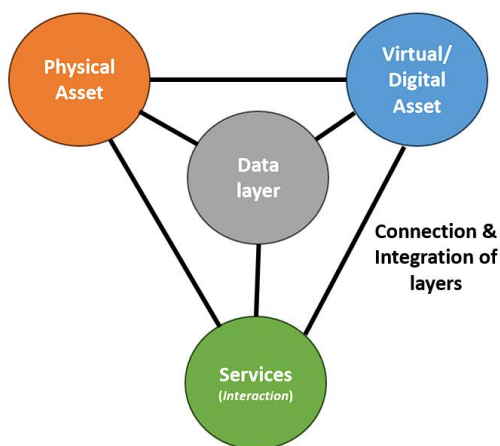


Figure 1. DT layers. Adapted from Massafra *et al.* (2023)

## Methodology

### Systematic Literature Review

This paper deploys a Systematic Literature Review (SLR) approach to establish the current state of occupant-centric DT applications within buildings. SLR was considered as

a suitable approach, as the method allows for a systematic approach to collate exiting literature. Moreover, the method enables further understanding, synthesis of evidence, and identification of research gaps (Kitchenham, 2004). Additionally, the systematic approach to selection of papers enables for an unbiased approach to collating and reviewing the literature. This method is particularly valuable in uncovering themes and research directions within evolving fields, such as the integration of occupant data within DT applications. The following section will present protocol used for the SLR, as well as establish the criteria for selection of resources included in the SLR.

### SLR procedure

The SLR commenced with the selection of Scopus as the primary database for literature search. Scopus was chosen over alternatives like Google Scholar due to its rigorous and well-curated nature, ensuring access to scholarly and peer-reviewed content. This decision aligns with the practices of previous SLRs in related fields, thereby upholding academic rigor and relevance. The process used to select the articles for inclusion in this review is presented in Figure 2.

The initial search, conducted on the 5th of January, utilised parameters such as “Digital Twins” AND “Built Environment” OR “Building” AND “Occupant” OR “End user” OR “Post Occupancy Evaluation”. To filter these initial results, criteria were set to include sources from peer-reviewed journal articles in English language, which narrowed the initial query in Scopus to 40 articles.

Further screening involved a manual analysis of these papers by the research team. In this step, articles were excluded from the review if they did not meet the following criteria:

- Articles not focused on buildings as the unit of analysis. Through this criteria papers excluded for instance articles focused on a system of systems level, such as cities.
- Papers that did not met the previously established characteristics of a DT established in the introductory section of this paper were also omitted. These excluded papers that lacked a data layer combining real and virtual asset information.

The final sample (Table 1) of articles included in the revision included 20 articles.

### SLR Results

Initial results showcase that the most common journal where occupant-centric DT research is being featured is *Building & Environment* (n=5), followed by *Energy & Buildings* (n=3), and *Sustainable Cities & Society*, *Applied Sciences* and *Buildings* with (n=2). These journals feature articles with a focus on Indoor Environmental Quality (IEQ) and energy issues within the

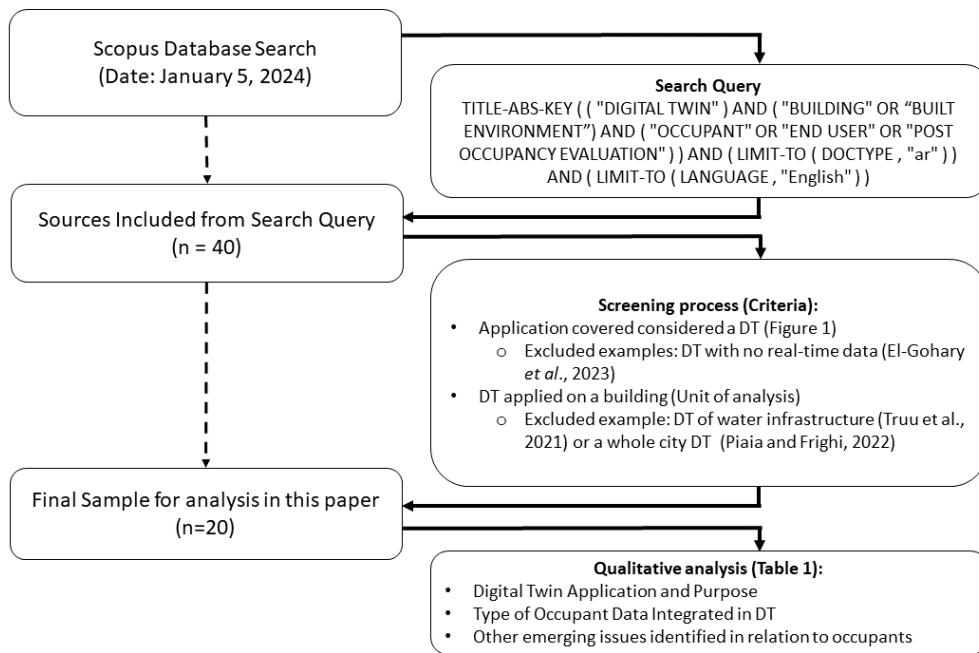


Figure 2. SLR procedure followed for the selection of the final 20 articles reviewed.

built environment. In terms of the country of affiliation of the first author, the country with the most extensive DT applications exploring occupancy issues is China with links to 4 of the reviewed studies. This is followed by 3 applications from Singapore and Italy. The remaining of the research appears quite widespread across a range of different countries, with Norway and Canada having multiple applications in the reviewed sample (n=2). Regarding publication year, the earliest article addressing

## Findings and themes from the SLR

### Applications of occupant-centric DTs

#### Purpose 1: Systems & energy efficiency optimisation

One of the main applications identified refers to energy optimisation during the operation of buildings. In most cases, energy optimisation focuses on heating and cooling-related savings—i.e. mostly on the optimised use of Heating, Ventilation and Air Conditioning (HVAC) systems (Clausen *et al.*, 2021; Hosamo *et al.*, 2023b; Massafra *et al.*, 2023; Desogus *et al.*, 2023; Li *et al.*, 2023). Noticeably, the DT application presented in Seo and Yun’s research (2022) places a strong focus on optimising energy consumed by lighting systems using schedules and simplified probability based behavioural models of occupants.

Regarding energy optimisation, the integration of occupant data into the DTs is expected to provide clearer insights into building operations for Facilities Management (FM). With some of the reviewed studies (Clausen *et al.*, 2021) aiming to establish an automated zone-based control that optimises the use and energy consumption from buildings. or allowing for the automation of building systems to optimise performance.

#### Purpose 2: Support of occupant comfort

The second purpose, while closely related to the previous, aims to develop DT applications that can better optimise the IEQ conditions to the occupants of the building. This application, often goes hand in hand with the previously discussed energy focus, presenting the DT as the key enabler of system performance improvements without the need to sacrifice occupant comfort.

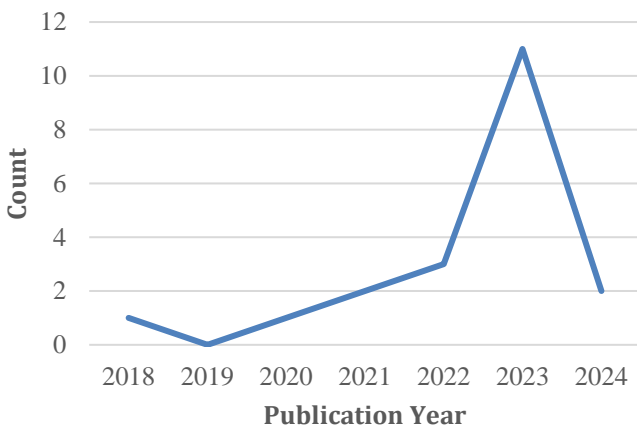


Figure 3 Publications per year (Up to 05/01/2024)

occupant data in building DTs included in the final review was published in 2018. The publication curve (figure 3) showcases an exponential growth in publications where the last 3 years (i.e. 2021-2023) have shown an increase in published articles in this area, with 55% (n=11) of the papers having been published in 2023. Table 1 presents a summary of the articles included in the final review.

Table 1. Articles included in SLR for review (n=20)

Reference	1 <sup>st</sup> Author Affiliation	Journal	Purpose of DT application	Approach to occupant data
Massafra <i>et al.</i> (2023)	Italy	Sustainability	Energy optimisation in building operations	Passive: Simplified occupancy schedule data
Seghezzi <i>et al.</i> (2021)	Italy	Applied Sciences	Optimising operation & maintenance costs; supporting FM decisions	Passive: Occupancy tracked through camera- based visual sensors
Abdelrahman <i>et al.</i> (2022)	Singapore	Building & Environment	Optimisation of building systems for thermal comfort	Passive and Active: Spatial location tracking & physiological data; subjective experience feedback
Gnecco <i>et al.</i> (2023)	Italy	Energy & Buildings	Optimising buildings and systems for occupant comfort	Passive and Active: Spatial location tracking and physiological data; subjective experience feedback
Desogus <i>et al.</i> (2023)	Canada	Buildings	Early assessment/detection of occupant comfort issues	Passive: Application of Predicted Mean Vote model for occupant comfort
Wang <i>et al.</i> (2024)	China	Building & Environment	Understanding occupancy patterns for energy optimisation in historic buildings	Passive: Indoor location tracking data via Bluetooth Low Energy beacon sensors
Park <i>et al.</i> (2018)	South Korea	Applied Sciences	DT for early detection of emergencies and support of evacuation	Interactive: Occupant interaction with DT via Augmented Reality for evacuation guidance and feedback
Hosamo <i>et al.</i> (2023a)	Norway	Energy & Buildings	Early detection of failures/faults in building services and systems	No occupant data integrated
Qian <i>et al.</i> (2023)	China	Building & Environment	Optimising heating & cooling for occupant comfort	Passive and Active: Spatial location tracking; Longitudinal thermal comfort surveys
Abdelrahman & Miller (2022)	Singapore	Building & Environment	Understanding building components and elements' effects on occupant comfort	Passive and Active: Physiological data and spatial tracking; subjective thermal comfort data
Clausen <i>et al.</i> (2021)	Denmark	Energy Informatics	Optimised Zone Control DTs for energy consumption reduction	Passive: Sensing usage demands through CO <sup>2</sup> sensors
Huynh & Nguyen (2020)	Finland	Open Engineering	Support to FM decision-making & cost optimisation via DT interfaces	Occupant data collection not detailed; focus on DT interfaces for facilities managers
Li <i>et al.</i> (2023)	China	Energies	Energy optimisation in building operations	Passive: Occupancy data collected via sensors such as CO <sup>2</sup> sensors
Lee <i>et al.</i> (2023)	Singapore	Building & Environment	Optimising energy and comfort; building interactive DT interfaces	Interactive: Subjective experience data; passive physiological data; occupant DT interaction/control through interface.
Chamari <i>et al.</i> (2023)	Netherlands	IEEE Access	Establishing DT development process in systems architecture	Passive: Data integration includes CO <sup>2</sup> sensors and other passive occupancy sensors
Hadjidemetriou <i>et al.</i> (2023)	Greece	Sustainable Cities and Society	Visualising performance & integrating simulation tools for building operation improvement	Passive: Limited integration of occupant data via sensors (e.g., CO <sub>2</sub> )
Hosamo <i>et al.</i> (2023b)	Norway	Energy & Buildings	Early failure detection of Building Systems	Passive and Active: Passive occupant sensor data; Subjective experience surveys
Seo & Yun (2022)	South Korea	Buildings	Energy savings through optimisation of lighting systems	Passive: Behaviour modelled on schedule data; no real-time data
Tripathi <i>et al.</i> (2023)	Canada	Frontiers in Built Environment	Understanding occupant behaviour through DT-enabled POE	Active: Presented DT does not integrate user feedback, however, use case presented with subjective experience data collection.
Qian <i>et al.</i> (2024)	China	Sustainable Cities and Society	Optimising building system performance to reduce carbon emissions during building operation	Passive and Active: End user location tracking and physical sensors in buildings, additionally, survey data on subjective preferences integrated.

In this context, articles reviewed focus mostly on the thermal comfort dimension, while acknowledging the potential for DTs to expand into other (IEQ) dimensions such as acoustic or visual comfort. Applications focusing on improved occupant comfort tend to integrate a wider range of occupant data into their DTs, including feedback prompts from users on their subjective experiences. Examples of these studies include the studies undertaken by Qian *et al.* (2023;2024) in residential building, as well as those in office environments conducted by Abdelrahman *et al.* (2022) and Lee *et al.* (2023).

### Purpose 3: Early failure detection

Another major purpose identified is the application of DTs for early failure detection of building systems. For instance, the DT application proposed by Hosamo *et al.* (2023a) integrates the end-user feedback with sensor data to determine faulty zones and building system. The DTs data is analysed through Bayesian networks to integrate a logic that can allow for more concrete diagnostics. The suggested model also integrates different ML algorithms to enhance and automate the failure detection process. The study also discusses the emerging topic of the use of ML in processing IoT data in DTs, while resulting analysis showcase very promising accuracy results, ranging from 94% for Fine Tree to 97% for Artificial Neural Networks, these still require substantial computing time. As such, trade-offs between accuracy of results and processing time will remain important considerations in occupant-centric DT data analytics.

### Niche Purposes:

A few other purposes for the implemented DTs have also been identified. For instance, Seghezzi *et al.* (2021) model focuses on supporting the FM function through the provision of opportunities for maintenance cost optimisation using camera-based sensors to identify maintenance needs based on occupancy and usage patterns. Another niche application is proposed by Park *et al.* (2018). Their DT provides an early disaster detection system for fire safety, as well as including an interactive AR interface linked to the DT to support occupants with guidelines and feedback during evacuations.

## Occupant Data Types

A focus of the SLR is to determine the methods and types of data collected in the identified applications. As such, categorising the different types of data will provide the structure for the following section. In this regard, the conceptual framework from Abdelrahman and Miller (2022) provides a good conceptualisation of data collected as objective data and passive data. The framework in this paper enhances the initial one by adding a dimension of occupant interaction, which can be considered passive (i.e. occupant data collected passively), or active (i.e. direct input from occupants). The following section will present findings regarding the main categories identified: 1) objective/passive occupant data collection, and 2) active/subjective occupant data collection (see Figure 4).

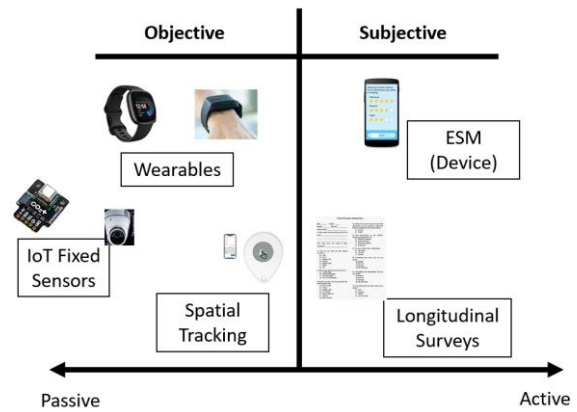


Figure 4. Clustered occupant data means

### Objective-Passive: Occupant data integration

The most common tracking method across the studies is the use of passive IoT sensors. Available sensors to monitor occupancy and usage, include CO<sup>2</sup> concentration sensors, light and infrared sensors, camera-based sensors, wireless networks, or RFID sensors (Seghezzi *et al.*, 2021). With these initial types of sensors, the aim is the monitoring of zone/area occupancy across the building in real time. Within the sampled papers, the most common occupancy sensors are CO<sup>2</sup> concentration change sensors (Clausen *et al.*, 2021; Hadjidemetriou *et al.* 2023; Li *et al.*, 2023; Chamari *et al.*, 2023), which have a relatively high accuracy rate (over 90%) in detecting general fluctuations in rooms with limited issues regarding data privacy. The data collected through sensors such as CO<sup>2</sup> or infrared sensors, while providing data on general occupancy patterns fail to achieve the accuracy of other sensing devices. Shegezzi *et al.* (2023) explore the use of camera-based sensors in their study. These types of sensors while presenting a series of calibration issues, that can affect accuracy when tracking occupants indoors, present additional opportunities for monitoring. First, data from camera-based sensors can potentially yield more granular insights on individual occupancy and usage patterns across the building, as well as provide additional insights on maintenance needs and condition of spaces. This requires further processing and analysis of video data through methods like computer vision.

Other studies present a simplified approach to occupancy monitoring (Seo & Yun, 2022; Massafra *et al.*, 2023). These do not include real-time sensing of occupancy, and instead integrate occupancy considerations and room usage data through occupancy schedules. These involve the integration of data from the organisational asset management system, including scheduled room bookings within the building. While this data allows to partially integrate occupancy into DTs in a simplified manner, it fails to achieve the insights that data collected in real-time can yield. On a similar approach, using data captured through climatic stations (e.g. humidity, temperature...), Desogus *et al.*, (2023) integrate issues of occupant thermal comfort in their proposed DT solution. These methods lack direct occupant input, and instead they rely

on commonly used methods like the Predicted Mean Vote (PMV) to determine problematic areas in buildings.

The final set of passive sensors identified refer to personal wearables. The most comprehensive use of these is within the research studies undertaken by Abdelrahman *et al.* (2022). In these, participants utilised smartwatches, which enabled the collection of real-time physiological data (i.e. heart rate and corporeal temperature) while inside the physical building. Additionally, perceptual, and spatial data from users was collected. At a smaller scale, and using an experimental setting, Gnecco *et al.* (2023) integrated the use of wearables to track a range of similar physiological data within their DT. While these are promising sources of data, results from co-design workshops by Lee *et al.* (2023) reveal a myriad of challenges. Workshop participants highlighted concerns regarding privacy and security of their personal data collected through wearable sensors. This raises questions about the ethics of such sensors, as well as the practical scalability at commercial scale.

#### *Objective -Passive: Spatial Data*

Spatial tracking and the integration of spatial data with semantically rich asset information models, can be considered its own category within passive and objective occupant data. These represent unique challenges for sensing and indoor positioning. As such, it has been the focus of several papers, warranting separate consideration from general IoT sensing (Wang *et al.*, 2024; Abdelrahman *et al.*, 2022; Gnecco *et al.*, 2023).

Tracking occupants indoors has historically been challenging indoors. Unlike urban environments, where GPS can be used with high accuracy, indoor settings present a series of accuracy challenges. Often, a combination of sensors is required for precise spatial tracking. Wang *et al.* (2024) analyse various indoor tracking methods. Ultra-wideband sensors, while precise, are difficult to implement at larger scale. In contrast, more affordable options like wireless or Bluetooth Low-Energy (BLE) beacons, though less accurate (error-prone by 2-5m), are more feasible. BLE beacons, which refer to signal emitters detectable by smartphone applications, enable trilateration for indoor positioning.

Linking user positioning with building components and features can offer deeper insights into end-user behaviours and preferences, however, this integration also presents challenges. In this regard, Graph Neural Networks emerge as a promising solution, enabling mapping the proximity of occupants to building elements and zones. Thus, providing the means to link occupant data to information from these assets (Abdelrahman *et al.*, 2022; Gnecco *et al.*, 2023; Wang *et al.*, 2024). Recent studies, such as Tripathi *et al.* (2023), are examining GIS in the context of indoor environments. This approach, while challenging, also holds potential for enhancing understanding of spatial dynamics within built assets.

#### *Subjective – Active occupant data integration*

Another approach involves the collection of data from occupants regarding subjective and experiential

dimensions. In this context, influenced by longstanding research on the measurement of perceptions of comfort from occupants, a few applications have integrated this data within their digital counterparts. Following best practices in comfort studies, Qian *et al.* (2023) conducted a 1-year longitudinal study where they collected 60-80 survey responses per month from residents in the study. These surveys were modelled on the ASHRAE's comfort scale and questions. While the exact points of entry are not clearly established, the approach while yielding additional insights raises questions regarding the labour-intensive nature of integrating data collected from surveys into DTs.

Alternatively, several studies have aimed to utilise the interfaces afforded by wearable sensors and smartphones to collect periodic experiential data from occupants. This approach builds on research on Experience Sampling Methods (ESM), a common approach used in psychology studies (Beal, 2015). Abdelrahman *et al.* (2022) utilised simple ESM to capture the subjective experience of users through a smartwatch application. Lee *et al.* (2023) utilises a similar approach in 15-day study to collect data from office users at regular times of the day, through push notifications prompting for feedback. The collection through these devices allows for automation in the integration of the data, compared with traditional surveys. Subjective occupant data has the potential to address limitations of traditional occupant surveys (i.e. one-off surveys), by enabling collection of longitudinal datasets on user preferences, potentially leading to opportunities to provide a personalised approach to comfort in buildings (Preiser and Nasar, 2008). However, limitations are not to be overlooked. On one hand, the ethical considerations of personal data collected. Additionally, survey fatigue, a well-known phenomenon is also a consideration (Beal, 2015). Systems to collect data actively from users could be designed to be triggered only when specific events occur, limiting survey fatigue.

#### **Emerging themes: Occupant interaction with DTs**

A niche approach regarding occupants that emerged from the reviewed articles is the opportunities for end-user interaction with the DT platforms. Most of the reviewed papers, when discussing interaction with the DT, often refer to the FM or building operator (Chamari *et al.*, 2023; Huynh & Nguyen, 2020; Hadjidemetriou *et al.*, 2023; Li *et al.*, 2023). Within these interaction with data for visualisation and control occurs through dashboards (E.g. Grafana) only accessible for FMs. Tripathi *et al.* (2023) suggest the expansion of these interaction and visualisation to the occupants. Park *et al.* (2018) expands on the end-user occupant interaction aspect. The proposed DT application, centred on early fire detection and evacuation, integrates an interactive AR application to provide occupants with real-time data regarding guidelines and evacuation procedures.

Going a step forward, Lee *et al.* (2023) in their aims to 'democratise' future DT applications, explore the issue of limited interaction built-in in DTs faced by occupants.

The issue can be mapped out to previous research on smart buildings. They not only define interaction regarding visualisation of data, but also explore the expansion to the control dimension (i.e. ability of occupants to control building systems). Moreover, based on occupant comfort theories, particularly the adaptive comfort theory (de Dear and Brager, 2001), such interaction and control of systems might not only enhance satisfaction but might also yield significant energy savings by increasing user tolerance to discomfort.

### **Occupant-Centric DTs: Directions for future research**

The review highlights a prevalent focus on occupant thermal comfort within occupant-centric DTs. This is evident in the dominance of DTs for energy optimisation of building systems and early failure detection. While some studies touch upon visual comfort for energy savings, other dimensions of IEQ such as acoustics remain largely unexplored. Future research should expand the focus to encompass these, particularly considering the relevance of acoustics in public environments.

The integration of occupant data beyond passive occupancy sensors remains limited. Notably, the comprehensive occupant-centric DT by Abdelrahman *et al.* (2022) stands out for its integration of physiological and spatial data through wearables, offering insights beyond thermal comfort. Leveraging such longitudinal occupant data can provide evidence-based information for design teams, opening avenues for evidence-based design in sectors like healthcare or education.

Finally, Lee *et al.*'s (2023) study underscores challenges associated with occupant-centric DTs. Participants expressed concerns regarding data privacy and ownership, highlighting the need for robust data security, especially when collecting subjective and physiological data. Addressing these challenges will remain key for the successful implementation and adoption of occupant-centric DTs at scale within real-world contexts.

### **Conclusions**

Digital Twins (DTs) represent an emerging paradigm offering multiple opportunities in the AECO sector. This review focused on exploring how recent building DT applications are integrating occupant data. The findings highlight a variety of methods and challenges faced by developers of occupant-centric DTs. The review categorises these approaches based on the level of user involvement required. Additionally, it uncovers the challenges in integrating these data into DT platforms. The primary focus of these so far has been on building performance optimisation, especially in terms of energy efficiency. The review also sheds light on emerging applications and approaches to actively involve occupants, and provides directions for future research.

Reflecting on the early POE studies from the 1960s and 1970s, the central aim was to understand how buildings support end-users, such as understanding the influence of hospital design on patient healing rates or the impact of

prison design on inmate behaviour. While common POE methods have provided valuable insights over the years, we argue that new paradigms, especially DTs, have the potential to establish these relationships with more rigorous and longitudinal evidence. Ultimately, this can lead to the design of built environments that more closely align with the needs and requirements of end-users.

The chosen method, an SLR, has several limitations. Firstly, it was restricted to peer-reviewed journals, resulting in a selection of a final 20 articles. The limitation of relying solely on peer-reviewed journal sources may exclude relevant literature from other publication types. With DTs being such a recent topic, preliminary research and applications presented in conferences might provide examples of other alternative applications. Using solely Scopus as the data source may have introduced bias, potentially overlooking relevant studies indexed in other databases (e.g. WoS). The review focused on two primary aspects: the purposes of the DT applications and the types of occupant data integrated. While this approach provided depth in analysing these, it may have overlooked broader aspects of occupant-centric DTs.

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