Leveraging Digital Twins towards an Occupancy-centric built environment: A review

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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 utilization 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, emphasizing 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 optimizing 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 optimize 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, sensors, and IoT allow for dynamic data collection and integration, emphasizing 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 optimizing 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.

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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, utilized 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 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 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.

Findings and themes from the SLR

Applications of occupant-centric DTs

Regarding the applications of the DTs presented in the article’s reviews, a series of main purposes for which these DT applications were identified.

Purpose 1: Systems performance optimization & energy efficiency

One of the main applications identified refers to energy optimization 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 optimizing 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.
<table>
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<th>Reference</th>
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<td>Park et al. (2018)</td>
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<td>Hosamo et al. (2023a)</td>
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<td>Abdelrahman &amp; Miller (2022)</td>
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</tr>
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<td>Clausen et al. (2021)</td>
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<td>Huyah &amp; Nguyen (2020)</td>
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<td>Lee et al. (2023)</td>
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</tr>
<tr>
<td>Chamari et al. (2023)</td>
<td>Netherlands</td>
<td>IEEE Access</td>
<td>Establishing DT development process in systems architecture</td>
<td>Passive: Data integration includes CO₂ sensors and other passive occupancy sensors</td>
</tr>
<tr>
<td>Hadjidemetriou et al. (2023)</td>
<td>Greece</td>
<td>Sustainable Cities and Society</td>
<td>Visualising performance &amp; integrating simulation tools for building operation improvement</td>
<td>Passive: Limited integration of occupant data via sensors (e.g., CO₂)</td>
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<td>Hosamo et al. (2023b)</td>
<td>Norway</td>
<td>Energy &amp; Buildings</td>
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<tr>
<td>Seo &amp; Yun (2022)</td>
<td>South Korea</td>
<td>Buildings</td>
<td>Energy savings through optimisation of lighting systems</td>
<td>Passive: Behaviour modelled on schedule data; no real-time data</td>
</tr>
<tr>
<td>Tripathi et al. (2023)</td>
<td>Canada</td>
<td>Frontiers in Built Environment</td>
<td>Understanding occupant behaviour through DT-enabled POE</td>
<td>Active: Presented DT does not integrate user feedback, however, use case presented with subjective experience data collection.</td>
</tr>
<tr>
<td>Qian et al. (2024)</td>
<td>China</td>
<td>Sustainable Cities and Society</td>
<td>Optimising building system performance to reduce carbon emissions during building operation</td>
<td>Passive and Active: End user location tracking and physical sensors in buildings, additionally, survey data on subjective preferences integrated.</td>
</tr>
</tbody>
</table>
Purpose 2: Support of occupant comfort
The second purpose identified, 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, while stated as important, 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.

In this context, articles reviewed focus mostly on the thermal comfort dimension, while still 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 buildings, 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 in these occupant-centric DT studies is their application for early failure detection in building systems. For instance, the DT application proposed by Hosamo et al. (2023a) integrates the end-user feedback (particularly as a trigger for further investigations) with sensor data collected to determine faulty zones and building systems in a building. The DT is embedded with Bayesian networks to integrate a logic that can allow for more specific diagnosis. Moreover, the approach suggested 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 and AI 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 time for computing. As such, trade-offs between speed of results and processing time will remain important considerations in developing and automating DT applications.

Specialised Purposes:
While more niche, a few other purposes for the implemented DTs have also been covered. Related to failure detection and focused on optimization of maintenance costs, Seghezzi et al. (2021) study aims for reductions in maintenance costs and support to FM function using camera-based sensors to identify maintenance needs such as cleaning needs based on occupancy and usage patterns. Another niche application is that proposed by Park et al. (2018), which functions both as an early disaster detection system around fire safety, as well as includes an AR based interface linked to the DT to support occupants with guidelines/feedback for evacuation.

Occupant data perspectives
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. Moreover, the conceptual framework presented here enhances the initial one by adding a dimension of occupant interaction with the DT, which can be considered passive (i.e. passive data collected), active (i.e. direct inputs requested from occupant), and includes an interaction dimension (i.e. allows for interaction with DT through an interface). The following section will present findings regarding the main approaches identified: 1) objective/passive occupant data collection, and 2) active/subjective occupant data collection (see Figure 4).

Figure 4. Occupant data sensors clustered based on interaction and data collected.

Objective-Passive: Occupant data integration
The most common tracking method showcased across the studies is the use of passive IoT sensors installed in the building. The range of available sensors to automatically monitor occupancy and usage, discussed in the sampled articles includes CO2 concentration change sensors, Visual light and infrared sensors, camera-based sensors, wireless networks, and RFID sensors (Seghezzi et al., 2021). With these initial types of sensors, the aim is the tracking of occupancy of zones across the building in real time. Within the sampled papers, the most common occupancy sensor addressed are CO2 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 on zones with limited to no issues regarding data privacy of occupants. The data collected through sensors such CO2 or Infrared sensors, while providing data on general occupancy patterns fail to achieve the accuracy and granularity 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 the accuracy when tracking occupants indoors, present a series of additional opportunities beyond occupant tracking. 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 to FM on maintenance needs and condition of spaces. This requires not only the integration, but the further processing and analysis through methods like computer vision.

In a simpler approach, a few of the studies (Seo & Yun, 2022; Massafra et al., 2023), while not including real-time sensing to monitor occupancy, integrate occupancy considerations and room usage data through occupancy schedules. These for example, involve the integration of data from the organisational asset management system, which includes scheduled bookings for rooms in the building analysed. While this data allows to partially integrate occupancy into DTs in a simplified manner, it fail to achieve the granularity of insights that data collected in real-time can yield. On a similar approach, using data captured through climatic stations (e.g. humidity, temperature...), Desousos et al., (2023) integrate issues of occupant thermal comfort in their proposed DT solution. Although these methods lack direct occupant input, they instead rely on commonly used methods like the Predicted Mean Vote (PMV) to determine potential problematic areas in buildings.

A final set of passive sensors refer to the use of wearables. The most comprehensive of these is the series of research studies undertaken by Abdelrahman and colleagues (2022). In these, the 30 participants involved in the case-study utilized smartwatches, which enabled among others the collection of real-time physiological (i.e. heart rate and corporeal temperature) data of users while inside the physical building. Additionally, perceptual, and spatial data from users, which is further elaborated in later sections. At a smaller scale, and using an experimental room for testing their DT, Gnecco et al. (2023) also integrated the use of wearables to track a range of similar physiological data and the integration of these onto the DT. While these are promising sources of data that previously were only common within experimental research (Hou et al., 2023). results from co—design workshops undertaken with occupants by Lee et al. (2023) appear reveal a myriad of challenges. For example, occupants showed concerns regarding the privacy and security of their personal data collected through wearable sensors, which raises questions about the ethics of such sensors, as well as the practical scalability of these at commercial scale.

Objective - Passive: Spatial Data

Spatial tracking and the integration of spatial data with semantically rich asset information models, typically categorised under passive and objective data collection, present unique challenges in sensing and indoor positioning. This 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, especially in achieving high accuracy. Unlike urban environments, where GPS tracking integrates seamlessly with Geographic Information Systems (GIS), indoor settings like buildings face accuracy issues. Often, a combination of sensors is required for precise occupancy tracking. Wang et al. (2024) analyse various indoor tracking approaches. Ultra-wideband sensors, while precise, are difficult to implement at larger scale. In contrast, more affordable options like wireless networks or Bluetooth Low-Energy (BLE) beacons, though less accurate (typically erring by 2-5m), are more feasible. BLE beacons, which refer to signal emitters detected through smartphone applications, enable trilateration for indoor spatial positioning. This method, also adopted by Abdelrahman et al. (2022), utilises a smartwatch application for triangulation.

Integrating spatial tracking data into the virtual layer of semantically rich BIM models poses another challenge. However, linking user positioning with building components/features can offer deeper insights into end-user behaviours and preferences. Some studies investigate mapping data from semantic models and component information. Graph Neural Networks emerge as promising solutions, enabling mapping the proximity of occupants to building elements and zones. Thus, providing the means to link both occupant data and data from these assets (Abdelrahman et al., 2022; Gnecco et al., 2023; Wang et al., 2024).

In urban planning contexts, GIS integration with GPS and graph networks has been explored for mapping proximity (Mackerron and Mourato, 2013). Emerging studies, such as those by Tripathi et al. (2023), are examining GIS integration with indoor spaces and environments. This approach, while challenging, holds potential for enhancing understanding of spatial dynamics within built assets.

Subjective - Active occupant data integration

Distinctly, another approach that involves data directly collected by users relates to subjective and experiential dimensions. In this context, probably influenced by longstanding research on the measurement of perceptions of comfort from occupants, a few of the 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 about 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 in the article, the approach while yielding important insights raises questions regarding the feasibility at a scale and the labour-intensive task of integrating data collected into DTs.
Alternatively, several studies have aimed to utilise the interfaces provided 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). For example, Abdelrahman et al. (2022) utilized simple ESM to capture the subjective experience of users through a smartwatch application. Lee et al. (2023) utilise 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 POE surveys (i.e. one-off surveys), by enabling collection of longitudinal datasets/evidence on user preferences, potentially leading to opportunities to provide a personalised approach to comfort and design of buildings (Preiser and Nasar, 2008). However, limitations are not to be overlooked. On one hand, the ethical considerations of personal data collected are not to be ignored. Additionally, survey fatigue, a common phenomenon is also an important consideration (Beal, 2015). As such, systems to collect data actively from users could be designed to be collected only when specific trigger events occur, limiting the potential for 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. The majority of the papers, when discussing interaction with the DT, often focus on the FM or building operator (Chamari et al., 2023; Huynh & Nguyen, 2020; Hadjidemetriou et al., 2023; Li et al., 2023). In these cases, interaction with the DT often discusses the use and integration of data for visualization and control purposes, through open-source dashboard toolkits (E.g. Grafana). Tripathi et al. (2023), while not embedding into the presented DT application, suggest the expansion of these visualization (i.e. overviews of user comfort profile) to the occupants. It is the application from Park et al. (2018), around fire safety evacuation, the one that expands on the end-user occupant interaction aspect. The proposed DT application, centred on early emergency (fire) detection and evacuation, integrates Augmented Reality through a smartphone app to provide residential occupants with real-time data regarding guidelines and evacuation procedures.

Going a step forward, Lee et al. (2023) in their aims to “democratize” future DT applications, extensively explore the issue of limited interaction built-in in DTs faced by occupants, an issue that can be mapped out to previous research on smart buildings (e.g. Building Management Systems). They not only define interaction within the visualization dimension, but also explore the expansion to control (i.e. ability of occupants to control building systems).

When looking at the evolution of occupant comfort theories, particularly the adaptive comfort theory (de Dear and Brager, 2001), such interaction and control of systems are likely to not only enhance satisfaction but also, by increasing tolerances to discomfort, likely yield a significant energy reduction. Moreover, synergies with ongoing research on the nascent field of Human Building Interaction (HBI) can also look promising for future DT applications (Becerik-Gerber, 2022).

Towards Occupant-Centric DTs: Directions for future research

The review highlights a prevalent focus on occupant thermal comfort within operational-phase occupant-centric DTs. This is evident in the dominance of DTs for energy optimisation of HVAC 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 overlooked dimensions, especially considering the significance of acoustics in environments like public buildings and shared offices.

Furthermore, the integration of occupant data beyond occupancy sensors remains limited in reviewed articles. Notably, the comprehensive occupant-centric DT by Abdelrahman et al. (2022) stands out for its integration of physiological and spatially tracked 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 and education.

Finally, Lee et al.’s (2023) participatory study underscores the challenges associated with occupant-centric DTs, particularly concerning privacy and security. Participants expressed concerns regarding data privacy and ownership, highlighting the need for robust data security, especially when dealing with subjective and physiological data as the ones collected in Abdelrahman et al.’s (2022) study. Addressing these challenges will remain key for the successful implementation and adoption of occupant-centric DTs in 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 DT applications in building contexts are integrating occupant data. The findings highlight a variety of methods and emerging challenges faced by developers of occupant-centric DTs. The review categorizes these approaches based on the level of user involvement required, such as passive, active, or built-in interactions. Additionally, it uncovers the challenges in integrating these data into DT platforms. The primary focus of these applications 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 engaging users, as well as provides some directions for future research.

Reflecting on the early studies of the built environment, particularly POE from the 1960s and 1970s, the central aim was to understand how buildings support end-users, such as the influence of hospital design on patient healing or the impact of prison design on inmate behaviour. While POE surveys and qualitative methods have provided valuable insights over the years, we argue that new paradigms, especially DTs, have the potential to reveal these relationships with more rigorous evidence and data collected in natural settings. Ultimately, this could lead to the design of built environments that more closely align with the needs and requirements of end-users.

The chosen method, an SLR, had several limitations. Firstly, it was restricted to peer-reviewed journal sources, resulting in a selection of only 20 articles from an initial query of 40. The limitation of relying solely on peer-reviewed journal sources may have excluded relevant literature from other publication types. With DTs being such a recent topic (i.e. earliest identified article is from 2018), preliminary research and applications presented in conferences might provide examples of more alternative applications. Using solely on 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 specific two dimensions, it may have overlooked broader aspects of occupant-centric DTs.

References


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