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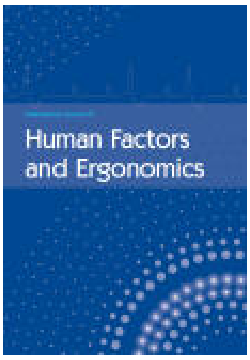

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Applications of digital twin in human factors, ergonomics and organisational dynamics

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Abstract: Digital twin (DT) technology has significantly advanced, integrating into various industries, however, its application and implications within the human factors and ergonomics and industrial and organisational psychology fields remains underexplored. This paper explores the potential of DT technology to advance human-centric design and streamline organisational processes through a narrative review. Our analysis highlights ten critical domains where DT applications can drive meaningful improvements. The human factors and ergonomics scope includes workplace design, safety analysis, equipment optimisation, human-robot collaboration, and training simulations. In the context of industrial and organisational psychology, the focus extends to workforce planning, performance analysis, managing organisational change, promoting employee well-being, and fostering leadership development. Our findings suggest that integrating DT technology with HFE and IOP principles can lead to more efficient, safe, and productive work environments. We also discuss challenges such as data privacy concerns, technological integration hurdles, and the necessity of maintaining a human-centric focus in DT implementations. This paper contributes to the dialogue on integrating advanced technological and human-centric approaches, proposing possible pathways for future research.

Keywords: digital twin; human factors and ergonomics; HFE; industrial psychology; organisational dynamics; safety analysis; performance analysis; organisational change; technology integration; skill development; training simulations.

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1 Introduction

Digital twins (DTs) represent a transformative concept that integrates physical and digital realms, enabling real-time monitoring, simulation, and optimisation of physical systems. A DT can be defined as a dynamic digital representation of a physical object or system, which is continuously updated with data from various sources, including internet of things (IoT) devices and artificial intelligence (AI) models (Glaessgen and Stargel, 2012; Shahzad et al., 2022). This integration allows for comprehensive analysis and decision-making based on the real-time status of the physical counterpart (Botín-Sanabria et al., 2022).

The foundational elements of a DT include three critical components: the physical asset, its virtual representation, and a communication interface that facilitates data exchange between the two (Liu et al., 2024). This triadic structure ensures that the DT not only mirrors the physical entity but also evolves alongside it throughout its lifecycle. Such a relationship is essential for applications in various sectors, including manufacturing, healthcare, and energy systems, where DTs are employed to enhance operational efficiency and predictive maintenance (Liu et al., 2024; Lu et al., 2020; Rasheed et al., 2020).

Despite the growing recognition of DTs, there is still no universally accepted definition, reflecting the concept's evolving nature. Various interpretations exist, often tailored to specific applications or industries (Richstein and Schröder, 2024). Nevertheless, the core idea remains consistent: a DT acts as a sophisticated simulator of its physical counterpart, leveraging real-time data to enhance understanding and facilitate informed decision-making (Zhang et al., 2023).

DTs distinguish them from simpler digital models and digital shadows, which lack the comprehensive interactivity and dynamic capabilities inherent to true DTs. Digital models are static representations that do not engage with real-world data, while digital shadows involve one-way data transfer from the physical entity to the digital model, providing a limited view of the system's status (Hüsener et al., 2022). In contrast, DTs enable a continuous flow of information in both directions, allowing for real-time updates and interactions that reflect changes in the physical counterpart. As Kritzinger et al. (2018) highlight, this two-way communication allows the digital model to mirror the physical system while providing feedback that can be implemented in the real world, over a relatively fast timeframe. This dynamic, real-time interaction is fundamental to the advanced capabilities of DTs, thus allowing real-time updates and optimisations, enhancing operational efficiency and decision-making processes (Wu et al., 2023; Zocco et al., 2023). In this way, DTs are seen as a method of achieving convergence between physical and virtual spaces (Botín-Sanabria et al., 2022; Hemdan et al., 2023; Liu et al., 2023).

DT technology has seen significant growth and diverse applications in Europe and globally since 2020. The DT market in Europe is experiencing rapid growth, with a projected Compound Annual Growth Rate of 43.7% from 2023 to 2030 (Grand View Research, 2023). The integration of DTs enhances product lifecycle management processes across various sectors, including aerospace, defence, automotive, transportation, manufacturing, healthcare, and energy. In Italy, recent advancements in DT technology have been implemented across various sectors, including electricity grids, maritime operations, and logistics. Notably, a company has employed a DT engine to create a real-time simulation of the Livorno Port area, significantly enhancing the efficiency of cargo handling and logistics processes (Neugebauer et al., 2023).

Within this framework, human factors and ergonomics (HFE) and industrial and organisational psychology (IOP) have traditionally been somewhat overlooked in the context of DT technology (Maruyama et al., 2021). HFE is an interdisciplinary field that focuses on understanding human abilities and limitations and applying this knowledge to design systems, tasks, and environments that enhance both human well-being and overall system performance. In this paper, we refer to HFE as a unified discipline that combines both HFE principles (Dul et al., 2012). IOP complements HFE by focusing on understanding and improving workplace behaviours and organisational dynamics. While HFE concentrates on the design of a socio-technical system that accommodates human abilities and limitations, IOP focuses on the behaviour of individuals and groups within (innovative) organisational settings (Spencer, 2021). Both disciplines are crucial for optimising human well-being and system performance, particularly when integrating advanced technologies like DTs into the workplace.

Historically, the application of DT technology has been predominantly centred around engineering, manufacturing, and infrastructure, with less emphasis on the human-centric aspects that HFE and IOP prioritise. The inherent nature of HFE and IOP, which necessitates a deep understanding of human behaviour, cognitive processes, and ergonomic principles, may not have been readily compatible with the early technical orientations of DT technology.

However, the increasing relevance of DT technology across HFE and IOP domains highlights its potential to transform traditional understanding and management of complex systems. As advanced digital replicas of physical systems, DTs offer unprecedented capabilities for real-time monitoring, simulation, and predictive analysis. These capabilities are rooted in systems theory, providing a comprehensive framework for exploring complex human-machine interactions and organisational processes (Kritzinger et al., 2018; Uhlemann et al., 2017).

Integrating DTs into HFE leverages ergonomics and systems engineering principles, aligning with the cognitive systems engineering framework that focuses on the interplay between human cognitive processes and operational environments (Hollnagel and Woods, 2005). Through simulating human interactions within various systems, DTs emerge as a critical method to analyse and enhance ergonomic design, thereby promoting safety, efficiency, and worker well-being (Greco et al., 2020).

From an IOP perspective, DTs may serve as a strategic asset for organisational analysis and development, drawing upon foundational principles of organisational theory. Here, DTs shine by offering insights into workforce dynamics, performance management, and organisational change, enabling a data-driven approach to analyse and shape organisational behaviours in alignment with behavioural science and management theory (Madni et al., 2019; Lim et al., 2020; Yan et al., 2022).

Through a narrative overview, this work examines the transformative potential of DT in fostering human-centric design principles while driving improvements in organisational processes. By integrating DT technology with HFE and IOP perspectives, we propose a vision for workplace optimisation where technological advancements align with human needs and organisational sustainability. Our approach aims to extend the traditional boundaries of DT applications beyond their established engineering, manufacturing, and infrastructure domains, exploring the fields of ergonomics and organisational dynamics.

2 State of the art

2.1 Applications of DT in various industries

DT technology has rapidly evolved, transforming operations across multiple sectors and experiencing substantial growth and widespread adoption in Europe and globally since 2020.

DTs are revolutionising industries ranging from healthcare and logistics to energy and construction (Fuller et al., 2020). In the manufacturing sector, DTs facilitate smart manufacturing by providing a comprehensive view of production processes. They enable organisations to simulate, predict, and optimise manufacturing systems, thus improving operational efficiency and reducing downtime through predictive maintenance (Li et al., 2020; Lu et al., 2020). The integration of DTs with advanced technologies such as AI and IoT allows for data-driven decision-making, which is essential for adapting to market demands and improving product quality (Barricelli et al., 2019; Chen, 2024).

The construction industry has also benefited from DT technology by integrating real-time data from various sources, including site monitoring technologies and AI functions (Mao et al., 2022). Abou-Ibrahim et al. (2022) developed an agent-based simulation model to mimic accurate building information modelling (BIM)-based design projects that allowed them to create a digital replica of the design process. Their findings revealed that DTs are revolutionising project management by integrating real-time data from various sources, including site monitoring technologies and AI functions. This integration of DT concepts allows for proactive management of construction processes, enhancing the efficiency of design, planning, and execution phases (Ryzhakova et al., 2022; Meng et al., 2023).

A particular focus has been on machine and health equipment monitoring, with significant applications in vaccine development and distribution. Sahal et al. (2022) investigated the role of DTs in healthcare, particularly in the context of the COVID-19 pandemic. They found that DTs enabled the simulation of various scenarios in vaccine development, accelerating the process significantly. Moreover, DTs are being used for patient monitoring and personalised medicine. In other words, by creating digital replicas of patients, healthcare providers can simulate treatment outcomes and optimise care plans based on individual patient data (Newrzella et al., 2022). This innovative approach can potentially improve patient outcomes, enhance resource allocation, and reduce costs.

In parallel, urban planners are utilising DTs to create intelligent cities, simulating and analysing urban dynamics to facilitate better decision-making regarding infrastructure development and resource management (Feng et al., 2022). Hämäläinen (2021) explored the use of DT in urban planning and innovative city development. The real-time interaction between virtual models and physical environments empowered urban planners with immediate assessment of system behaviours, rapid scenario testing, and proactive decision-making, essential for managing urban systems effectively. Additionally, DTs enhance stakeholder engagement and streamline communication, providing a shared platform for collaborative urban planning and fostering alignment across diverse interests. At the same time, in the transportation sector, DTs optimise logistics and supply chain management by improving the flow of goods and materials and enhancing efficiency in transportation networks (Lee and Lee, 2021; Qiu et al., 2023). Indeed, organisations can identify bottlenecks and develop strategies to mitigate delays by simulating transportation scenarios.

The aerospace industry has also embraced DT technology to create real-time virtual replicas of aircraft and their components. This application enhances operational efficiency and safety through comprehensive monitoring and predictive maintenance (Li et al., 2022; Wang et al., 2022). The widespread adoption of DT technology across these diverse sectors highlights its versatility and transformative potential. As DTs continue to evolve and integrate with other advanced technologies, their impact on industry operations and decision-making processes is likely to grow. This broad industrial application of DTs sets the stage for exploring their specific implementations in HFE and IOP, where the focus shifts to human-centric applications and organisational dynamics.

2.2 DTs in human factors and ergonomics

DT applications in HFE integrate real-time data, advanced analytics, and virtual modelling to generate interactive representations of human-system interactions (Botín-Sanabria et al., 2022; Jaribion et al., 2020; Tao et al., 2018). These applications can be categorised into distinct areas, each targeting specific dimensions of human-system dynamics. By offering accurate and timely insights into the interplay between humans, machines, and organisational processes, DTs provide a robust framework for analysing and optimising complex interactions (Herakovič et al., 2019). For example, the ergonomic risk assessment DT focus on real-time monitoring and analysis of physical stresses on the human body during work activities (Baratta et al., 2023). Concurrently, the cognitive workload DT has been designed to monitor and manage mental workload in complex operational environments (Sharma et al., 2022).

Also, the training and skill development DT may create personalised, adaptive training environments tailored to individual learning needs (Alazar et al., 2022).

Gaffinet et al. (2023) introduced a human-centric digital twin (HCDT) framework emphasising the importance of understanding human characteristics and behaviours to facilitate safe and efficient collaboration between humans and robots. HCDTs specifically focus on individual users' needs and their interactions with their environments. These models capture various data points related to user behaviour, physical attributes, and environmental conditions, enabling tailored interventions to mitigate ergonomic risks (Asad et al., 2023).

Practical implementations demonstrate the technology's potential across various industries. For example, Ogunseiju et al. (2021) proposed a DT-driven framework that empowers construction workers to self-manage their ergonomic exposures by providing real-time feedback about their working conditions. This proactive approach, built on reliable, real-time, and easily accessible data, supports the development of a health management culture among workers.

The maturity of DT applications in ergonomics continues to evolve. Most existing implementations are at lower maturity levels, primarily focusing on modelling and simulation without fully integrating user feedback and real-time data (Botín-Sanabria et al., 2022). However, this evolution represents a substantial step forward toward more integrated and interactive systems, where the combination of human insight and digital capabilities has the potential to drive innovative solutions for long-standing challenges in HFE (Tao et al., 2018).

2.3 DTs in industrial and organisational psychology

The integration of DTs within IOP focuses more on understanding and optimising human behaviour in work and organisational settings. DTs as virtual representations may enable the analysis of employee interactions within organisational structures and integration with technological systems. Additionally, these systems can be used to monitor workplace dynamics and assess employee performance. Evidently, these capabilities provide valuable insights into organisational functioning (Botín-Sanabria et al., 2022; Madni et al., 2019).

Semeraro et al. (2021) have significantly advanced our understanding of DTs in organisational contexts, particularly within cyber-physical systems (CPS). Their research demonstrates that DTs can function as digital 'twins' of employees, constantly adjusting to capture real-time changes in individual characteristics. This innovative approach allows organisations to monitor and respond to highly personal and dynamic factors, which were previously challenging to track and address effectively. These systems track employee preferences, work schedules, and skill sets while enabling bidirectional data flow between digital and physical realities. At the same time, these capabilities emphasise the need for smooth interoperability between humans and DTs within organisational systems.

As a matter of fact, one of DTs' key contributions to IOP is their capacity for real-time monitoring and analysis of workplace dynamics. McNair (2022) demonstrated how DTs can act as powerful tools to support the evolution of workplaces, combining technological innovation with a strong focus on human well-being. By analysing patterns in employee performance, engagement levels, and overall well-being, DTs enable organisations to design work environments that are more responsive to individual and collective needs, fostering both productivity and psychological health.

As highlighted by Zheng and Sivabalan (2020), DT implementation in smart manufacturing environments provides improved predictability of organisational processes, enhanced control mechanisms, reduced operational uncertainty, and strengthened decision-making capabilities. In that sense, DTs enhance organisational management mechanisms through data-driven insights.

Moreover, organisations can leverage DT data to create adaptive work environments tailored to employee needs. Berisha-Gawlowski et al. (2021) note that DT-facilitated interactions can deepen relationships between organisations and employees, enable more effective fulfilment of organisational objectives, improve employee satisfaction, and foster a culture of continuous improvement.

Finally, the digital organisational twin concept, as explored by Parmar et al. (2020), may facilitate organisational development and change management. This application of DTs enables organisations to simulate various scenarios and outcomes, prepare for organisational transitions, adapt to operational environment changes, and maintain agility in response to external pressures. This capability is particularly valuable in today's rapidly evolving workplace environment, where organisational adaptability and sustainability are essential for success.

3 Methodology

As Semeraro et al. (2021) emphasise, the bidirectional real-time data flow between DTs and their physical counterparts has significant implications for human operators and organisational dynamics. These implications, particularly regarding organisational functioning, decision-making processes, and human interactions, remain underexplored in current literature.

This study employs a narrative literature review methodology to examine DT applications within HFE and IOP. Following Hodgkinson and Ford's (2014) guidelines, we selected this approach due to two primary factors: the emergent nature of DT applications in these domains and the necessity for a comprehensive overview of their human and organisational impacts.

The review aims to accomplish three primary objectives: synthesise current knowledge about DT applications in HFE and IOP contexts; identify the critical intersections between DT technology and human-organisational systems; and demonstrate how HFE and IOP perspectives can inform the future development and implementation of DTs. Through this methodological approach, we intend to illustrate the central role that HFE and IOP considerations should play in advancing DT technology, particularly in understanding and optimising human-system interactions within organisational settings.

The literature search process followed a systematic approach across multiple stages. Initial searches were conducted across major electronic databases, including Scopus, Web of Science, Google Scholar, and IEEE. The search terms encompassed 'digital twin', 'human factor', 'ergonomic', 'human-robot', 'manufacturing', 'construction', 'industr*', 'system*', 'safety', 'workforce', 'workplace', and 'review'. Truncation symbols (e.g., 'industr*' and 'system*') were employed to capture term variations such as 'industry/ industrial' and 'system/systems'.

The search strategy yielded 11 recent comprehensive reviews on DTs. These reviews served as foundational sources, providing insights into the current state of the art, main research trends, primary application areas, and current challenges and barriers. We implemented a snowballing approach, examining references within these reviews to identify additional relevant articles, both conceptual and applied. To ensure comprehensive coverage, we also analysed recent articles citing these reviews, acknowledging the rapid development of this emerging field.

The inclusion criteria focused on articles that addressed both technological and human aspects of DTs, explored applications in working and industrial contexts, examined human, ergonomic, or organisational aspects, and were published in English. Articles focusing solely on technological or infrastructural aspects without human factors consideration were excluded. This selection process resulted in 43 articles that met our criteria, providing diverse perspectives and applications across multiple contexts. The analysis process comprised independent review by three researchers, documentation of key applications and practical implications, collaborative discussions to identify common themes, and iterative refinement of categories and themes.

While our approach diverges from traditional systematic reviews using predefined keywords and Boolean operators, the combination of leveraging existing reviews and snowballing proved effective for this rapidly evolving field. This methodology enabled us to focus on the most relevant literature, address both technological advancements and human-centric implications and provide a structured overview of DT applications in HFE and IOP.

We acknowledge potential limitations in our methodology, such as possibly overlooking studies not cited in the consulted reviews or published after their release. However, our approach's flexibility allowed us to capture relevant research in this dynamic field while maintaining methodological rigour.

4 Results

Our analysis revealed distinct categories of DT applications within HFE and IOP. Through a systematic examination of the literature, we identified five primary application areas within each domain.

The HFE applications reflect workplace systems' technological and human-centred aspects, focusing on the physical and cognitive interfaces between workers and their environment. In the IOP domain, the identified categories represent the psychological and organisational dimensions of DT implementation, emphasising human behaviour and organisational dynamics. Detailed mapping of these categories and their supporting references is presented in Table 1 (HFE applications) and Table 2 (IOP applications).

4.1 Applications of DTs in HFE

We identified five key areas for integrating HFE principles with DT technology: workplace design, safety analysis, equipment optimisation, human-robot interaction (HRI), and training simulations. These areas represent significant opportunities for enhancing workplace efficiency, safety, and employee well-being through the application of DT technology. Table 1 summarises these application areas, briefly describing each and listing key studies that have contributed to our understanding of DT implementation in HFE contexts.

4.1.1 Workplace design

The integration of DTs into workplace design is changing how work environments are conceptualised, developed, and optimised. DTs are deployed for real-time assessments and instant repair capabilities in industries such as aerospace and defence. This practice not only sets a new standard for dynamic models in informing workplace design within HFE but also ensures that work environments are optimised for safety and efficiency (Wang et al., 2021). On the other hand, the construction industry capitalises on the synergy between DT and virtual reality (VR) technologies to forge immersive and interactive training experiences. These experiences offer personalised feedback and dynamic training scenarios, enabling workers to practice in environments that closely mirror their specific tasks. This tailored training approach has significantly reduced accidents and enhanced operational efficiency by ensuring worker safety and readiness (Harichandran et al., 2021). These applications provide further insights into how integrating DT in workplace design may enhance employee comfort and ensure that workspaces are ergonomic and safe.

Table 1 Areas of applications of DTs in HFE

Areas of applications	*Description*	*Key studies*
Workplace design	Flexibility and adaptability; employee well-being; safety analysis.	Choi et al. (2022), Elyasi et al. (2023), Harichandran et al. (2021), Miller and Spatz (2022), Panariello et al. (2021) and Wang et al. (2021)
Safety analysis	Predictive maintenance; Safety protocols; real-time monitoring.	Björklund et al. (2023), Hou et al. (2020), Knebel et al. (2023), Mihai et al. (2022), Mortlock et al. (2021), Rosen and Pattipati (2023)and Ruppert and Abonyi (2020)
Equipment optimisation	Equipment efficiency; lifecycle data integration; user experience.	El-Din et al. (2022), Mortlock et al. (2021), Sani et al. (2022) and Shahzad et al. (2022)
Human-robot interaction	Collaboration dynamics; ergonomics and safety protocols.	Bilberg and Malik (2019), Coorey et al. (2022), Farhadi et al. (2022), Oyekan et al. (2019), Weistroffer et al. (2022) and Zhang et al. (2023)
Training simulations	Immersive environments; scenario fidelity; skills acquisition.	Boschert and Rosen (2016), Broo and Schooling (2023), Gaffinet et al. (2023), Hou et al. (2020), Reed et al. (2021), Sharma et al. (2022) and Wagg et al. (2020)

Further extending the utility of DTs, their application facilitates the merger of physical and virtual workspaces, offering unparalleled flexibility. In fact, workspaces can be configured and reconfigured through dynamic scheduling and modular construction to meet evolving needs, enhancing adaptability and responsiveness (Choi et al., 2022). Miller and Spatz (2022), using a unified view of a 'Human DT', simulate how scenarios related to lighting, temperature, and other environmental factors contribute to a more pleasant working atmosphere, thus prioritising employee well-being and aligning the physical work environment with ergonomic principles.

The role of DTs extends into the use phase of buildings and workspaces, where they support sustainable production and maintenance practices. DTs may reduce musculoskeletal disorders among workers, affirming the design's focus on productivity and health (Elyasi et al., 2023; Panariello et al., 2021). In other words, by integrating digital human modelling, workplace design benefits from enhanced visualisation and assessment capabilities, enabling a profound understanding of the design's impact on employee well-being and overall productivity.

Nevertheless, the implementation of DT technology faces several challenges. First, it requires substantial technological infrastructure and expertise, creating significant barriers, particularly for small and resource-constrained organisations (Tao et al., 2018). Second, organisations struggle to achieve seamless transitions between configurations and the integration of DT insights into physical workspaces. While stakeholder engagement is essential for successful implementation, it often proves difficult to maintain. Finally, as the field evolves, certain applications like the integration of digital human modelling still require empirical validation, highlighting areas for future research and development (Sharma et al., 2022).

4.1.2 Safety analysis

The incorporation of DT into safety analysis modelling represents a transformative shift in how safety assessments are conducted, and workplace hazards are mitigated. DTs offer a dynamic and continuously evolving platform that simulates various possible approaching scenarios by creating virtual replicas of physical assets. This capability is instrumental in identifying and analysing potential safety issues and hazards within the workplace, moving beyond static analyses to reflect the fluid and changing conditions of real-world environments (Mortlock et al., 2021).

As we mentioned, DTs excel in providing a comprehensive and dynamic representation of the workplace environment by integrating real-time data from sensors and operational systems (Ruppert and Abonyi, 2020), thus ensuring that safety analyses are current and reflective of the actual state of the workspace, enabling organisations to evaluate and refine safety measures effectively or, at least, minimise the negative effects of adverse events, now possibly identified without significant delay. More specifically, through the simulation of diverse scenarios, the robustness of safety protocols can be tested under various conditions, enhancing the preparedness and responsiveness of safety strategies (Rosen and Pattipati, 2023). Björklund et al. (2023) showed that predictive maintenance and fault diagnosis benefit from DT can offer a virtual testing ground for optimising safety procedures and protocol.

Predictive analytics within DTs enables a proactive approach to workplace safety. The analysis of historical data helps identify potential safety issues before they occur, allowing organisations to implement preventative measures (Mortlock et al., 2021). Therefore, DTs support the development of safety-critical applications, providing a virtual testing ground for optimising safety procedures without risking actual workplace integrity.

Specific industries, such as oil and gas, have utilised DTs to test procedures and hazard identification, assisting as a dynamic tool for safety analysis. Research, such as that conducted by Knebel et al. (2023), illustrates that DTs test and refine safety protocols within this high-risk industry and also enhance operational safety through real-time monitoring and predictive maintenance capabilities. The DTs application contributed to reducing downtime and preventing accidents by predicting equipment failures before they occur, thereby emphasising the integration of HFE principles thus safeguarding both human lives and infrastructure.

In another context, particularly supply chain management, DTs have demonstrated their ability to simulate various scenarios for identifying and analysing potential safety issues, thus promoting a safer work environment (Hou et al., 2020). In the context of railway systems and offshore structures, for example, the study by Mihai et al. (2022) highlights the effectiveness of DTs in employing predictive maintenance frameworks to monitor machine sensors meticulously. This proactive approach enabled the timely addressing of safety shutdown mechanisms in power stations, directly contributing to hazard prevention and operational safety.

The integration of DT in safety analysis modelling promises to improve safety standards and reduce workplace hazards. However, challenges include the need for robust technological infrastructure, seamless integration with physical spaces, and concerns about data privacy. Although promising for improving safety standards, the effective implementation of DTs necessitates addressing these limitations to strike a balance between operational efficiency and employee well-being and privacy (Mihai et al., 2022).

4.1.3 Equipment optimisation

DTs have also been deployed for the design and strategic placement of work equipment, aiming at optimising their utilisation for efficiency and user experience. Far surpassing traditional simulation tools, DTs emerge as dynamic repositories, assimilating lifecycle data artefacts into a comprehensive management system. This integration allows for the seamless querying of data and helps make informed predictions about the physical product for continual design optimisation and improvements in manufacturing systems. In that sense, DTs are recognised as the next generation of simulation technologies, unlocking the potential for refining design processes and products. For example, Shahzad et al. (2022) analyse the design, construction, and operation processes of built assets, indicating its potential for optimising equipment design and placement, serving as a cornerstone for advancements in this area.

The aerospace and defence sector’s adoption of DTs for continuous evaluation of physical entities aligns with the objective of optimising equipment through an HFE approach. Sani et al. (2022) demonstrated how aviation systems leverage accurate virtual representations, a feature also applied in HFE to enhance equipment design and optimise strategic positioning. This highlights the versatility of DTs in addressing technical and operational challenges while improving safety, efficiency, and effectiveness in both aviation and broader HFE contexts. Mortlock et al. (2021) further emphasised the proactive potential of DTs, particularly in enhancing user experience and optimising equipment performance.

Insights from DT technology enable organisations to tailor equipment to current operational conditions while strategically planning for future improvements. This forward-looking approach supports performance optimisation and maintenance and also ensures alignment with evolving standards through customised solutions. However, several significant challenges exist that warrant careful consideration. Integrating DT insights into physical environments can introduce complexities, potentially impacting optimisation efforts. Moreover, real-time data integration raises data security concerns, compelling the need for stringent measures to protect sensitive information against breaches. Additionally, the continuous evolution of DT technology may result in a lack of standardised practices, posing challenges in consistency and interoperability across industries with varied operational demands (El-Din et al., 2022).

4.1.4 Human-robot interaction

A significant area where DTs manifest their transformative capability is in enhancing HRI, a crucial aspect in the HFE field that seeks to foster safer and more effective collaboration between humans and robots. In this field, the integration of DTs in HRI serves as a cornerstone in developing collaborative robots and assembly systems by enabling the formation of flexible human-robot teams (Bilberg and Malik, 2019). By facilitating the creation of a digital representation of the human body, the DTs enable ergonomic assessment during human-robot collaboration, thereby contributing to safer interactions (Farhadi et al., 2022). This application of DTs is crucial in environments where precision and safety are paramount, as it allows for the detailed analysis and optimisation of human-robot workflows. Zhang et al. (2023), for example, leveraged the DT technology to analyse welding and welder behaviour, their findings indicate significant improvements in operational efficiency and comfort for human users during collaboration with robots. In another study from the healthcare sector, DTs have been used to support accurate replication of human hand movements in remote surgery scenarios (Coorey et al., 2022). Such advancements highlight the potential role of DTs in optimising HRI, making them safer and more effective by addressing ergonomic concerns and enhancing the overall user experience, particularly in procedures requiring high precision and reliability.

However, the integration of DTs in HRI requires a few reflections. The testing and implementation of human-robot collaboration systems throughout DT technologies could be dangerous if the high-speed movements and massive forces generated by the industrial robots are not fully detected in the virtual environment, highlighting the need for careful consideration of safety measures and standards (Oyekan et al., 2019). In other words, while DTs offer the potential for safer and more effective collaboration, there may be challenges in achieving real-time communication between the DT and the physical environment, impacting the seamless integration of HRI (Weistroffer et al., 2022). It becomes evident that a balance must be struck between technological innovation and adherence to rigorous safety and ergonomic standards, an equilibrium that is crucial for the successful implementation of DTs in dynamic industrial settings.

4.1.5 Training simulation

Another area in which the application of DTs has found strong interest concerns their significant role in transforming modern training methodologies. The integration of DTs into training simulations and skill development is particularly common within industries characterised by complex and notably risky tasks and processes, and it is crucial for enhancing the fidelity and efficacy of training environments. DTs utilise simulation-based modelling and data analytics to recreate realistic training scenarios. This methodology allows for quantifying margins and uncertainties in cost and performance and contributes to more effective skill development by providing trainees with a more detailed and realistic understanding of the tasks at hand (Boschert and Rosen, 2016; Reed et al., 2021). The capability of DTs to execute multiple simulations simultaneously is particularly beneficial, as it crafts comprehensive training environments that accurately reflect real-world conditions.

A significant breakthrough in training simulations has been the adoption of VR alongside DTs. This combination has propelled the creation of highly immersive and realistic training environments. By leveraging data from actual assets and incorporating it into virtual simulations, DTs ensure that training scenarios are grounded in reality, thus meaningfully enhancing the learning experience (Sharma et al., 2022). Additionally, DTs serve as tools for generating synthetic data, aiding in the performance of simulations that contribute to improved preparedness and skills enhancement (Wagg et al., 2020). For example, by tailoring scenarios to progressively increase complexity, trainees can build their skills without being overwhelmed, enhancing learning retention and operational efficiency. The complexity of tasks simulated through DTs and VR can be, therefore, adjusted to manage the cognitive load on trainees, aligning with HFE principles that seek to optimise cognitive processes.

Hou et al. (2020) reviewed the integration of VR and DTs for construction safety training. This combination creates immersive and realistic training environments, enabling workers to learn in settings tailored to their tasks, enhancing skill development effectiveness and avoiding on-the-job training hazards. In that sense, DTs can prepare trainees for unpredictable scenarios by simulating a wide range of operational conditions, including emergencies. This awareness is indispensable from an HFE standpoint, as it ensures that individuals are equipped to handle challenges safely and effectively, minimising the potential for errors and accidents in high-stress situations.

Table 2 Areas of applications of DT in HFE

Areas of applications	*Description*	*Key studies*
Workforce planning	Team performance; employee satisfaction; predictive capability.	Attaran and Celik (2023), Hazrat et al. (2023), Madni et al. (2019) and Shen et al. (2006)
Performance analysis	Process optimisation; performance monitoring and enhancements.	Balaji et al. (2023), El Saddik (2018), Popa and van Hilten (2021) and Preuveneers and Ilie-Zudor (2017)
Organisational change management	Decision support systems; transition strategies; impact evaluation.	Botín-Sanabria et al. (2022), Grieves and Vickers (2016), Mihai et al. (2022) and Warke et al. (2021)
Employee well-Being	Health and well-being metrics; comfort factors; workspace analysis.	Bucchiarone (2022) and Lu et al. (2019)
Leadership development	Leadership decision insights; adaptability training; personalised learning.	Attaran and Celik (2023), Madni et al. (2019) and Zhu et al. (2021)

Despite the advantages of DTs in training simulations, certain challenges and limitations must be acknowledged. Developing effective training curricula for Industry 4.0 and digital workplaces requires extensive documentation, efficient knowledge sharing, and alignment with shared goals. Without proper management, these factors could hinder the effectiveness of skill development (Broo and Schooling, 2023). On the technical side, integrating simulation platforms with physical data from industrial processes presents significant complexity. This challenge makes it difficult to create realistic training environments that accurately reflect the dynamic nature of future systems (Gaffinet et al., 2023). Addressing these organisational and technical hurdles is crucial to fully realise the potential of DTs in enhancing workforce training.

4.2 Applications of DTs in IOP

Within the IOP domain, we have identified five pivotal areas where the integration of DTs holds the promise to deepen our understanding of human behaviour and drive optimisation in organisational contexts. These domains encompass workforce planning, performance analysis, organisational change management, employee well-being, and leadership development, each representing a cornerstone of effective and adaptive organisational practices. Table 2 summarises these application areas, briefly describing each and listing key studies that have contributed to our understanding of DT implementation in IOP contexts.

4.2.1 Workforce planning

The integration of DTs into workforce planning offers transformative potential by enabling organisations to model and optimise team structures, roles, and schedules with unprecedented precision. Through advanced simulations and predictive capabilities, DTs allow planners to anticipate future scenarios, such as workload peaks or unexpected emergencies, and adjust resources accordingly. For example, Madni et al. (2019) provided insights on how DT technology can offer a sophisticated virtual environment where organisations can model and identify team configurations that maximise operational efficiency and enhance job satisfaction by leveraging detailed simulations based on skill sets, workload distribution, and performance metrics. In other words, the utility of DTs in analysing and optimising team structures facilitates the identification of the most effective team composition while improving job-fit measures. This approach can enhance team efficiency and job satisfaction, preserving personal preferences while considering organisational constraints, safety standards, and regulatory requirements.

Moreover, since DTs can simulate different scenarios, predicting the impact of changes in team structures on job satisfaction and overall team performance, thereby enabling informed decision-making in workforce planning, represents another key element in workforce planning (Shen et al., 2006). This predictive capability is crucial for strategic workforce planning, allowing for the anticipation of shifts in job satisfaction and team performance. This synergy fosters the development of efficient and productive teams while simultaneously enhancing job satisfaction and boosting overall organisational performance (Shen et al., 2006). Additionally, integrating DTs with active human involvement enhances decision-making processes by providing the technical depth needed for complex insights while simultaneously fostering stronger employee engagement. In fact, this integration holds promise for fostering stronger partnerships and creating sustainable job opportunities (Hazrat et al., 2023). When individuals are actively involved in organisational decision-making are more likely to feel connected to results and aligned with the organisation, strengthening trust and promoting shared responsibility (Valverde-Moreno et al., 2020). This interplay between DTs and workforce planning allows organisations to anticipate and adapt to changing needs, fostering agility and resilience in the face of evolving market dynamics.

It is noteworthy that the reliability and effectiveness of the workforce models generated by DTs depend on accurate and comprehensive data inputs (Attaran and Celik, 2023). The complexity of workforce dynamics, coupled with the multitude of influencing factors, may pose challenges in accurately capturing and representing all relevant variables within the DT models. Additionally, the successful implementation of DT in workforce planning requires a thorough understanding of the organisational context and the specific dynamics of the workforce, factors that may vary across different industries and organisational settings (Attaran and Celik, 2023). In addressing these challenges, IOP offers valuable perspectives and principles that can enhance the accuracy and efficiency of DT models.

4.2.2 Performance analysis

In the IOP field, the integration of DT can bring significant benefits to performance analysis tasks and goals, particularly in simulating various performance scenarios to identify areas for improvement. Specifically, these technologies can facilitate a deeper understanding and optimisation of human work performance, process efficiency, and product and system performance, thereby aligning closely with the strategic objectives of IOP to foster organisational outcomes and employee well-being.

An interesting application in enhancing human work performance has been shown by Balaji et al. (2023), who developed a human DT using the adaptive control of thought-rational (ACT-R) cognitive architecture to simulate control room operators' behaviour during various abnormal situations in process industries. This DT aims to mimic human operator monitoring processes and interventions, offering insights into improving operator performance and decision-making in real-time operation contexts.

Moreover, the integration of DTs for performance analysis can significantly optimise production processes and enhance safety measures. For instance, the use of DTs in healthcare has explored socio-ethical benefits and risks, demonstrating DTs' capacity to revolutionise performance-based contracting and operational efficiency (Popa and van Hilten, 2021). By simulating performance scenarios, the application of DTs can provide actionable insights into operational optimisation, thus providing recommendations for operations and maintenance through analytics and identifying areas for improvement.

Another use of DT is to seamlessly incorporate lifecycle data artefacts into a comprehensive management system, enabling the querying of data and making predictions about the physical products for performance optimisation and improvement. This approach improves the understanding of product performance through simulation and data analysis, facilitating performance optimisation, impacting product development, quality assurance, and lifecycle management and ultimately fostering innovation and quality improvement within organisations (Preuveneers and Ilie-Zudor, 2017).

However, the implementation details of the software architectures and their use case scenarios are somewhat abstracted, posing challenges in the development of DTs for cyber-physical production systems. Furthermore, limited interest in the concept of DTs has been observed in the domain of health and well-being, indicating potential challenges in the adoption of DTs for certain applications (El Saddik, 2018). Additionally, the theoretical and numerical analysis in specific contexts may have limitations, such as assumptions made during the analysis, which could impact the accuracy of the performance simulations. These limitations and caveats demonstrate the necessity for careful consideration and domain-specific customisation when implementing DTs for performance analysis.

4.2.3 Organisational change management

Organisational change management stands to benefit significantly from the support of DTs, serving as virtual replicas of an organisation's processes, systems, and structures. This innovative approach allows stakeholders to assess the potential impact of organisational structure or policy changes before their actual implementation. This capability empowers informed decision-making and can significantly reduce the risk associated with organisational transformations, ensuring smoother transitions and the effective mitigation of potential challenges (Botín-Sanabria et al., 2022). The proactive nature of DTs, therefore, enables the identification and resolution of potential issues and challenges in the virtual environment, preventing them from manifesting in the real world (Grieves and Vickers, 2016). In other words, DTs can facilitate the assessment of the impact of changes in organisational structure or policy by providing a platform for scenario testing and analysis. Simulating changes in a virtual environment allows organisations to explore their potential impacts in advance, fostering a deeper understanding of what to expect. Through these virtual representations, stakeholders and employees can interact with the proposed changes, enabling them to gradually adapt and align with the transformation. This process makes the transition feel more concrete and relatable, reducing uncertainty and increasing the likelihood of acceptance and successful implementation.

For example, organisations can explore different change scenarios and their potential consequences, aiding in the development of effective change management strategies (Mihai et al., 2022). In the context of smart manufacturing, DTs can be utilised to model and analyse the effects of reconfiguring production lines, implementing new technologies, or altering supply chain processes. This application provides valuable insights into how these changes might impact overall organisational performance, offering a forward-looking perspective for strategic decision-making.

Acknowledging the complexity and resource-intensive nature of developing and maintaining accurate DT models is essential. Reliable and valid simulation results require high-quality data input that captures up-to-date changes in organisational processes, structures, and external conditions, including unexpected and abrupt shifts. This level of data management requires meticulous attention to detail to prevent incomplete or biased assessments of organisational change impact (Warke et al., 2021).

4.2.4 Employee well-being

DTs have been further used to promote employee well-being by monitoring and predicting factors that affect their health and comfort. When integrated into workplace design, DTs create virtual representations of the physical work environment, enabling real-time monitoring of various parameters such as air quality, temperature, lighting, and noise levels. This comprehensive view enables the identification of potential environmental stressors and hazards, utilising edge devices and data analytics to enhance employee well-being. In a case study, the DTs' technology has been used to facilitate the prediction of potential issues or discomforts by simulating different scenarios and their impact on employee health and comfort (Lu et al., 2019). The implementation of DTs aligns with the broader trend of digital transformation in organisations, serving as a strategic management tool to support employee well-being and productivity. Organisations can gain insights into the interplay between the digital workplace and organisational culture and create environments that are conducive to employee well-being and satisfaction.

In education, DT has been used to enhance the learning environment, support organisational decisions, and ensure the integrity of the educational process. This innovative application mirrors its transformative impact in IOP, where DTs create data-driven frameworks to enhance workplace satisfaction and employee well-being (Bucchiarone, 2022).

Potential limitations or caveats associated with the implementation of DTs for employee well-being need to be considered. The stringent latency requirements for real-time monitoring and prediction in DT applications may pose challenges in processing data and delivering timely insights by monitoring and predicting health and comfort factors, identifying stressors, and simulating potential threats (Lu et al., 2019).

4.2.5 Leadership development

The utilisation of DTs in leadership development offers a unique opportunity to simulate leadership challenges and develop management skills through realistic and immersive simulations. Attaran and Celik (2023) highlighted the capacity of DTs to establish a secure environment, allowing leaders to experiment and refine decision-making and problem-solving abilities. This simulation-based approach exposes leaders to a diverse range of complex situations, promoting adaptability and resilience. Leaders can engage in hands-on experiences within a safe virtual space, cultivating a nuanced understanding of various challenges they might encounter in real-world scenarios.

Furthermore, the versatility of DTs extends to the personalisation of leadership development programs. Tailoring simulations to individual learning needs and career aspirations, as emphasised by Madni et al. (2019), facilitates continuous growth and skill enhancement. The adaptive nature of DT in leadership development positions it as a dynamic tool that evolves alongside the individual, ensuring targeted and effective skill enhancement over time.

Specifically, in the aerospace and defence industry, the application of DT is driving faster innovation, a critical advantage that can be mirrored in the domain of leadership development within IOP. The ability of DT to simulate complex scenarios in real-time enables leaders to engage with and adapt to rapidly changing circumstances, fostering a culture of resilience and forward-thinking. Similarly, the construction industry's integration of VR with DTs for immersive and interactive training experiences offers personalised feedback, a feature that can significantly enhance leadership development programs in IOP. This personalised approach allows for the tailoring of leadership training to individual needs and learning styles, ensuring that each leader receives the guidance and feedback necessary to maximise their growth and development (Zhu et al., 2021).

Nonetheless, the implementation of DT in leadership development necessitates careful consideration of real-world complexities. This ensures that DT scenarios authentically mirror genuine leadership challenges' dynamic and unpredictable nature. Through realistic simulations and personalised programs, leaders can navigate diverse challenges within a secure virtual environment, fostering adaptability and continuous growth.

5 Discussion

In this review, we explored the intersection between DT technology and the fields of HFE and IOP. Through a narrative review, we aimed to highlight the potential of DTs, especially when viewed through the lens of human factors and the psychological dimensions of workplace environments. We identified five critical areas of application for DTs in HFE: workplace design, safety analysis, equipment optimisation, HRI, and training simulations. Similarly, in IOP, we found five key areas: workforce planning, performance analysis, organisational change management, employee well-being, and leadership development.

5.1 Theoretical and practical implications

The integration of DT technology in HFE and IOP presents significant implications for both theory and practice. From a theoretical perspective, our review suggests a shift in understanding human-system interactions. The capability of DTs to create accurate and dynamic models of physical systems, including human behaviour, implies a need for theoretical frameworks that incorporate more dynamic, real-time models of human behaviour and cognitive processes in complex systems. This shift may fundamentally alter how we conceptualise and study human-system interactions in HFE and IOP.

Furthermore, the application of DTs in organisational studies, as highlighted by Grieves and Vickers (2016) and Warke et al. (2021), represents a move towards more data-driven approaches in organisational theory. This shift implies a potential paradigm change in how we theorise about organisational structures, processes, and change management, with a greater emphasis on predictive modelling and real-time data analysis. The concept of the 'augmented organisation', or 'augmented socio-technical system', introduced by Lorente et al. (2022), suggests a theoretical expansion of socio-technical systems theory. This expansion envisions DTs integrated into the very fabric of organisational systems, potentially leading to new theoretical models of how technology and human systems interact and evolve together.

On the practical side, our review indicates that DTs allow organisations to simulate and analyse scenarios in real-time, enabling more informed decision-making and proactive problem-solving. This capability implies that organisations adopting DT technology may need to revise their decision-making processes to incorporate these new capabilities, potentially leading to more agile and responsive management practices. The application of DTs in High-Reliability Organisations suggests significant practical improvements in operational efficiency and safety management. Organisations, especially those in high-risk industries, may need to consider integrating DT technology into their safety protocols and operational procedures.

The work of He et al. (2024) and Wang et al. (2024) on HDTs implies a practical shift towards more human-centric technology applications in the workplace. This shift suggests that organisations implementing DTs may need to focus on integrating human factors more deeply into their technological solutions, potentially requiring new approaches to employee training, ergonomics, and workplace design. However, as highlighted by Akash and Ferdous (2022) and Mittelstadt (2017), the use of DTs raises significant ethical concerns regarding data privacy and security. Organisations implementing DT technology will need to develop robust data protection measures, transparent data handling practices, and mechanisms for employee feedback and consent.

Ethical and privacy considerations are important when implementing DT. Given the extensive data these systems process, it is fundamental to rigorously safeguard sensitive information to prevent unauthorised access, which could compromise the integrity of replicated data (Abanda et al., 2024). This security is achieved by implementing robust data protection measures and establishing clear guidelines and agreements regarding data usage rights and sharing protocols. Moreover, the ownership and control of data generated by DTs bring up significant challenges that require clear protocols to govern data usage and sharing practices, ensuring that all actions are accountable and aligned with ethical and privacy standards of integrity and societal welfare.

The implementation of DTs also affects the workforce, as it may lead to job displacement and changes in skill requirements (Reiman et al., 2021). It is crucial to address these impacts with a human-centric approach that emphasises worker empowerment, skill development, and job enrichment to mitigate adverse effects on job security and worker well-being. Considering these ethical and privacy principles in developing and deploying DTs, organisations can utilise digital technologies' benefits while safeguarding ethical standards and protecting the well-being of individuals and society at large.

5.2 Limitations and future research

The emergent nature of DTs in these fields posed significant methodological constraints, precluding a systematic review approach. Instead, this work relied on a theoretical review constrained by the limited number of published studies on the subject. This limitation in scope potentially impacts the thoroughness and breadth of the insights offered.

A key limitation of this study is the absence of empirical data, which is characteristic of theoretical reviews. This lack of empirical validation limits the study's capacity to substantiate hypotheses or validate the practical implications of integrating DTs in real-world settings. While the review provides a conceptual framework based on existing literature and theoretical constructs, it lacks the empirical grounding typically offered by case studies or data-driven research. Furthermore, the rapidly evolving nature of DT technology presents an additional challenge, as findings and discussions risk becoming outdated quickly, given the pace of advancements in the field.

Addressing these limitations, future research should prioritise empirical investigations to validate the conceptual frameworks and theoretical constructs presented in this review. This could include case studies, experimental designs, and longitudinal research to assess the long-term impacts of DT implementations on organisational performance and employee well-being. Researchers should employ diverse methodologies, including mixed-methods approaches, to gain a more comprehensive understanding of DT applications in HFE and IOP.

There is a need to establish standardised practices for DT implementation, ensuring consistency and interoperability across diverse industries. This could involve developing industry-specific guidelines and best practices for DT integration. Future research should also focus on the practical implementation of DTs, especially in areas such as employee well-being and leadership development. This necessitates a meticulous examination of real-world complexities to ensure that digital scenarios accurately mirror genuine challenges and dynamics.

Given the multifaceted nature of DT applications, future research should foster collaboration between HFE, IOP, computer science, and engineering disciplines to develop more sophisticated and holistic DT models. As DT applications involve sensitive data and potential privacy concerns, the development of comprehensive ethical guidelines for the use of DTs in workplace settings is crucial. Investigation of synergies between DTs and other emerging technologies, such as AI, machine learning and the IoT, could yield valuable insights for HFE and IOP applications. Conducting long-term studies to assess the sustained impact of DT implementations on organisational culture, employee attitudes, and overall performance would provide valuable insights into the efficacy of these technologies.

Addressing these limitations and pursuing these research directions, future studies can significantly advance our understanding of DT applications in HFE and IOP. This will contribute to the academic discourse and provide practical guidance for organisations seeking to maximise DT technology to create more efficient, safe, and human-centred work environments. As the field continues to evolve, it is imperative that research keeps pace, providing empirically grounded insights to guide the responsible and effective implementation of DTs in workplace settings.

5.3 Conclusions

Our analysis reveals that while DTs show great promise, their effective implementation requires addressing technical and practical challenges. As DT technology continues to evolve, its integration with HFE and IOP principles promises to drive significant advancements in creating more efficient, safe, and human-centred work environments.

The future of work, shaped by these digital innovations, holds the promise of workplaces that are more productive and more attuned to human needs and well-being. However, realising this potential will require continued research, interdisciplinary collaboration, and a commitment to ethical and human-centred design principles.

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