

BEYOND DATA: CONCEPTUALIZING HUMAN-CENTRIC DIGITAL TWINS FOR THE FUTURE OF CONSTRUCTION

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ABSTRACT: The construction industry is a labor-intensive sector that relies heavily on human expertise, physical effort, and team interactions within complex systems. Advancements in digital technologies have led to a paradigm shift towards digital twin (DT) systems, which enable real-time data analysis, predictive modeling, and enhanced decision-making processes. However, despite these advancements, existing DT implementations in construction mainly focus on technologies, processes, and physical spaces, often neglecting the essential role of human workers within these environments. This paper proposes a novel conceptual framework for a human-centric digital twin (HCDT) in construction, emphasizing the integration of human factors and interactions to optimize safety, productivity, and well-being on-site. The framework incorporates emerging technologies such as wearable devices, Internet of Things (IoT) sensors, and advanced data analytics to capture physiological, behavioral, and environmental data. These insights aim to enhance situational awareness, predict potential risks, and enable adaptive responses to dynamic construction site conditions. Additionally, the proposed HCDT framework provides a foundation for the development of personalized digital representations that support skill enhancement, ergonomic interventions, and workforce management. The proposed framework addresses the gap in DT research by shifting the focus towards a more inclusive model that prioritizes human factors alongside traditional construction aspects. This framework thus lays the groundwork for future research and practical applications in the development of DTs that are tailored to human needs in construction.

1. INTRODUCTION

Known for its tardiness in joining the digital transformation era, the construction industry is often described as one of the least digital industries (Greif et al. 2020) and has long been plagued with process and labor inefficiencies. The lack of integration between the construction site and potential digital systems for construction projects has led to lowered management efficiency and information fragmentation (Zhang et al. 2022). However, the construction industry could benefit greatly from digital transformation in the upcoming years (Greif et al. 2020). Therefore, several researchers have been proposing new digital transformation approaches to improve construction performance, including suggesting the broader implementation of Digital Twin (DT) technologies in construction (AlBalkhy et al. 2024).

Defined as creating a digital model of a physical system, DTs provide “real-time monitoring, updating, simulating, analyzing, controlling, predicting, optimizing, validating, and coordinating” throughout the project life cycle (Zhang et al. 2022). The basic architecture of a DT usually consists of (1) a physical layer which includes the physical component and the data acquisition and communication tools, (2) a digital layer which includes the data integration, modelling tools, and data management and analytics systems, (3) an application layer in which reports, dashboard, autonomous activities, and warnings are created, and (4) a

users layer which includes the clients, owners, managers, operators, or workers that could benefit from the developed DT (AlBalkhy et al. 2024).

Current DT proposals and developments in construction focus primarily on technical aspects of projects like site logistics (Greif et al. 2020), while others incorporate some human factors, mainly ergonomics, into the proposed construction DTs (Ogunseiju et al. 2021). However, some gaps remain in developing standardized frameworks that integrate a comprehensive human experience, including physiological, behavioral, and cognitive data with construction processes to enable human-centered solutions that are tailored for human needs.

To address this gap, this paper proposes a novel Human-Centric Digital Twin (HCDT) framework that incorporates wearable devices, IoT sensors, and advanced analytics to create personalized digital representations of workers. It is grounded in a conceptual approach that synthesizes elements from digital twin architecture, human-computer interaction, and human-centered design principles, and aims to answer the research questions: “How can Digital Twin frameworks be extended to meaningfully incorporate human physiological, cognitive, and behavioral data in construction environments”, and “What are the practical implications and limitations of implementing Human-Centric Digital Twins in the construction sector?”. The proposed framework aims to enhance worker safety, productivity, and well-being by providing adaptive, real-time insights and predictive capabilities tailored to the dynamic nature of construction sites. First, comprehensive literature review of DTs in construction is conducted, followed by a literature review of DTs with a focus on human factors in construction. Afterwards, a three-layer conceptual framework for a HCDT is proposed, with each layer meticulously described. Implications and applications of the proposed HCDT are presented, followed by conclusions. This study aims to lay the groundwork for the development and practical implementation of HCDTs in construction. Beyond the construction industry, human-centric digital systems have the potential to influence overall societal practices by promoting safer and more adaptive work systems.

2. LITERATURE REVIEW

2.1. Digital Twins in Construction

Digital Twins (DT) are digital replicas or representations of physical objects, products, assets, processes, or systems (AlBalkhy et al. 2024) and are implemented in several industry sectors, such as aviation, transportation, manufacturing, medical sciences, and healthcare (Akanmu et al. 2021). Generally, they are supported by technologies such as simulations and digitalization (Kor et al. 2023), sensors, GPS, communication networks, audio technologies, medical and health sensors, and distance, location, and travel measurements (Salem and Dragomir 2022).

In construction, despite the slow pace of digitalization, DT research and implementations have been gaining momentum. A study by El-Din et al. (2022) conducted a systematic review on the lack of standardization for DTs in the AEC industry and proposed a conceptual framework for DT development for construction assets using existing BIM information management standards. They identified the most recurrent fields of investigation in DT studies in the AEC industry and found that facility management was the research field with the most studies, followed by structural health monitoring, concept framework, construction management, and finally, circular construction (El-Din et al. 2022). In construction management, they found that the studies were divided into robotics in construction, safety management, and project performance monitoring, with the latter two focusing on workers or humans.

Another study shed light on the importance of increasing DT and cyber-physical systems' deployment in the construction industry and described the integration of emerging technologies with the physical systems as the next generation DT for improving workforce productivity, health, and safety, lifecycle management of building systems, and workforce competency (Akanmu et al. 2021). The study also explored enabling technologies for next generation DTs, which included virtual design and modeling technologies, sensing technologies, data analysis techniques, data storage techniques, data communication technologies, human-computer interaction technologies, and robotics (Akanmu et al. 2021). A key observation by this

study is that workers' ability to perform work safely can be enhanced through personalized feedback (Akanmu et al. 2021).

A study by Salem and Dragomir (2022) reviewed the literature on DT in construction project management and proposed a framework for analyzing and supervising the development of DT. They also identified three existing and envisioned stages for DT implementations in construction, the first being BIM, the second being building control techniques and applications, and the third being the development of DTs for construction projects, which is described as the improvement on the first two stages (Salem and Dragomir 2022).

Yang et al. (2024) analyzed the commonly used architectures for digital twins in construction literature and summarized the commonly used technologies to implement them. They focused on seven digital technologies, which are: artificial intelligence, machine learning, cyber-physical systems, Internet of Things, data mining, virtual reality, and augmented reality (Yang et al. 2024). They also explored how DTs can be used throughout the different phases of a construction project's lifecycle, including design, construction, operation and management, and demolition and restoration (Yang et al. 2024).

In another study by (Ammar et al. 2022), interviews were conducted to understand construction practitioners' perceptions on the use and challenges of DTs. Through thematic analysis of the collected data, they found that contractual awareness and knowledge, data understanding, preparation, and usage, financial uncertainties, human capital development, organizational structure and processes, and technology deployment were among the most commonly reported challenges for DT implementation in construction (Ammar et al. 2022).

Omran et al. (2023) conducted a systematic literature review to understand current DT implementation in construction and explore technologies enabling their operation. They identified eight key areas of DT implementation including virtual design, project planning and management, asset management and maintenance, safety management, energy efficiency and sustainability, quality control and management, supply chain management and logistics, and structural health monitoring (Omran et al. 2023). They also identified challenges hindering their widespread adoption in construction and recommended some measures to address these challenges.

Some studies dug deeper into how DTs can be used in specific domains in the construction industry, like Greif et al. (2020) who focused on site logistics processes, characterized by limited visibility and inefficient organization. They designed and implemented a decision support system for silo-dispatch and replenishment activities on construction sites. Their DT included order data, silo data, and truck data that are obtained from real-world processes and are analyzed to feed the decision support system with proper silo repositioning and replenishment planning (Greif et al. 2020).

From another perspective, Zhang et al. (2022) proposed a framework for utilizing DTs and extending the existing level of details (LODs) of BIM in construction site management. They analyzed and improved the operation principle and mechanism of DTs, including the BIM-based digital representation, Internet of Things, data storage, integration, and analytics, and interaction with the physical environment (Zhang et al. 2022). They also conducted questionnaires and interviews that showed that their developed framework acknowledges the contribution of LODs' extension to construction site management.

In a study focused on integrating deep learning with DTs, qualitative and quantitative analysis of collected data from interviews and questionnaires were used to develop a conceptual model of a framework that integrates deep learning and DTs (Kor et al. 2023). They also suggested the use of technologies like BIM, sensors and data communication technologies, and Internet of Things and explained the benefits of using machine learning in construction (Kor et al. 2023).

2.2. Human-Centric Digital Twins in Construction

Given that DT implementations in construction are still in their early stages, it is unsurprising that human-centric DTs (HCDTs) in construction are even less prevalent. However, a study by Soman et al. (2025) developed a framework for human-DT interfaces and evaluated it on a real construction project. The study

followed a Design Science Research (DSR) methodology, guiding the development and iterative refinement of the human-DT interface through problem identification, artifact design, and real-world evaluation. While not anchored in a specific formal theory, it reflects principles from sociotechnical systems thinking and user-centered design. The framework integrates a several technologies, like BIM, artificial intelligence, GIS, and real-time data sources like cameras and sensors. They found that control rooms can serve as dynamic interfaces within the DT ecosystem and highlighted the importance of real-time data visualization, user-centric design, and predictive analytics to anticipate project risks and constraints (Soman et al. 2025). Despite challenges like data integration and stakeholder adaptation, the study highlights the potential of human-centered digital twins to transform construction management through enhanced collaboration and efficiency.

Another significant contribution to the HCDDT domain is the comprehensive review by Asad et al. (2023), which highlighted technologies, such as sensors, artificial intelligence, and simulation tools that enable HCDDTs to monitor and optimize human performance, ergonomics, and safety. This review employed a systematic literature review approach, incorporating bibliometric tools like VOSviewer to cluster research themes and visualize co-occurrence networks. The study identified six major application areas for DTs with strong human involvement: ergonomics and safety, robotics training, user education, design validation, cybersecurity, and healthcare. By integrating real-time data from humans and machines, HCDDTs can create adaptive, efficient, and safe environments.

A study by Rafsanjani and Nabizadeh (2023) explored the transformative potential of Virtual Design and Construction (VDC) and Digital Twin (DT) technologies in the AEC industry. These technologies, built on BIM and Internet of Things, enable real-time data analysis, predictive modeling, and enhanced project management. VDC optimizes design and construction phases, while DT facilitates smart operation and maintenance. By integrating augmented and virtual reality, along with artificial intelligence, these advancements promise cost savings in design, construction, and operations by 2025. However, challenges like high costs, technological interdependencies, and limited adoption persist (Rafsanjani and Nabizadeh 2023).

An interesting study by Ogunseiju et al. (2021) developed a DT-driven framework for improving self-management for ergonomic risks by using wearable sensors to track the kinematics of floor framers' body segments. It adopts an experimental design using simulated floor framing tasks and wearable sensor data, analyzed via a sequence-to-sequence LSTM network for posture classification. The proposed DT communicates the ergonomic risks via an augmented virtual replica, revealing the potentials of DTs for personalized posture training and paves the way for future research on DTs for improving construction workers' health and wellbeing.

However, despite the advancements in DT technology and its integration with human-centric approaches, existing research in the construction industry primarily focuses on technological innovations, such as BIM, IoT, and predictive analytics, with limited attention to the comprehensive incorporation of human factors within DT ecosystems. Current studies highlight the potential of HCDDTs in optimizing safety, ergonomics, and performance through real-time monitoring and adaptive measures. However, some gaps remain in developing standardized frameworks that integrate human physiological, behavioral, and cognitive data with construction processes to enable human-centered solutions that are tailored for human needs. To address this gap, this research proposes a novel HCDDT framework that incorporates wearable devices, IoT sensors, and advanced analytics to create personalized digital representations of workers. This framework aims to enhance worker safety, productivity, and well-being by providing adaptive, real-time insights and predictive capabilities tailored to the dynamic nature of construction sites. This study aims to lay the groundwork for the development and practical implementation of HCDDTs in construction.

3. METHODOLOGY

This study follows a conceptual research approach to develop a Human-Centric Digital Twin (HCDDT) framework for construction, integrating insights from digital twin models, human-computer interaction, and construction safety research. A systematic literature review was conducted using databases such as Scopus, ScienceDirect, and Google Scholar, focusing on publications from the past 10 years that

addressed digital twins, construction safety, wearable technologies, physiological monitoring, and human-computer interaction. Keywords included combinations of terms such as “digital twin,” “construction safety,” “wearable sensors,” “physiological monitoring,” and “human factors”. These sources informed the identification of gaps in existing digital twin implementations, particularly the limited focus on human physiological and cognitive factors. Afterwards, a three-layer conceptual framework was developed, aligning with existing DT architectures while incorporating novel human-centric enhancements. The framework was structured by mapping sensor capabilities (e.g., physiological, environmental, and location data) to AI-enabled processing functions such as stress detection and adaptive scheduling. It also integrates decision-making models based on human-in-the-loop (HITL) principles to support safety and productivity interventions. Framework components were benchmarked against capabilities reported in relevant literature to ensure theoretical feasibility. While this study presents a conceptual model, future research should focus on empirical validation through pilot implementations, assessing the effectiveness of real-time physiological monitoring, adaptive safety interventions, and AI-driven workforce optimization in construction environments.

4. CONCEPTUAL FRAMEWORK FOR HCDDT IN CONSTRUCTION

In the process of developing the conceptual framework for an HCDDT, three layers that will form the overall structure of the framework are identified. The three layers are (1) a data collection and acquisition layer, (2) a data processing and analysis layer, and (3) a decision-making and feedback layer (Figure 1).

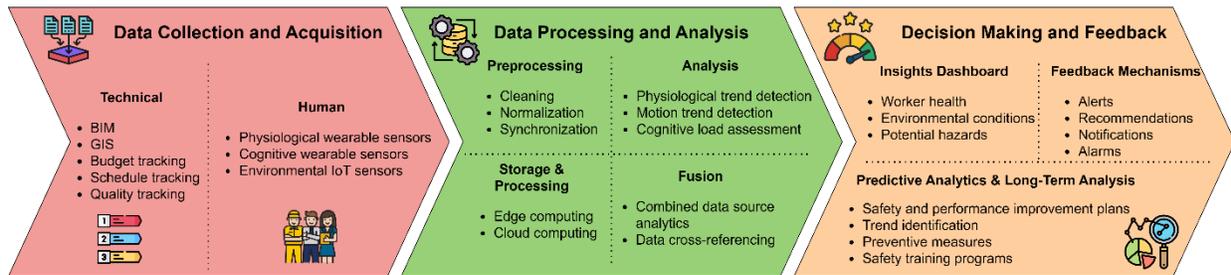


Figure 1: HCDDT Conceptual Framework Layers

4.1. Data Collection and Acquisition Layer

The data collection and acquisition layer includes some key components that are needed to ensure a comprehensive and reliable system. In this layer, traditional components of a construction DT are included, such as Building Information Modelling (BIM), Geographic Information Systems (GIS), and real-time data sources for schedule, budget, and quality tracking and measurement. These measurements are used provide continuous updates on construction site conditions, equipment status, and structural integrity. The traditional components enable building the foundation of digital representation in construction projects by integrating various data sources from the physical system to reflect real-world conditions dynamically.

However, in an HCDDT, this layer extends beyond traditional DT elements to incorporate physiological behavioral, cognitive, and even environmental data collected from workers working on the project in real-time. To achieve this, additional data sources that involve the state, wellbeing, and health of the workers are deployed to bridge the gap between digital modelling and human factors.

First, to ensure real-time monitoring of the physiological, behavioral, and cognitive data of project members, wearable sensors are key. Wearable sensors can be used to collect physiological data in real-time, which can later be translated into meaningful information regarding each member’s psychological, behavioral, and cognitive states. This information is essential for determining each worker’s physical and mental readiness, identifying stress or fatigue levels, and optimizing task assignments based on individual capabilities. For example, Electrocardiogram (ECG), Photoplethysmogram (PPG), and Electrodermal activity (EDA) can be used to assess stress (Lee and Lee 2024), fatigue (Lee et al. 2024), risk perception (Lee et al. 2021), and workload (Shehab and Hamzeh 2023). Electromyography (EMG) sensors also have good potential in tracking muscle activity and fatigue, which helps in assessing ergonomic risks among workers and project

members (Shehab and Hamzeh 2024). Skin temperature sensors can also be used to measure temperature variations that may indicate physical exertion, stress (Lee and Lee 2024), or potential heat exhaustion, which is a common and possible risk on many construction sites. Moreover, blood oxygen monitors can be utilized to ensure proper oxygen levels, especially in hazardous environments with poor ventilation. Finally, eye-tracking sensors can be used to monitor visual attention, providing insights into situational awareness and risk assessment abilities.

Second, while wearable sensors can be used to monitor human conditions, Internet of Things (IoT) sensors can be deployed across construction sites to monitor environmental conditions, such as temperature, noise levels, and air quality, which can impact workers' performance and safety. For example, temperature and humidity sensors can be used to prevent possible accidents emerging from extreme cold or heat conditions. Air quality sensors can also be employed to measure dust, CO₂, Volatile Organic Compounds (VOCs), and other pollutants that are commonly found in construction sites, in order to mitigate respiratory risks. Next, noise sensors may be used to monitor excessive noise levels arising from heavy machinery and construction equipment, which may cause hearing loss or cognitive fatigue. Light sensors are also an essential tool that can be used to detect inadequate lighting conditions, especially in night shifts, which could lead to eye strain or accidents. Finally, gas sensors can be used to identify hazardous gases such as methane and carbon monoxide, triggering safety protocols in enclosed spaces.

4.2. Data Processing and Analysis Layer

After data collection, data processing and analysis is key to transform raw data into meaningful information. This layer integrates advanced computing technologies, including Artificial intelligence (AI), machine learning (ML), and computer simulations to analyze and interpret the collected data.

The first step in this layer is data aggregation and preprocessing. After physiological, behavioral, and environmental data are collected, they must undergo data cleaning and synchronization to ensure accuracy and reliability. Filtering techniques can be used to remove noise, outliers, and irrelevant data caused by sensor malfunctions, signal errors, or external interferences. Normalization is also performed to ensure consistency across the different sensor types and units. Finally, synchronization is performed to align multiple sensor data streams, such as heart rate variability with environmental temperature, to provide a holistic understanding of the workers' physical and cognitive conditions.

Once the data is preprocessed, ML algorithms are used to analyze the complex datasets and to detect patterns and trends among the preprocessed data. These models are used to evaluate and detect trends in vital physiological markers, such as heart rate variability (HRV), EDA, and skin temperature fluctuations. They are also used to detect patterns in motion tracking data to identify inefficient body movements, unsafe postures, or repetitive strain that could potentially lead to musculoskeletal injuries. Additionally, cognitive load assessment techniques analyze brainwave activity and eye movement patterns to determine a worker's level of attention, focus, and situational awareness.

Beyond individual assessments, data fusion techniques combine multiple sensor inputs in order to enhance the reliability and accuracy of the processed data. By integrating physiological, behavioral, and environmental data, a more comprehensive understanding of worker conditions is achieved, ensuring that single data sources are not interpreted in isolation. Multi-sensor data fusion methods enhance the accuracy of fatigue detection by corroborating findings from heart rate variability with electrodermal activity and motion tracking. Similarly, environmental hazard assessment is strengthened by cross-referencing temperature and air quality sensor readings with physiological stress indicators, improving the reliability of risk evaluations.

To support real-time data interpretation, processing occurs at multiple levels: (1) Edge computing, on one hand, enables immediate **local** analysis of sensor data on-site, allowing for continuous monitoring of workers and site conditions with minimal latency (Bajic et al. 2019). This ensures that physiological and environmental data are processed without significant delays, allowing for real-time assessments of stress, fatigue, and exposure to harmful conditions. (2) Cloud computing on the other hand, facilitates **long-term**

storage and analysis, enabling pattern recognition over **extended periods** and improving the precision of predictive models (Bajic et al. 2019). The employment of both based analysis techniques refines machine learning algorithms by continuously learning from new data while improving the accuracy of physiological and environmental risk assessments over time.

4.3. Decision Making and Feedback Layer

The decision making and feedback layer is the final component of the proposed HCDDT conceptual framework. It is responsible for translating the processed data into suggestions for decisions, interventions, or even corrective and preventive measures.

At the core of this layer is the decision support system (DSS), which provides real-time insights into worker health, environmental conditions, and potential hazards. The DSS consolidates output from AI and ML models to generate situational awareness dashboards for project managers, safety officers, and site supervisors. These dashboards display real-time physiological and cognitive conditions of workers, environmental risk levels, and predictive safety alerts, which allows decision-makers to implement timely interventions. For example, if environmental sensors detect elevated levels of harmful gases, automatic safety alarms can be triggered, including ventilation adjustments or site evacuations.

In addition to decision-making level interventions, this layer incorporates automated feedback mechanisms that deliver real-time alerts and recommendations directly to workers and site supervisors. These feedback mechanisms can take multiple forms, such as wearable device notifications, mobile alerts, or audible site alarms, ensuring that safety recommendations are effectively communicated. For example, if motion tracking sensors detect an unsafe posture, workers may receive instant haptic or vibrational feedback through their wearable devices, prompting them to adjust their movements to prevent injury. Similarly, if AI models predict high levels of cognitive overload, workers may receive an alert advising them to take a short mental break before resuming high-risk activities. These interventions are more personalized to ensure that safety and well-being measures are seamlessly integrated into daily construction activities.

A key aspect of this layer is also the incorporation of predictive analytics and long-term trend analysis. This enables construction firms to develop strategic safety and performance improvement plans. By analyzing historical data on worker stress levels, fatigue patterns, and environmental exposures, the models can identify trends that contribute to accidents and inefficiencies over time. This allows decision-makers to implement preventative measures, refine safety training programs, and optimize shift schedules based on data-driven suggestions.

To further enhance decision-making effectiveness, Human-In-The-Loop (HITL) integration is incorporated into the feedback loop, allowing for human oversight and judgment in critical situations. HITL, which is a sub-discipline of Human-Computer Interaction (HCI), refers to systems that enable direct human intervention during AI model operations (Wilchek et al. 2023). It combines AI and automation with human decision-making, ensuring that complex processes benefit from both computational efficiency and human expertise. In the context of the proposed HCDDT, HITL allows construction site decision makers, like supervisors and safety managers, to interact with AI-driven insights, validate automated recommendations, and make informed adjustments based on real-world conditions. While AI and automation can provide risk detection recommendations, supervisors retain the ability to override automated recommendations based on contextual knowledge and on-site conditions. This balance between automation and human expertise ensures that decision-making remains both data-driven and adaptable to complex and real-world scenarios.

5. IMPLICATIONS OF HCDDTS IN CONSTRUCTION

In general, digital twins in construction and the built environment can aid in improving workforce productivity, health, and safety, which leads to enhanced facility management and workforce proficiency and reduced construction and operation costs (Ammar et al. 2022). Their applications range from structural performance (Majumdar et al. 2013) to structural health management (Hochhalter et al. 2014), work environment safety (Fotland et al. 2020), and more (Opoku et al. 2021).

In the context of HCDDT, implications gain a broader scale thanks to the human-centered aspect that they possess. With the proposed three-layer conceptual framework, more transformative possibilities beyond traditional workforce monitoring and safety management can be provided. HCDDTs introduce a paradigm shift that extends the role of digital intelligence into human well-being, cognition, and adaptive workforce dynamics by providing instant interventions reinforced by human supervision through HITL systems.

5.1. Personalized AI-driven Work Environments

Traditional construction environments treat workspaces as static, with no adaptation to human needs. HCDDTs could revolutionize this concept by proposing construction sites that are self-regulating, which means that they dynamically adjust environmental conditions based on real-time collected human physiological data. This could be translated into smart construction sites where sensors detect workers' fatigue levels and automatically adjust lighting, ventilation, or temperature to optimize performance and well-being. Noise-canceling zones could be activated when stress levels rise, and AI-driven ergonomic interventions could adapt workstations to minimize strain and prevent long-term injuries.

5.2. Cognitive Load Balancing for High-risk Tasks

Cognitive fatigue is one of the most underestimated risks in construction, which often leads to errors, miscalculations, and accidents. By integrating real-time cognitive and eye-tracking data, HCDDTs could predict cognitive fatigue and optimize work schedules accordingly. Workers involved in high-risk tasks, such as crane operation, welding, or working at extreme heights, could be assigned to tasks based on their real-time mental alertness and cognitive endurance, rather than a rigid or fixed pre-planned schedule.

5.3. Digital Twin Avatars for Workforce Simulation and Optimization

HCDDTs allow for the development of AI-generated digital worker agents or avatars that can simulate and predict workforce behavior under different site conditions. These avatars, built based on real-time physiological and behavioral data, could be used to model how workers respond to different stressors, shifts, and workloads over time. Decision makers could run predictive computer simulations, such as agent-based simulations, to determine the best team compositions for high-stress environments, ensuring that the most cognitively and physically capable individuals are assigned to critical tasks and at the right time.

5.4. Emotionally Responsive Construction Management

Current construction safety models focus on physical and cognitive well-being, often neglecting the emotional and psychological states of workers. HCDDTs could analyze emotional biomarkers such as voice tone and facial expressions to assess worker morale and well-being. This would allow decision makers to detect burnout, dissatisfaction, or anxiety in real-time, which enables emotional interventions such as automated mental health support or dynamic workload adjustments to prevent emotional exhaustion.

5.5. Autonomous Risk Prevention and Worker Assistance Drones

HCDDTs could also integrate with AI-powered drones that can assist workers based on real-time physiological and environmental data. For example, drones could deliver water bottles or oxygen masks to workers experiencing dehydration or heat exhaustion. In hazardous environments, drones could deploy smart safety nets or provide real-time visual guidance using augmented reality overlays, assisting fatigued or cognitively overloaded workers in executing complex tasks safely. These autonomous systems would act as an additional safety net, ensuring that early warning signs of worker distress trigger immediate physical assistance rather than mere alerts.

5.6. Physiological Interventions through Exoskeletons

HCDTs could further enhance worker safety and performance by integrating exoskeletons that respond to real-time physiological data. Traditional construction work often leads to musculoskeletal strain, fatigue, and repetitive stress injuries, especially in physically demanding tasks such as lifting heavy materials, operating power tools, and prolonged standing or bending. By using wearable exoskeletons, HCDTs could provide adaptive physical support by reducing fatigue and injury risks.

With real-time monitoring of muscle activity, heart rate variability, and stress levels, exoskeletons could dynamically adjust their level of mechanical assistance based on worker fatigue and task intensity. For example, if an HCDT detects that a worker's muscle fatigue is increasing, the exoskeleton could automatically engage additional support to reduce strain on the worker's body. Additionally, AI-powered exoskeletons could provide postural correction feedback, ensuring that workers maintain proper lifting techniques and ergonomic postures.

6. APPLICATIONS OF HCDTs ACROSS CONSTRUCTION PHASES

While the primary focus of HCDTs is real-time site monitoring, their impact extends beyond active construction. Pre-construction planning, real-time execution, and post-construction phases can benefit from an integrated human-centric approach.

Before a project begins, HCDTs can simulate site conditions and test team compositions under different physical and cognitive loads. Suppose a project involves deep excavation in hot weather, HCDT simulations can predict how different workers will respond physiologically, helping planners assign roles, schedule breaks, or introduce exoskeletons in advance. By analyzing historical physiological and cognitive data, AI could determine which workers are best suited for high-pressure roles, ensuring that physically demanding tasks are assigned appropriately.

During the construction phase, HCDTs can monitor human factors and site conditions simultaneously. For example, if a concrete pouring task is scheduled during peak heat hours, HCDTs can detect early signs of heat exhaustion and trigger alerts for cooling breaks or activate smart fans at the location. AI-powered adaptive scheduling algorithms could dynamically reassign tasks based on real-time stress, fatigue, and attention levels. In hazardous environments, workers could receive haptic feedback on their smart wearable devices, proactively alerting them of risks before they become too critical or dangerous. A crane operator showing signs of cognitive overload could be replaced with a more alert team member, while drones assist with supervision and progress tracking.

The use of HCDTs does not end once construction is completed. After execution, HCDTs can offer valuable insights into long-term workforce health and performance, helping organizations understand how construction work affects not only safety, but also long-term worker health and career satisfaction. For example, data on repetitive strain, stress patterns, and cognitive load can be analyzed to adjust ergonomic training programs, refine jobsite protocols, or improve shift scheduling. Beyond individual projects, aggregated HCDT data can inform future project designs by identifying recurring high-risk tasks, durations that lead to fatigue, or site conditions that frequently trigger stress responses. These insights could guide the optimization of task sequencing, site layout, and resource planning. Moreover, such findings may support the development of industry-wide standards, including acceptable thresholds for physiological load, dynamic task reassignment guidelines, and minimum sensor deployment requirements for high-risk environments.

However, a critical challenge to the widespread adoption of HCDTs lies in construction workers' acceptance of these technologies. As highlighted by (Choi et al. 2017) perceived privacy risk is one of the strongest predictors of a worker's willingness to use wearable devices in the field. Workers may resist using devices such as smart vests or physiological wristbands if they believe their personal data, like location or biometric signals, could be accessed, shared, or misused without consent. Even when workers recognize the benefits of these technologies, privacy concerns may outweigh perceived usefulness, especially in the absence of clear communication about data protection. Therefore, to overcome these limitations, industry-wide adoption, pilot testing, and inclusive stakeholder engagement, including workers, are crucial.

7. CONCLUSIONS

This paper proposed a HCDDT conceptual framework for construction, addressing the gap in traditional DTs that focus primarily on structural and operational aspects of projects, while neglecting human workforce. A three-layer conceptual framework was developed, integrating various sensors for human and environmental conditions monitoring. AI-driven data processing is suggested for risk assessment and accident prevention. Finally, a decision-making layer incorporating predictive analytics and HITL insights is designed. This framework aims to enhance worker safety, productivity, and risk management in construction projects by integrating human factors into DTs.

The implications of the proposed framework extend beyond conventional project monitoring and control, integrating AI-driven adaptive work environments, cognitive-based task allocation, and predictive safety interventions. It enables real-time optimization of working conditions by reducing fatigue-related accidents, enhancing decision-making, and fostering emotionally-responsive construction management approaches. For example, real-time physiological data such as elevated heart rate or abnormal skin conductance could signal early signs of heat stress, prompting AI systems to initiate cooling protocols or reassign tasks to prevent incidents. Likewise, continuous EEG or eye-tracking data can be used to detect signs of cognitive fatigue in equipment operators, enabling automated task switching or enforced rest periods before errors occur. Additionally, its integration with autonomous safety drones, exoskeletons, and digital worker avatars paves the way for next-generation, human-optimized construction sites. Such systems can assist in monitoring dangerous areas remotely, physically supporting workers performing repetitive lifting, or simulating worker responses to new site layouts in virtual environments.

Despite its contributions, this study is conceptual and has not been empirically tested. The lack of real-world implementation and validation presents a limitation, as the feasibility of integrating wearable sensors and AI-driven decision-making into construction workflows remains untested. Additionally, challenges such as data privacy, worker acceptance, cost constraints, and industry resistance to digital transformation must be addressed before widespread adoption.

Future research should focus on pilot studies and experimental validation of the framework in real construction environments. This could be done through testing the accuracy and reliability of physiological and cognitive monitoring, refining AI algorithms for predictive risk assessment, and evaluating the impact of adaptive task allocation on worker efficiency and safety. Further exploration into cybersecurity measures, ethical considerations, and regulatory frameworks will also be essential to ensure the responsible and appropriate deployment of HCDDTs. By bridging the gap between digital intelligence and human well-being, HCDDTs have the potential to reshape construction safety and workforce management, paving the way for smarter, more adaptive, and human-centric construction ecosystems.

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