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Digital Twins for Construction Projects—Developing a Risk Systematization Approach to Facilitate Anomaly Detection in Smart Buildings

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Abstract: This study aims to analyze and discuss the risks facing construction projects by reviewing some of the processes and procedures that address risks through the use of the digital twin technology. The paper studies generic risks and their treatment, and it develops a proposal for risk management systematization using the Digital Twin for Construction Projects approach, previously developed by the authors. It addresses how to classify risks so that the digital system is fed with the proper information and data, which is based on processing and analysis, to reach understandable decisions and overcome anomalies. The research reached a set of results, the most prominent of which is that the digital twin can be used to enhance risk management in construction projects through adapted techniques such as the ones proposed in the paper; namely, a risk treatment procedure and a custom risk matrix. In addition, risk management treated according to a digital approach helps to improve the prediction capabilities, and this helps human decision-makers to avoid potential unplanned costs and failures, and to maximize efficiency. The study also recommends new investigations in the field of safeguarding shared information and data to protect from intentional and accidental mismanagement in order to reach a comprehensive digital system.

Keywords: digital twins for construction projects; engineering project management; construction management; risk management

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1. Introduction

Construction projects are considered complex endeavors due to the volume of operations and activities that are involved, and they are also one of the types of projects most exposed to risks of all natures. When approaching this topic in the construction industry, one must be aware of the ramifications of implementing such an initiative that involves a considerable number of diverse stakeholders. For this reason, it is necessary to develop clear approaches to construction risks and analyze them in detail to identify the most prominent sources that cause anomalies and to find the appropriate solutions to assist management. Risk management is one of the most important tools that decision makers can employ to avoid exposure to failure in construction projects [1]. It aims to increase the probability of positive effects and reduce the probability of events that negatively affect the project activities [1]. When conducting activities under this paradigm, technical, operational and financial aspects must be considered simultaneously in order to deliver effective results and not unnecessarily burden the project team.

In this paper, we will define and analyze a taxonomy approach through which improved success can be achieved to avoid, diminish or completely remove risks within construction projects with the help of digital solutions. This goal is intended to address the current gap between the level of sophistication encountered in the managerial approach to risk, as it can be encountered in manufacturing or software development, and the capabilities of modern cyber-physical systems that can be employed on construction sites.

The main contribution proposed is based on a specific understanding of the conceptual approaches presented in the literature, including a self-developed model, and the tailoring of the risk management procedure to the needs of construction projects forecasted to be implemented with the help of digital twins.

It should be noted that the construction projects are surrounded by risks due to the scope and the complexity of the activities they include and, therefore, it is expected that risks will occur during implementation related to such aspects as: costs, time, human resource management, procurement and commissioning, contracts between project parties, occupational safety, negligence, etc. This negatively affects the achievement of the project objectives, so the risks must be accurately and timely evaluated to avoid project anomalies such as shutdown, failure or cost and time overruns.

The current paper analyzes the existing studies and scientific articles that discuss the applications of digital twins in managing construction projects and mitigating potential risks in order to achieve a comprehensive vision that guides the employment of digital twins for risk management in construction projects. Our previously published vision of digital twins for construction projects (DTCP) [2] is used as a thinking pattern upon which additional tools are integrated and calibrated for use. By linking the results of the previous studies and scientific articles and extending our approach, we sought to obtain a digital taxonomy through which construction projects can be managed better and operations management can be organized in a digital way that natively exhibits less risks and keeps one step ahead the ones that remain.

The process of identifying risks in construction projects can be considered one of the most difficult for the project managers due to the fact that the resulting delivery pressures usually supersede the need for risk management, although, in a paradoxical way, it is the very unmanaged risk that creates anomalous delays and cost issues. Various tools must be available for those involved to confront the potential risks and manage them in a way that ensures avoiding their occurrence/re-occurrence, such as providing the correct information about potential risks, making decisions on time and implementing them, and using alternative plans that ensure the achievement of project objectives within the prepared operational plan [3]. Additionally, the risk identification phase should be the trigger of external risk alleviation measures that the organization can employ, such as seeking better insurance, establishing cooperation networks or creating public-private partnerships. In each direction, it is critically important to follow up on the results of the risk identification stage during the implementation stage and to correct the solutions according to the concrete circumstances. When addressing these issues within digitalized construction projects, the DTCP approach mentioned above can be specifically focused on:

- Unexpected or changing environmental conditions;
- An imbalance in the workforce and the result of the employees;
- Accidents for human resources that cause bodily injury;
- Technical anomalies such as design, workmanship and technical issues;
- The occurrence of fire, earthquakes or approaching dangerous places;
- Cybersecurity and privacy issues related to the employment of digital technologies;
- Interfacing problems generated by integrating different solutions;
- Insufficient or conflicting solutions from the DTCP database;
- Intentional damage, theft or other crime inflicted by third parties.

While considering the issues above, a project management team should seek to customize the analysis to the actual situation at hand and to generate proportional solutions in terms of costs, operational efforts and improvement potential.

2. Methodology

The current study's methodology relied on the analysis and review of previous research, with the aim of linking the previous results and matching them to the existing technologies related to digital twins in order to reach an integrated system for construction and, in larger sense, industrial project management. The effort employed aims to combine simulation and the most common components of digital twins to provide a logical and technical framework that helps decision makers in their work related to the operations needed to manage the successive activities in the construction project stages.

In order to achieve this, the authors have performed a document analysis using the READ method, also used in other fields [4], that involves readying the materials, extracting the data, analyzing the data, and distilling the conclusions. This was complemented by the experience of the authors in managing technical projects in two different project management cultures, in the Middle East and Europe.

The documents collected and readied for processing were selected through the following criteria and work stages:

- The use of mostly recent studies and articles that were published during the past five years, 2017–2022, in order to keep pace with recent developments and generate a correct image about risk management and the role of digital twins in it;
- The selection was performed using the databases of ScienceDirect and Google Scholar, which cover a large variety of the scientific publications in this domain;
- In the searches, the study used keywords derived from our initial concept DTCP, namely "digital twins for construction projects", in various combinations.

A total of 55 of studies, articles and scientific papers in the same field were obtained, and they were used to extract the relevant information to reach a comprehensive perception about risks and their management in construction projects, and the possibilities of employing the digital twins. Subsequently, 32 works were selected and used in the thorough analysis and discussion process based on the content that aligns with the current study, informing the inferential discovery process, which was structured based on the authors' experiences in the field of project management.

The final step of the methodology performed the distillation of the know-how into new contributions that can support the development of DTCPs:

- The brainstorming of possible configurations of the technical systems needed to assist the project managers to conduct the risk management process;
- The aggregation of information into generic solutions that reflect the sum of previous experiences encountered in construction projects by the authors;
- The discussion of possible use cases in which the proposed approach can be implemented successfully to deliver a perceivable impact.

3. Results

3.1. Analysis of Digital Systems in Construction Management

The AEC (Architecture, Engineering and Construction) industry exhibits large scale complexity and is subject to a diversity of risks as it contains many interdependent activities. Thus, the use of smart technologies to mitigate and reduce risks and help manage operations and activities is both welcomed and necessary [5]. By employing virtual environment operations in all phases of construction project implementation (such as building information modeling, virtual/augmented reality assistance, advanced analytics based on sensor data, etc.), project management relies on large amounts of data to improve the performance and decision-making processes [6]. It should be noted that the employment of digital twins in the management of the construction industry increases productivity, saves time in addition to reducing costs, and contributes to enhanced risk and process management, which in turn improves the quality and safety [7]. Projects that depend on modern technology are becoming more energy efficient and rely on sustainable innovation through the use of technologies such as robots, artificial intelligence, nanotechnology, etc. [8].

The digital transformation in the construction industry reveals new principles and guidelines for exploiting previously untapped opportunities to improve the performance and quality and reduce the potential risks. In addition, these technologies, specific to the Industry 4.0 and Industry 5.0 approaches, also create niches for the use of big data within an Internet of Things approach that leads to advanced Building Information Modeling

(BIM) [9]. Most of the aspects of addressing risk in construction projects using such digital means are represented below (see Figure 1):

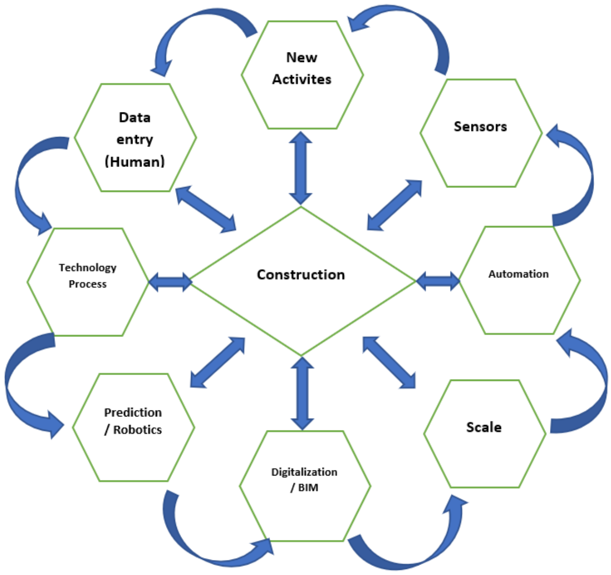

Figure 1. Systemic model for digital risk management in construction projects.

The digital twin is one of the modern technologies being used in many industries, providing support in modeling, simulation, analysis and prediction and improvement in performance [10]. The DTCP system consists of three basic components: the physical system, which includes the target AEC entity; the virtual system, which includes a computerized representation of the physical artefacts; and the medium, which represents the carrier environment and communication system, where the data are collected from the physical system and transferred to the virtual system for evaluation and timely decisions [2]. It should be noted that the digital twin combines the real-time and historical data as it supports analytics with a high degree of integration, which helps in rapid planning and predictions; thus, in addition to saving time and facilitating monitoring, it contributes to the process of sustainably improving the performance and removing anomalies over the lifetime of the project [11].

The technology used in the sensors depends on the data they carry regarding some measurements such as movement, angle, speed, temperature, pictures, videos; these data are extracted and converted into information for displaying on computer screens to understand the processes or for performing some algorithmic analysis and digital processing [12]. This information can be used for examining construction site situations (both consistent and divergent with the plans), analyzing the movement of workers and machines or examining equipment condition and taking preventive measures, which helps to achieve security and occupational safety.

3.2. Analysis of Risk Management in Construction through Digital Twins

Risk management in construction projects can be conducted through digital twins in a more efficient manner than before by addressing the potential risks for the construction project based on inputs that cover all of the basic processes and some previously elusive ones (e.g., worker-equipment interaction or real time procedural compliance). The existing literature classifies the risks faced by construction projects (see Figure 2) into five main categories that should be tackled in a coordinated manner [13]:

1. Construction Planning and Monitoring Management (CPMM).
2. Construction Security and Safety Management (CSSM).
3. Construction Quality Management (CQM).
4. Construction Human Resource Management (CHRM).

5. Construction Execution Activities Management (CEAM).

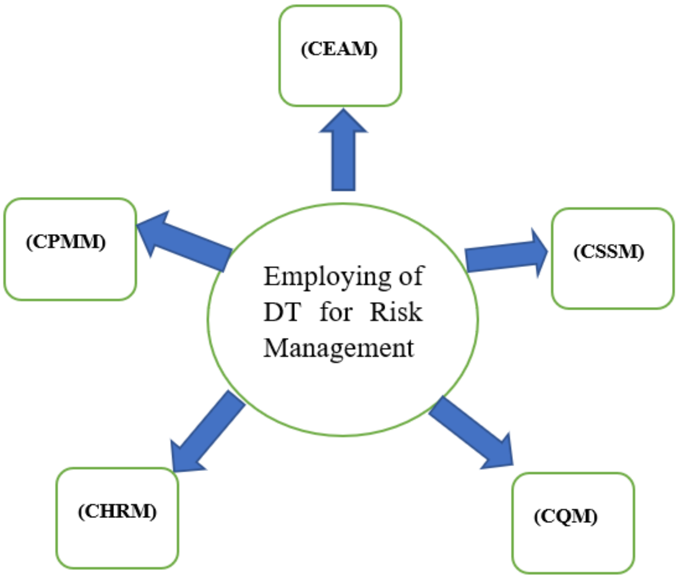

Figure 2. DT use for risk management according to [13] (figure adapted by the authors).

In the following, we have compared the above-presented model with the possibilities detected in the literature regarding the use of digitalization to achieve a full DTCP, the goal of our undertaking. The digital twin is used in the planning, design and control processes by entering the activities to be implemented and by tracking the activities to be achieved through timelines based on the work conducted and taking control measures to correct them, when necessary. The DTCP compares the reported implemented activities with the activities entered according to the plans that were included into the construction BIM. This helps to determine the real-time situation on the site, and then the digital twin provides reports, through which deviations or potential risks are detected, in addition to tracking construction costs. This process helps decision makers to take the necessary steps to avoid potential undesired effects and perform activities evaluation according to the prepared plans in a more effective manner, while also enabling advanced predictive and preventive capabilities for the project [14]. These data can also be used for planning future projects, while other companies can benefit from it in similar construction projects, especially regarding management and leadership aspects that involve high responsibility [15].

The DTCP can be used in occupational safety management at construction project sites by tracking worker movement, monitoring hazardous locations or preventing the use of unsafe materials based on specific analyses (what if or scenario-based). The system can monitor the operations through surveillance cameras and image analysis, allowing alarm systems to be triggered when the personnel are approaching dangerous sites or are failing to comply with safety procedures [16]. Through this mechanism, the digital twin can synchronize the behavior of the physical twin regarding movement control by extracting the three-dimensional skeleton model from videos and images and making comparisons with the predetermined movement paths [17–21].

One study [22] signals the availability of deep learning algorithms that can extract hidden information from the data and facilitate the realization of the concept of a digital twin, as it increases the performance and accuracy of personal protective equipment and helps security and safety managers to detect risks related to occupational security and safety of workers. An important aspect of implementing this is the proper integration of physical sensors and their virtual counterparts under specific frameworks [23]. This technology can also detect risky behaviors of workers that have the ability to generate accidents or incidents or impact the effectiveness on the job, such as alcohol or substance abuse and fatigue or absentmindedness [24].

The digital twin technology helps in quality management in construction projects by tracking resource consumption according to the technical specifications that are entered in the BIM, addressing, at the same time, the need to coordinate the construction site activities with the suppliers. The DTCP allows technical tests to inspect and diagnose materials and components, which provides speed and accuracy on site. In addition, it runs the necessary simulations to check the loads and weights for structural soundness, particularly in the construction bases and columns, which is a critical part of the technical construction risk evaluation. The digital twin allows flexibility in dealing with technical specifications and change orders, which enhances the overall quality approach and reduces the costs and potential quality risks, as this process helps in discovering potential problems in the early stages [25].

The digital twin technology can help in tracking resource management and linking between the construction project site and the office through secure data transmission, keeping track of the financial items according to the financial plan prepared and stored in the BIM [26]. This will help in calculating the expenditure for each budget item, for example, worker salaries, raw materials, fixed and overhead costs etc., and can also be useful during the active life of the building [27]. The necessary functions could include a comparison with the tables entered in the system, calculating costs and allocations, monitoring financial flows, as well as operational requests [28] per the project requirements at each stage through a live data flow that also monitors the status of the work. The tracking of the expenses, schedules and supplies helps to understand the progress of the project activities [29]. DTCP also assists decision makers in making estimates about resource availability and calculating the time to completion, which helps in time and deadline management, in addition to recording the inputs and outputs of resources and managing logistics [15,30]. Additionally, it is possible to expand the scope of DTCP with blockchain technology, which can aid in establishing cybersecurity measures and in achieving compliance management and environmental management tasks [31].

The process of implementing construction projects is a complex one that requires constant follow-up and control in terms of tracking the activity versus the prepared plans, and the digital twin can perform these tasks faster than its human counterparts [2], while also increasing productivity, as results are achieved by collecting the data from the work site and then using it in accomplishing tasks without anomalies. These beneficial aspects are limited by the current intricacies of self-developed systems that combine various technologies and the lack of standardization in data collection and processing [32]. Ensuring the achievement of project objectives, avoiding potential risks and assisting decision makers are critical features for digital twins to be implemented in this sector. The digital replica collects data through sensors and other devices and then compares them to the stored data, including its own history, within a dynamic and interlocking process, providing the possibility for future predictions by use of the proper analytics and algorithms [33]. However, the further development of DTCP towards artificial intelligence solutions compatible with human team members requires considerable efforts in both technical capabilities and project organization [34].

4. Discussion

The digital twin technology provides a wide space for engineers using flexible approaches for improvement and development to reach high quality results, while the beneficiary can ask for the necessary modifications. It can be understood that, in addition to the simulation and virtual modeling of the activities and components, the DTCP can increase the performance and accuracy at this stage by removing uncertainty [2,33]. Digitalization supports real-time data sharing, which fosters the integration and coordination process of all project tasks by updating the data quickly and sequentially, as the development process takes place within a detailed virtual environment of the real entity, whose lifecycle starts before the project implementation begins [33]. In addition, the monitoring, evaluation and control features ensure accurate and high-quality measurement and assessment processes during the actual implementation of the construction projects.

The DTCP approach provides tools through which improvement processes can be implemented for maintenance and operation, thus reducing costs and providing decision makers with risk assessments in situations of uncertainty [35]. Forecasting the potential problems can also be conducted through intelligent operating techniques that work based on data analysis from multiple sources, helping in control and maintenance [2]. Our previous study indicated the usefulness of the digital twin for managing construction related activities, from the project level to site level. In the current undertaking, we also propose that it can have a significant beneficial impact in reducing the potential risks that may face the implementation of project activities through the digitalization of operations within its three stages of complexity [2]: BIM (Phase 1), Control techniques (Stage 2) and Digital twin customized solutions (Stage3).

The following flowchart (Figure 3) illustrates the process of monitoring the work site through digital instruments and distributed remote sensors, which track the situation in the work environment for enabling decisions to be made by human managers or automated digital systems. The flowchart shows two variants: the first is a steady state situation (safe condition) and the second process is an anomaly treatment scenario (unsafe condition) based on the conceptualized risk systematization:

1. *Safe condition:* the process proceeds normally by sending the data from the physical environment to the virtual system and then analyzing and comparing it with the stored data according to the safety and security procedures provided.
2. *Unsafe condition:* the physical system is tracked, and the data is sent through the sensors to the virtual system and then comparisons are made between the physical state and the stored data to determine the proper project intervention.
3. *Warning and recording:* gives advanced notice about the risks and records them to start the verification procedures; the warning can be through sound or light signals, messages on the display screens and other methods (e.g., mobile alerts), and then the process of recording the risk is conducted by the system to supply the process of preventive interventions in the future.
4. *Define the risks:* the risks are identified in the system so that it can, through the tracking process, make a correct determination and classification; the risks are revealed based on the information provided in the system about the definition of risks, while the decision makers are provided with flexible and understandable reports that reflect the state of the work environment and the expected issues.
5. *Risk analysis:* is divided into two parts, probability analysis and impact analysis, usually in the form of a Risk Matrix (see Table 1 (A) below for a consecrated version of this matrix).
6. *Probability analysis:* measures the degree of plausibility of an event being triggered that can influence the outcome of the construction project.
7. *Impact analysis*: measures the degree of deviation from the desired results brought upon by the consequences of the unwanted event.
8. *Determining the level of risk:* based on the criteria that are entered according to the risk matrix, where the degrees and levels of risks are defined, the system classifies the risks using the bidimensional scale and previous history (see Table 1B below for a proposed adjusted matrix that uses the DTCP concept as it was expanded in this paper, to incorporate the features of digital twins and eliminate redundant or excess work while facilitating improved anomaly treatment).
9. *Risk assessment:* the system, based on the ratings and levels defined above, evaluates the risks as Extreme, High, Medium, Low and Very low, and determines guidelines for intervention.
10. *Risk mitigation and intervention:* The DTCP is operated in the detection and examination of anomalies, and then the risks are characterized and evaluated based on the degrees and levels proposed. If there is no risk, the process can be accomplished as is, but if

the risk requires intervention, then security, safety and operational measures are taken to mitigate it and the process is entered into the system again to conduct rechecking. Based on our previous experience in the AEC sector, we recommend mitigation to follow the guidelines comprised in Table 1 (B), by addressing the probability of the hazard to materialize as the impact is usually difficult to reduce. The goal is to use the DTCP to reduce occurrences in such a way that the overall risk assessment falls mostly in the area of low and very low risks. The means to accomplish these reductions depend on the structure, context and contents of each construction project.

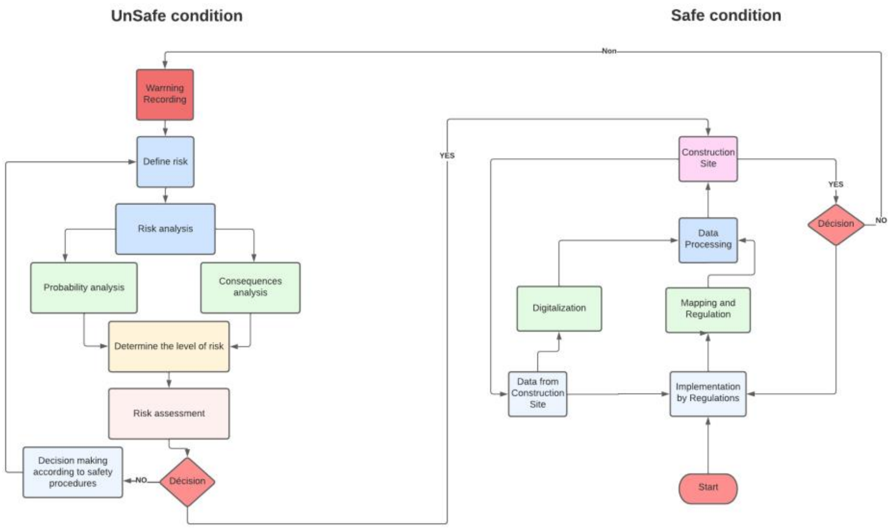

Figure 3. Risk management flowchart using DTCP to handle anomalies.

Table 1. Original risk assessment (**A**) and recommended improvements (**B**).

Variant—A			**Impact**		
Probability	**Extreme**	**High**	**Medium**	**Low**	**Very low**
Extreme	Extreme	Extreme	High	Medium	Medium
High	Extreme	Extreme	High	Medium	Low
Medium	High	High	Medium	Low	Low
Low	High	Medium	Medium	Low	Very low
Very low	Medium	Medium	Low	Low	Very low
Risk assess.	**Extreme**	**High**	**Medium**	**Low**	**Very low**
Variant—B			**Impact**		
Probability	**Extreme**	**High**	**Medium**	**Low**	**Very low**
Extreme	High	High	Medium	Low	Low
High	High	Medium	Medium	Low	Low
Medium	Medium	Low	Low	Low	Very low
Low	Medium	Low	Low	Very low	Very low
Very low	Low	Low	Very low	Very low	Very low
Risk assess.	**Medium**	**Low**	**L ow**	**Very low**	**Very low**

Through the analysis conducted above, our study discussed a set of articles and contributions that can be employed to make the use of the digital twins in managing construction risks more concrete, completing the impact of our proposed DTCP approach. The physical system is chronically deficient in the AEC industry and, most of the time, this is attributed to a lack of awareness and information. Risk management using digital twins can help decision makers take actions to achieve the project's goals concerning time and resource costs, the biggest threats in the field. As such, our work recommends that researchers and practitioners pay attention to the possibilities of development and improvement around the use of digital twins in risk management in construction projects by reducing the frequency of their occurrence to within acceptable limits, according to a predetermined intervention scheme.

The digital twins help protect workers and secure occupational safety from the potential failures that may occur during the implementation of project activities [36]. In this context, the study also recommends to approach construction risk management with a focus on the personnel involved in the activities, thus requiring more upfront investment in atypical sensors and devices than a manufacturing counterpart (e.g., cameras, thermal vision, sound meters, pollutant detectors, etc.).

The option of using the digital twin for risk management is one of the expected transformations in the field of AEC industries as it can address various problems in construction projects, including occupational safety for workers, engineering plans implementation, time management, cost management and other logistical, administrative and technical issues. Researchers and information security specialists should also delve into the study of data transmission protection and information security in the digital twin, as this constitutes a new class of risk and is a possible drawback of the proposed solution, which is little understood in the field of construction management or engineering project management in general.

5. Conclusions

With the continuous increase in the development of the economy and the employment of digitalization, studies have shown that the world today is moving towards the use of modern technologies in most areas. This is expected to include all aspects of industry, business, healthcare and other domains, with a desire to improve product performance, expedite services and generate quality of life. The digital twin has become an important component in all fields, including the AEC industries, and it should be noted that the digital twin has many advantages in reducing risks, as has been proven in other fields, such as medical interventions. From an economic and technical perspective, it is able to analyze and detect risks and provide an ideal model in taxonomic systematization and help decision makers take actions to avoid problems and unwanted consequences.

The current study focused on a guided review of the literature, through which an in-depth insight was gained about the risks facing construction projects and the connection of the concept of digital twin to risk management in construction. In this way, it helps close the identified research gap, providing specialists with a structured way of developing digital twins for construction projects (DTCP) that can benefit research and practical initiatives. Comprehensive solutions that include managing all risks faced by construction projects using digital twins, as well as detailed studies and research, are still in the process of development, seeking to link common frameworks within a functional approach. This paper presented a straightforward conceptual model to achieve this goal, which could contribute to enhancing the access of more companies to this type of development.

The analysis mode proposed within the article brings more clarification to the follow-up activities and what should happen when a fully deployed virtual copy assists the project implementation. In the event of a risk, the system sends an alert and then identifies and investigates the risks to be addressed. It is worth noting that the model can provide valuable assistance within the compliance and maintenance process of occupational health and safety issues and provides contributions through which the impacts and costs can be reduced, and the quality can be improved. In addition, it helps researchers in developing a more robust digital system based on a structured taxonomy. Through this model, the authors propose a way in which the project activities could be further automated by the deployment of machine learning algorithms and artificial intelligence solutions, which are a natural extension when implementing digital twins in other areas, such as smart manufacturing. Taking into account the particularities of the proposed concept, the authors also put forward a dedicated evaluation procedure in the form of a simplified flowchart and a recommendation for a risk matrix, with the assessment levels reduced by the use of the digital twins.

Finally, after conducting the study, it was determined that there is a need to allocate a set of resources related to electronic data protection and enhanced information security as a new type of safeguard that is specific to digital systems and virtual worlds. Moreover, this should be integrated from the start with the operational functions of the digital twins to minimize possible losses. Future research should further analyze the need to overcome various human machine interface issues, as well as the psychological impact of job automation and regulatory compliance, especially in the case of tasks that require mandatory human intervention. The main limitations of the research are related to the narrow domain of studies that can be aligned with the goals of the DTCP concept through analysis and the use of individualized experiences for scrutiny, both of which will be addressed in future contributions.

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References

1. Akrouche, J.; Sallak, M.; Châtelet, E.; Abdallah, F.; Chehade, H.H. Methodology for the Assessment of Imprecise Multi-State System Availability. *Mathematics* **2022**, *10*, 150. [CrossRef]
2. Alhammadi, S.A.; Tayeh, B.; Alaloul, W.; Salem, T. Risk Management Strategies in Construction Organizations. *Open Civ. Eng. J.* **2021**, *15*, 406–413. [CrossRef]
3. Boje, C.; Guerriero, A.; Kubicki, S.; Rezgui, Y. Towards a semantic Construction Digital Twin: Directions for future research. *Autom. Constr.* **2020**, *114*, 103179. [CrossRef]
4. Bortolini, R.; Rodrigues, R.; Alavi, H.; Dalla Vecchia, L.F.; Forcada, N. Digital Twins' Applications for Building Energy Efficiency: A Review. *Energies* **2022**, *15*, 7002. [CrossRef]
5. Dalglish, S.L.; Khalid, H.; McMahon, S.A. Document analysis in health policy research: The READ approach. *Health Policy Plan.* **2020**, *35*, 1424–1431. [CrossRef] [PubMed]
6. Deng, M.; Menassa, C.C.; Kamat, V.R. From BIM to digital twins: A systematic review of the evolution of intelligent building representations in the AEC-FM industry. *J. Inf. Technol. Constr.* **2021**, *26*, 58–83. [CrossRef]
7. Deria, A.; Ghannad, P.; Lee, Y.-C. Integrating AI in an Audio-Based Digital Twin for Autonomous Management of Roadway Construction. In *Construction Research Congress*; ASCE: Arlington, VA, USA, 2022; pp. 530–540.
8. Draghici, A.; Dursun, S.; Bașol, O.; Boatca, M.E.; Gaureanu, A. The Mediating Role of Safety Climate in the Relationship between Transformational Safety Leadership and Safe Behavior—The Case of Two Companies in Turkey and Romania. *Sustainability* **2022**, *14*, 8464. [CrossRef]
9. Fang, D.; Huang, Y.; Guo, H.; Lim, H.W. LCB approach for construction safety. *Saf. Sci.* **2020**, *128*, 104761. [CrossRef]
10. Fang, Q.; Li, H.; Luo, X.; Ding, L.; Luo, H.; Li, C. Computer vision aided inspection on falling prevention measures for steeplejacks in an aerial environment. *Autom. Constr.* **2018**, *93*, 148–164. [CrossRef]
11. Fang, W.; Zhong, B.; Zhao, n.; Love, P.E.; Luo, H.; Xue, J.; Xu, S. A deep learning-based approach for mitigating falls from height with computer vision: Convolutional neural network. *Adv. Eng. Inform.* **2019**, *39*, 170–177. [CrossRef]
12. Gatti, U.C.; Schneider, S.; Migliaccio, G.C. Physiological condition monitoring of construction workers. *Autom. Constr.* **2014**, *44*, 227–233. [CrossRef]
13. Gattullo, M.; Scurati, G.W.; Fiorentino, M.; Uva, A.E.; Ferrise, F.; Bordegoni, M. Towards augmented reality manuals for industry. *Robot. Comput.-Integr. Manuf.* **2019**, *56*, 276–286. [CrossRef]
14. Greif, T.; Stein, N.; Flath, C.M. Peeking into the void: Digital twins for construction site logistics. *Comput. Ind.* **2020**, *121*, 103264. [CrossRef]
15. Guo, Z.; Zhang, Y.; Zhao, X.; Song, X. CPS-Based Self-Adaptive Collaborative Control for Smart Production-Logistics System. *IEEE Trans. Cybern.* **2020**, *51*, 188–198. [CrossRef] [PubMed]
16. Han, S.; Lee, S. A vision-based motion capture and recognition framework for behavior-based safety management. *Autom. Constr.* **2013**, *35*, 131–141. [CrossRef]

17. Hongling, G.; Yu, Y.; Ding, Q.; Skitmore, M. Image-and-Skeleton-Based Parameterized Approach to Real-Time Identification of Construction Workers' Unsafe Behaviors. *J. Constr. Eng. Manag.* **2018**, *144*, 04018042.
18. Hou, L.; Wu, S.; Zhang, G.; Tan, Y.; Wang, X. Literature Review of Digital Twins Applications in Construction Workforce Safety. *Appl. Sci.* **2020**, *11*, 339. [CrossRef]
19. Lee, J.; Azamfar, M.; Singh, J.; Siahpour, S. Integration of digital twin and deep learning in cyber-physical systems: Towards smart manufacturing. *IET Collab. Intell. Manuf.* **2020**, *2*, 34–36. [CrossRef]
20. Li, H.; Li, X.; Luo, X.; Sibert, J. Investigation of the causality patterns of non-helmet use behavior of construction workers. *Autom. Constr.* **2017**, *80*, 95–103. [CrossRef]
21. Li, M.; Lu, Q.; Bai, S.; Zhang, M.; Tian, H.; Qin, L. Digital twin-driven virtual sensor approach for safe construction operations of trailing suction hopper dredger. *Autom. Constr.* **2021**, *132*, 103961. [CrossRef]
22. Opoku, D.-G.J.; Perera, S.; Osei-Kyei, R.; Rashidi, M. Digital twin application in the construction industry: A literature review. *J. Build. Eng.* **2021**, *40*, 102726. [CrossRef]
23. Ozturk, G.B. Digital Twin Research in the AECO-FM Industry. *J. Build. Eng.* **2021**, *40*, 102730. [CrossRef]
24. Park, M.W.; Elsafty, N.; Zhu, Z. Hardhat-Wearing Detection for Enhancing On-Site Safety of Construction Workers. *J. Constr. Eng. Manag.* **2015**, *141*, 04015024. [CrossRef]
25. Patias, I.P. Engineering and construction project management in the digital twin era. In Proceedings of the CBU International Conference on Innovations in Science and Education 2020 (Natural Sciences and ICT), Prague, Czech Republic, 18–20 March 2020; CBU Research Institute: Prague, Czech Republic, 2020; pp. 85–90.
26. Qi, Q.; Tao, F.; Zuo, Y.; Zhao, D. Digital Twin Service towards Smart Manufacturing. *Proceedia CIRP* **2018**, *72*, 237–242. [CrossRef]
27. Rafsanjani, H.N.; Nabizadeh, A.H. Towards digital architecture, engineering, and construction (AEC) industry through virtual design and construction (VDC) and digital twin. *Energy Built Environ.* **2023**, *4*, 169–178. [CrossRef]
28. Reja, V.K.; Varghese, K. Digital Twin Applications for Construction Project Management. In Proceedings of the Joint Indo-Japanese Smart City Symposium (IJSCS-2022), Chennai, India, 24–25 March 2022.
29. Saco, Z.M.; Burhan, A.M. Construction Risk Management. *J. Eng.* **2006**, *12*, 373–378. Available online: https://www.researchgate.net/publication/330638915_CONSTRUCTION_RISK_MANAGEMENT (accessed on 9 November 2022).
30. Salem, T.; Dragomir, M. Options for and Challenges of Employing Digital Twins in construction Management. *Appl. Sci.* **2022**, *12*, 2928. [CrossRef]
31. Shahzad, M.; Shafiq, M.T.; Douglas, D.; Kassem, M. Digital Twins in Built Environments: An Investigation of the Characteristics, Applications, and Challenges. *Buildings* **2022**, *12*, 120. [CrossRef]
32. Tao, F.; Qi, Q.; Wang, L.; Nee, A. Digital Twins and Cyber–Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison. *Engineering* **2019**, *5*, 653–661. [CrossRef]
33. Tayeh, B.; Salem, T.; Aisheh, Y.I.; Alaloul, W. Risk Factors Affecting the Performance of Construction Projects in Gaza Strip. *Open Civ. Eng. J.* **2020**, *14*, 94–104. [CrossRef]
34. Teisserenc, B.; Sepasgozar, S. Adoption of Blockchain Technology through Digital Twins in the Construction Industry 4.0: A PESTELS Approach. *Buildgings* **2021**, *11*, 670. [CrossRef]
35. Wang, W.; Guo, H.; Li, X.; Tang, S.; Li, Y.; Xie, L.; Lv, Z. BIM Information Integration Based VR Modeling in Digital Twins in Industry 5.0. *J. Ind. Inf. Integr.* **2022**, *28*, 100351. [CrossRef]
36. Zhang, P.; Li, N.; Jiang, Z.; Fang, D.; Anumba, C.J. An agent-based modeling approach for understanding the effect of worker-management interactions on construction workers' safety-related behaviors. *Autom. Constr.* **2019**, *97*, 29–43. [CrossRef]