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Transitioning from BIM to Digital Twin to Metaverse

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1 From BIM to Digital Twin

In the Architecture, Engineering, and Construction (AEC) sector, Building Information Modelling (BIM) has been at the forefront of the digital revolution. BIM makes it easier to create detailed digital models that capture a building's functional and physical attributes. Throughout the project lifecycle, these models allow stakeholders to exchange insights and make better-informed decisions. But as company demands have increased, likewise has the demand for more advanced digital tools (Singh, 2019; Shahzad et al., 2022; Doherty, 2023; Azhar, 2011; Shehata et al., 2024).

Digital Twin is a real-time, dynamic digital clone of a system, process, or physical item. Digital Twins combine real-time data streams from sensors implanted in physical assets, in contrast to BIM, which primarily concentrates on static models, enabling continuous monitoring, simulation, and analysis. Digital twins have been used in a variety of ways, providing unprecedented opportunities to improve decision-making and operational effectiveness. For instance, DTs allow for real-time energy usage monitoring, maintenance requirement prediction, and space optimization in smart buildings. Facility managers may reduce downtime and increase the lifespan of building systems by using distributed testing (DT) to identify and prevent possible problems before they arise by modelling various scenarios (Zhang et al., 2020).

Digital Twins provides an entire perspective of assets in infrastructure management, enabling improved operating, maintenance, and planning methods. The quality and dependability of these digital replicas are enhanced by the integration of DTs with current BIM models, which makes them essential tools for contemporary asset management. Digital Twin adoption in the AEC sector is not without obstacles, despite its benefits. The primary hurdle is the lack of compatibility across various software platforms and systems. To be valid, DTs need to work well with other digital tools, IoT devices, and current BIM models—many of which run on different platforms.

Privacy and data security are also major issues. Since Digital Twins depend on real-time data, it is critical to preserve sensitive data. The industry now lacks standardization, which is made necessary by the complexity of digital systems growing (Stergiou et al., 2023).

2 The role of Metaverse in the future of built environment

The next frontier of digital innovation is the Metaverse, an idea that has gained a lot of traction recently. It is a 3D virtual world that combines artificial intelligence (AI), augmented

reality (AR), virtual reality (VR), and Internet of Things (IoT) technology to allow users to interact with digital items and settings in real-time. The Metaverse offers a new level of interaction, design, and management within the built environment of the AEC industry (Chang et al., 2024; Uddin et al., 2024).

The fields of facility management and construction represent some of the most exciting uses of the Metaverse in AEC. The Metaverse provides a completely immersive virtual environment for architects, engineers, and clients to work in all through the design process. This dramatically lowers the possibility of mistakes and rework by enabling real-time design reviews, virtual site inspections, and the flexibility to make changes as needed.

In order to provide managers with a risk-free virtual environment for performing inspections, monitoring systems, and training personnel, facility managers may use the Metaverse to construct virtual duplicates of actual structures. The Metaverse offers a complete platform for controlling a building's lifetime, from construction to deconstruction, by combining data from Digital Twins and BIM. The AEC sector stands to gain a great deal from Metaverse's integration, including more interaction, better stakeholder involvement, and more effective project delivery. Users may experience and engage with complicated systems in a controlled virtual environment thanks to the immersive nature of the Metaverse, which makes it an excellent tool for training and simulation.

On the other hand, there are a number of obstacles to Metaverse's broad adoption. A completely immersive Metaverse requires a significant technical infrastructure, which includes fast internet, cutting-edge VR/AR tools, and reliable data management systems. It is also essential to address concerns about privacy, data security, and the moral ramifications of developing and using virtual environments (Heruatmadja and Ramadhan, 2024).

3 Integrating BIM, Digital Twin, and the Metaverse

Although BIM, Digital Twins, and the Metaverse have different advantages, their integrated potential is most significant when used together. The AEC sector may attain a level of operational efficiency and innovation that was previously considered to be unachievable by combining the extensive modelling skills of BIM with the real-time data and simulation capability of Digital Twins and the immersive environments of the Metaverse. For example, a project may start with a BIM model for the structure's design and planning. A Digital Twin could be created while construction moves on to track and improve the building's performance. Lastly, the structure might be managed by the Metaverse once it has been constructed, offering a virtual platform for continuing training, upkeep, and upgrades.

4 Mainstream trends of relevant literature

Recently, there was a notable rise in production in the relevant literature about the evolution from BIM, DTs, to the Metaverse. The Scopus database search was used, searching about "BIM" AND "Digital Twin" AND "Metaverse" which restricted the results to final journal articles written in English and related to architectural design, turned up over 3,597 documents published in high-impact journals. This implies that while the subject has received a great deal of attention in the academic community. Figures 1, 2 generated using VOS viewer, illustrate the relationships between terms and concepts within a scientific or technological domain over time. The network visualization shows the development of BIM to Digital Twin to Metaverse in the construction industry. BIM is critical to managing digital representations of buildings, with connections to blockchain and information management. Digital Twins, on the other hand, enhance BIM capabilities by integrating real-time data from the physical world via sensors and the Internet of Things (IoT), enabling dynamic updates and real-time decisions. These interactive simulations provide insights for predictive maintenance, sustainability and performance optimization.

Also, distinguishing between Digital Twins, AR, VR and XR, the Metaverse emerges as the next major advancement in digital settings. In order to enable stakeholders to engage with models in real-time across borders and devices, Metaverse expands on Digital Twins by providing immersive, user-interactive settings. As a result of this change, there are potential wider uses outside design and construction, such as human-computer interaction, education, and sustainable development. In order to create immersive environments, smart cities, and the digital transformation of industries, it is imperative that we go beyond BIM to Digital Twins and Metaverse. Besides all of these objectives, there are some other aspects—like standardized procedures, data security and privacy, and ethical and social implications—remain largely unexplored.

There have been several attempts to discuss the transition from BIM to Digital Twin to Metaverse. The development of Digital Twins from BIM in the framework of the building life cycle had been systematically reviewed by Deng et al. (2021); this study attracted other researchers. The citation of this study until now reached 215 citations, with a total citation per year equal to 53.75. This study emphasizes the shift from BIM to Digital Twin to virtual representations of the built environment that are dynamic and real-time, providing real-time data synchronization, continuous monitoring, and operational insights. This technology might be developed further by the Metaverse, opening up interactive virtual places for stakeholder participation (Deng et al., 2021).

Another study discussed the adoption of BIM in the AEC sector, with an emphasis on project management and construction management. By integrating real-time data with IoT systems for dynamic monitoring, it establishes the foundation for Digital Twin applications (Chen et al., 2023). With the development of BIM, more complex digital environments are made possible, which opens the door to Digital Twin technologies and the Metaverse. Other researchers were drawn to this work. This study has received 112 citations, and 14.00 for an annual total citation (Olawumi et al., 2017). Additionally, Baghalzadeh Shishehgarkhaneh et al. (2022) highlighted the importance of BIM in the building industry, as its function in static digital representations. It also discusses how Digital Twins and the IoT are integrated to provide real-time data flow and link actual assets with virtual models. This study has also a high citation impact that reaches 96 citations, and 32.00 for an annual total citation (Baghalzadeh Shishehgarkhaneh et al., 2022).

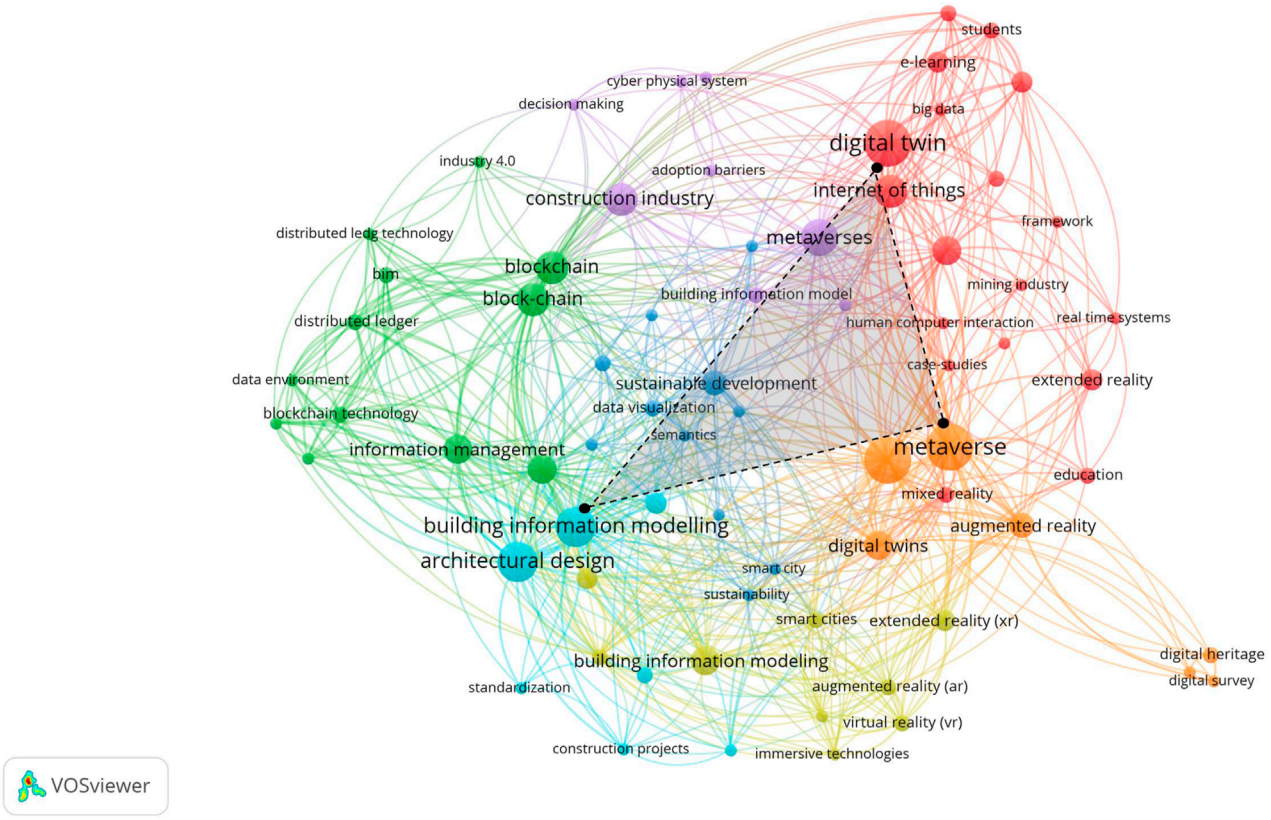

FIGURE 1
Co-occurrence keywords network. Source: the authors, by VOSviewer.

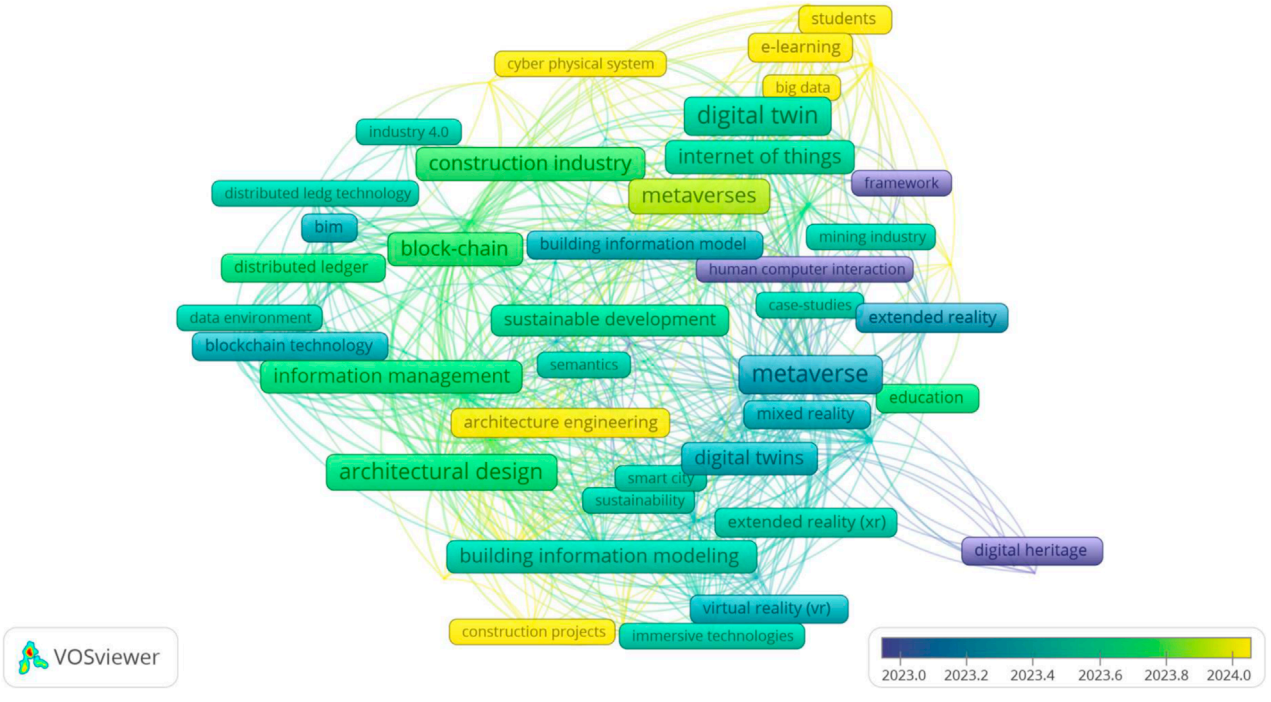

FIGURE 2
Trending topics and future research potentials. Source: the authors, by VOSviewer.

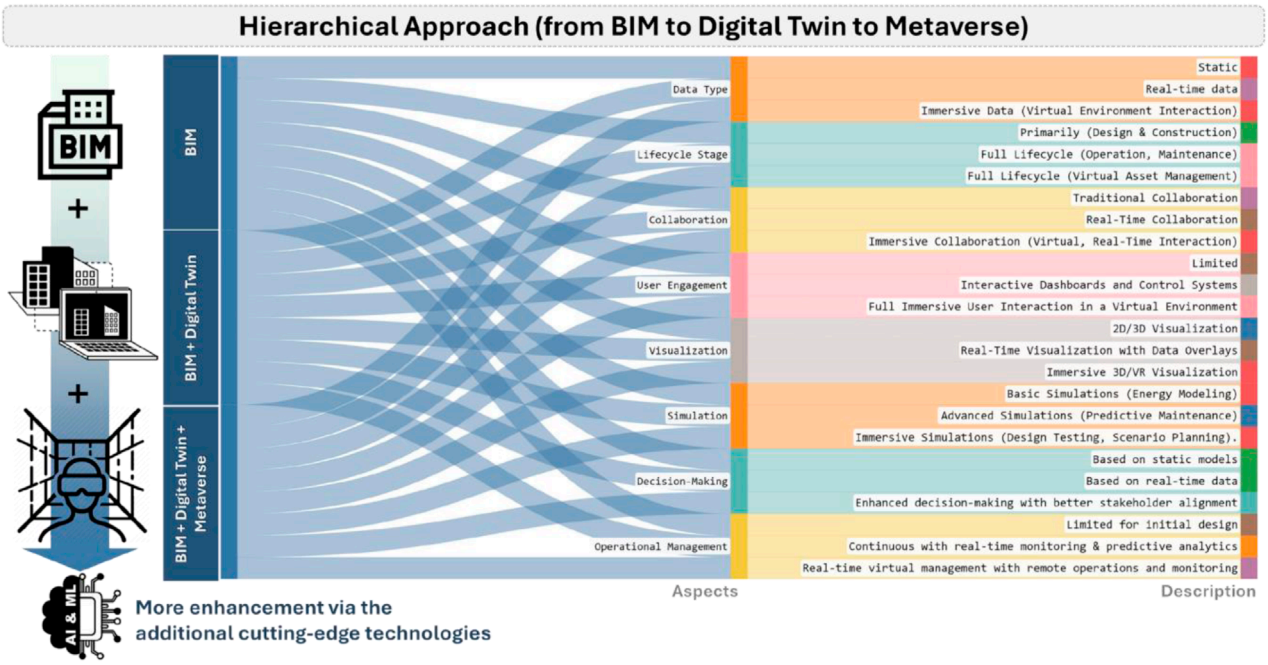

FIGURE 3
The hierarchical approach impacts several aspects of AEC. Source: the authors.

Managing the full building lifecycle was the main topic of discussion in the research of Su et al. (2023)-with 26 citations-, which included the evolution of Digital Twin technologies. Enhancing simulation, prediction, and control, it demonstrated the progression from BIM to Digital Twin. Also, mentioned the Metaverse as future research (Su et al., 2023). Furthermore, some studies extents to cover the evolution of transition the construction industry to the Metaverse based on BIM and Digital Twin as a foundation. Khan et al., (2021) demonstrated that the integration of BIM with immersive technologies such as VR, AR, and MR in the AEC sector through improving design, construction planning, and monitoring. Real-time synchronization between the digital and physical worlds is made possible by Digital Twins. Virtual worlds that are interactive are offered via the Metaverse (Khan et al., 2021).

This study has garnered attention from other researchers, accumulating 75 citations to date, with an average of 18.75 citations per year. Moreover, Markopoulos et al. (2024) elaborated the integration of Digital Twin and Metaverse into the building sector based on human-centric approach to BIM and sustainable development goals (SDGs) implementation. Mourtzis, (2023) explored the role of Digital Twin in the industrial Metaverse as a foundational technology for Industry 4.0 and 5.0, proposing Metaverse-enabled platforms to enhance interactions between operators and cyber-physical systems (Mourtzis, 2023).

In addition, some paper discussed the adoption of BIM, Digital Twin, and Metaverse, particularly in heritage sector by proposing a workflow that allows users to use virtual twins for historical building and heritage building modeling (H-BIM) (Cruz Franco et al., 2022; Guo et al., 2024). Also, Lv et al. (2022) enhanced the idea of Digital Twins to extent from the building scale to the urban scale "city", reviewing their impact and the role of digitalization in urban management and development, based on the historical progression of digital cities (DCs), explores the potential of the Metaverse in enhancing the interaction between the physical and digital worlds, ultimately providing valuable insights for improving urban governance and operational efficiency (Lv et al., 2022). Also, Domenico, (2023) discussed the urban scale to represent a virtual environment where the interaction between human and digital models occurs in architectural and urban settings (Domenico, 2023). Overall, BIM, Digital Twin, and the Metaverse all offer some important combinatory benefits they can enable in construction industry efficiency, productivity, decision-making, and collaboration. Most importantly, they become the guiding light toward more creative and sustainable approaches within a connected digital framework.

From the perspective of the hierarchical approach (from BIM to Digital Twin to Metaverse), as shown in Figure 1, BIM can be considered the starting point for construction projects. Also, the integration with BIM and Digital Twins can provide data, analytics, simulations, visualisation, automation, and predictions. Additionally, Metaverse can provide several key benefits to the AEC industry, offering enhanced results in aspects of schedule, cost, quality, and safety. Metaverse enables the efficient production, supervision, and sharing of data among stakeholders (Hadavi and Alizadehsalehi, 2024; Alizadehsalehi and Yitmen, 2021).

Looking forward, a number of developments and trends are probably going to influence how BIM, Digital Twins, and the Metaverse develop in the AEC sector. The capabilities of

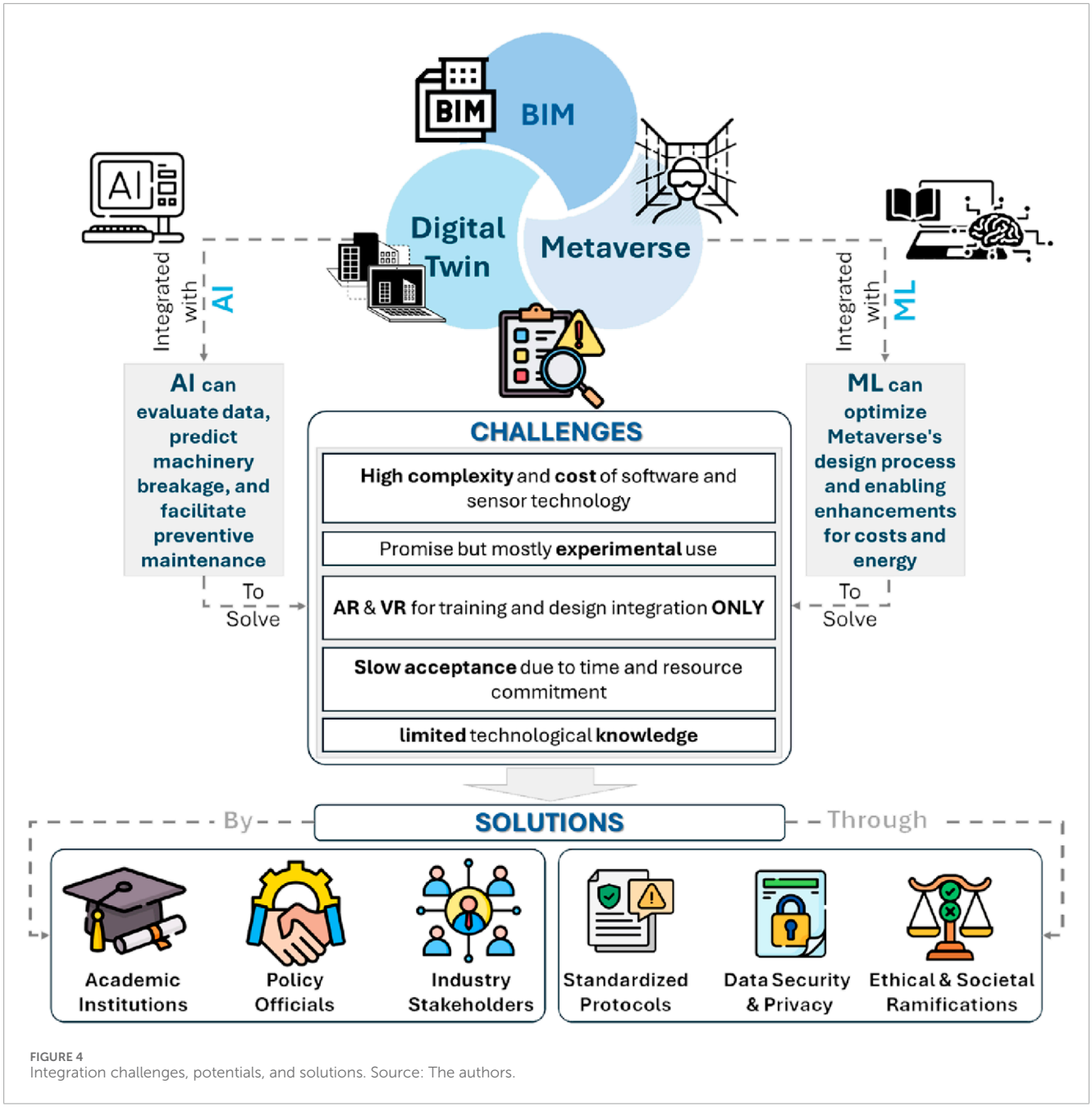

FIGURE 4
Integration challenges, potentials, and solutions. Source: The authors.

these technologies will be significantly enhanced by artificial intelligence (AI) and machine learning (ML), especially in areas like automation, decision assistance, and predictive analytics. Enhancing digital system intelligence and interoperability will also need the inclusion of semantic technologies. These technologies will aid in bridging the gap between the physical and digital worlds by allowing more intuitive interactions between people and machines, increasing the built environment's responsiveness and adaptability to changing demands. In addition to AI, other disruptive technologies, including IoT, AR, VR, blockchain, and generative design, have the potential to speed up the transformation of AEC industry, thereby moving it to unknown heights of efficacy (efficiency), sustainability, and innovation in all building, designing construction and operating stages. McKinsey and Company estimates that by these technologies, as well as improvement of productivity the global construction industry could unlock up to $1.6 trillion annually. This has the potential to redefine both our lifestyles and architecture (Filipe et al., 2017).

5 Discussion

The AEC sector is seeing a turning point with the integration of BIM, Digital Twins, and the Metaverse; nevertheless, the shift is not without its challenges, as presented in Figure 2.

Industry is now struggling to incorporate new technologies into processes that are already in place. While BIM has become commonplace, Digital Twin adoption is still in its early stages. This is sometimes due to the high price of the complex software required to run these systems and the necessary sensor technology.

Furthermore, although the Metaverse holds significant promise, its use in the AEC industry is still mostly experimental. While numerous businesses are experimenting with augmented and virtual realities (AR/VR) for training and design, a complete integration of these technologies into everyday operations is still a way off. This slow pace of acceptance may be attributed, in part, to the substantial time and resource commitment needed. Another reason is that these cutting-edge technologies come with a high learning curve, which may be a barrier for businesses with little technological know-how.

On the other hand, integrating AI and machine learning with Digital Twins and the Metaverse is one of the most promising areas of research. These innovations have the potential to significantly improve Digital Twins' predictive power, resulting in more precise simulations and improved decision-making. AI may be used, for example, to evaluate data from a Digital Twin and forecast when a piece of machinery is likely to break, enabling preventive maintenance that could save money and effort.

Algorithms for machine learning might also be used to optimize Metaverse's design process. These algorithms might provide recommendations for design enhancements that save costs or increase energy efficiency by examining data from earlier projects. In this sense, the Metaverse has the potential to develop into a potent platform for innovation and optimization rather than only a visualization tool.

There are a lot of chances for research and development as the AEC sector moves towards being entirely digital. The creation of standardized protocols for data interchange across Digital Twins, BIM, and the Metaverse is one important topic (Figure 3). At the moment, a significant obstacle to the integration of these technologies is the incompatibility of various software platforms. Creating a global standard for data sharing will make integrating these technologies more effortless and more accessible to businesses of all sizes.

Data security and privacy constitute a key study field as well. Sensitive data collection and storage will rise at an exponential rate as the AEC sector becomes more digitally integrated. This data comprises real-time information from sensors embedded in buildings as well as architectural drawings and blueprints. Adopting Digital Twin's and Metaverse's success will depend on ensuring this data is safe from cyberattacks.

However, further study is required to fully understand the ethical and societal ramifications of the Metaverse. We need to think about how developing more immersive virtual worlds can affect society as a whole and the workforce in particular. What effect, for instance, would the growing use of virtual reality in training have on employment opportunities in the AEC sector? What privacy problems result from real-time monitoring of every facet of a building's operation? As we transition to a future that is more digital, these are crucial concerns that must be answered.

Adopting these technologies will need cooperation from academic institutions, industrial players, and policy officials. To create best practices for integrating BIM, Digital Twins, and the Metaverse into practical projects, industry stakeholders must collaborate. Academic institutions may help by teaching the next generation of engineers and architects in the use of these technologies and by doing research that tackles the technical difficulties.

There is also a function for policymakers. They may hasten the adoption of these technologies by contributing funds for research and development. Additionally, they have the authority to create laws that guarantee the ethical and secure deployment of these technologies while also safeguarding people's security and privacy.

Adoption may also be significantly aided by the creation of regulations that support the use of BIM, Digital Twins, and the Metaverse in public infrastructure projects. Governments worldwide are realizing how vital digital technologies are to enhancing the sustainability and effectiveness of public infrastructure. They may assist in developing a market for these technologies and promoting their acceptance by the private sector by requiring their usage in public projects (Figure 4).

6 Conclusion

The AEC industry's approach to the design, construction, and administration of the built environment has undergone a substantial change, as seen by the transition from BIM to Digital Twin to Metaverse. When merged, these technologies provide unique chances to improve productivity, teamwork, and sustainability throughout the building lifecycle.

Stakeholders must embrace these technologies as the AEC sector develops and make the required investments in infrastructure, R&D, and training to realize these technologies' full potential. By doing this, the construction sector can provide a physical environment that is more inventive, durable, and adaptable to future problems.

Author contributions

ENF: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. AS: Conceptualization, Methodology, Visualization, Writing–original draft, Writing–review and editing. MR: Conceptualization, Methodology, Writing–original draft, Writing–review and editing. NG: Conceptualization, Methodology, Writing–original draft, Writing–review and editing. SM: Conceptualization, Methodology, Writing–original draft, Writing–review and editing.

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Conflict of interest

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