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Assessing The Challenges to Digital Twins in the Metaverse Environment: Strategic Management Decisions Perspective

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Abstract

Purpose: This study investigates the challenges associated with integrating digital twins into the metaverse for supporting strategic management decisions. By synthesizing insights from scholarly literature and expert opinion, this study investigates in depth the interrelationships between these challenges and creates a hierarchical framework for organizing them. The identified challenges are categorized according to their technical, operational, user experience, and data management aspects. Design/methodology/approach: This study utilizes a modified version of total interpretive structural modeling (M-TISM) to systematically identify, interpret, and acknowledge the main challenges associated with the integration of digital twins within a metaverse setting. Findings: This study identifies and emphasizes seven key challenges associated with the integration of digital twins into the metaverse by conducting a comprehensive literature review on the subject. These challenges include synchronization in real time, scalability, interoperability, resource management, data privacy and security, virtual-physical integration, and user experience and interaction. The study places special emphasis on the significant influence that user experience and virtual-physical integration have on the successful integration of digital twins into the metaverse environment. Research implications: This research expands the strategic applicability of digital twin technology by analyzing the main challenges and their interrelationships. The study presents a hierarchical structural model that provides organizations with a practical and invaluable framework for systematically evaluating and ranking the integration challenges they may face in their operational context. Originality/value: This study provides a hierarchical conceptual framework that facilitates a comprehensive understanding of the difficulties associated with integrating digital twins into a metaverse environment. By providing valuable insights and strategies, this study equips organizations with the means to exploit the full potential of this technology, allowing them to enhance virtual experiences and boost real-world applications to new heights.

Keywords: *Digital Twins, Metaverse, Modified Total Interpretive Structural Modeling, TISM, India.*

Introduction

The "digital twin" concept, introduced by Michael Grieves in 2003, is now seen as a key driver of Industry 4.0 (Liu et al., 2021). Digital twins are accurate digital representations of assets, processes, and systems in the built environment. Creating a digital twin involves creating a virtual model of a physical entity, animating its behavior in the real-world using data, and improving its capabilities using virtual and real interactive feedback (Qi et al., 2021). This technology helps companies detect physical issues, predict process outcomes, and create high-quality products. Digital twins are popular in manufacturing, healthcare, and smart cities (Hämäläinen, 2021). Previous studies have focused on the development and implementation of digital twins in specific industries to optimize process optimization, predictive

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maintenance, and informed decision-making (Attaran & Celik, 2023; Hyre et al., 2022). Digital natives are the children of digitalization and mobile devices. Mobile devices have made virtual learning, gaming, socializing, and working natural for this generation (Fang et al., 2009; Monahan et al., 2008). The metaverse lets people socialize, learn, and work in a parallel digital world (Dwivedi et al., 2022). Industries have seen the metaverse's potential as a digital workplace, and the industrial metaverse has begun. Studies suggest that the metaverse can improve production efficiency by allowing location-independent control of consumer product manufacturing machinery (Yao et al., 2022; Yang et al., 2022). Digital twins in the metaverse environment are virtual representations or copies of physical objects or systems that operate in the metaverse's virtual reality space (Dwivedi et al., 2022; Qi et al., 2021). Integrating real-time data from sensors, Internet of Things (IoT) devices, and other sources with computer models and algorithms generates digital twins (Kor et al., 2023). Users can interact with these digital twins in a simulated and immersive manner within the metaverse. The digital twins provide dynamic and interactive simulations within the metaverse. Studies highlight that digital twins in the metaverse provide users with real-time data, simulation capabilities, and the ability to make well-informed decisions about the physical entities they represent. By providing virtual counterparts of physical entities, digital twins in the metaverse enhance the overall immersive experience (Lv et al., 2022). Existing literature indicates that research on digital twins in the metaverse has covered a variety of topics, including user interface, security and privacy challenges, COVID-19 travel anxiety, fluid machinery pumps, training and maintenance, among others (Singh et al., 2022; Zaman et al., 2022). In addition, numerous studies have investigated the implementation of digital twins, privacy challenges, robotic systems, user interface, and metaverse experiences in digital marketplaces (Huang et al., 2023; Lv et al., 2022; Shankar et al., 2023). Studies have discussed, for instance, user interface, security, and privacy issues, as well as scalability issues associated with managing a large number of interconnected digital twins and their real-time data (Nguyen et al., 2023; Yang et al., 2022). In addition, ensuring real-time synchronization and addressing data privacy and security concerns are crucial challenges to integrating digital twins successfully into a metaverse environment.

Despite the growing interest in digital twins and the metaverse, there are still a number of unanswered research questions. First, there is a need for a comprehensive examination of the management challenges associated with the integration of digital twins into a metaverse environment (Yang et al., 2022). This requires comprehension of the organizational and managerial implications, as well as the effect on decision-making procedures. Second, while some studies have highlighted the importance of interoperability and scalability (Ray, 2023), the metaverse context lacks a detailed analysis and proposed solutions for these challenges. Hence, this study addresses the research questions (RQs) as follows:

RQ1: *What are the key challenges associated with the integration of digital twins into a metaverse environment?*

RQ2: *What are the interrelations between these challenges identified on the integration of digital twins in the metaverse environment?*

RQ3: *How can these challenges be evaluated so that digital twins can be successfully integrated into a metaverse environment?*

Considering the above research questions, the key research objectives (ROs) of this study are formulated as follows:

RO1: *To identify the key challenges associated with the integration of digital twins into a metaverse* environment.

RO2: *To assess and examine the interrelationships between these identified challenges.*

RO3: *To develop a hierarchical structural model of the identified challenges and prioritize them according to their interrelationships.*

Through a comprehensive literature review, we identified seven significant challenges in this study and classified them into the technical, user experience, operational, and data management categories. We employ the M-TISM methodology (Sushil, 2017; Rajan et al., 2021) to identify critical challenges and construct a hierarchical structural model that explains the inter-relationships between them.

The organization of the subsequent sections of this study is as follows: The background section provides an overview of digital twins in the metaverse environment and their main challenges. The methodology section explains the M-TISM methodology utilized in this study. The results and discussion section presents the findings and an in-depth analysis of the challenges of digital twins in metaverse environment. The conclusion section provides a summary of the study, highlights its limitations, and provides recommendations for future research. This research concludes with recommendations for future academic research, managers, practitioners, and policymakers, particularly in the context of emerging economies such as India.

Digital Twins in Metaverse Environment: Background

In recent years, the concept of digital twins has garnered considerable interest in a variety of industries, such as manufacturing, healthcare, and smart cities. Extensive research has been conducted on the development, implementation, and benefits of these technologies in these industries (Hämäläinen, 2021; Qi et al., 2021; Yan et al., 2022). Digital twins, for example, have been used in the manufacturing industry to optimize production processes, enable predictive maintenance, and improve product quality (Melesse et al., 2021). In addition, their use has expanded beyond traditional industries, with research into their potential in energy systems, transportation, and infrastructure management. Researchers have also investigated the integration of digital twins with emerging technologies such as the IoT, artificial intelligence, and data analytics in an effort to improve their capabilities (Mourtzis et al., 2021). With the development of virtual reality, augmented reality, and mixed reality technologies, the metaverse has emerged as a prominent concept. Prior research has focused on the potential applications of the metaverse in fields such as gaming, social networking, education, and remote collaboration (Chen, 2022; Mourtzis et al., 2021). Researchers have also studied technical aspects of the metaverse, such as network architecture, rendering techniques, and user experience (Du et al., 2022; Zhao et al., 2022). In addition, social and cultural implications of the metaverse, such as identity, privacy, and ethics, have been the subject of research (Bibri & Allam, 2022; Chen, 2022). While some studies have discussed the potential benefits of integrating digital twins into the metaverse, such as facilitating real-time collaboration, immersive simulations, and improved decision-making (Attaran & Celik, 2023; Du et al., 2022; Hyre et al., 2022), the specific frameworks and challenges associated with this integration remain largely unexplored. Hence, the current study has primarily focused on investigation into the challenges associated with integrating digital twins into the metaverse environment.

Challenges to Digital Twins in the Metaverse Environment

This section provides an overview of the major seven challenges encountered when integrating digital twins into the metaverse. These challenges span the categories of technology, user experience, operations, and data management, and collectively affect the seamless integration and optimal utilization of digital twins within the metaverse.

Virtual-Physical Integration

Digital twins represent physical entities within a virtual environment, acting as a bridge. In the metaverse, virtual-physical integration is the integration of digital representations (virtual) with physical objects, systems, or processes (physical) (Jiang et al., 2021). However, there are challenges to achieving seamless integration between virtual and physical representations in the metaverse. Prior research has highlighted the importance of establishing a robust connection and synchronization between digital twin models and their physical counterparts. These include the accurate integration of sensor data, realistic physics simulations, and the maintenance of consistency between the digital twin and its physical attributes (Luo et al., 2020; Mi et al., 2021).

User Experience and Interaction

User experience and interaction are crucial to the successful integration of digital twins into the metaverse (Lv et al., 2022). Past studies highlight that seamless interaction between users and digital twins, as well as their physical counterparts, is necessary for the creation of an immersive and engaging experience (Buhalis et al., 2023). Past works emphasize the importance of designing intuitive and user-friendly interfaces that enable users to navigate, manipulate, and interact with digital representations of physical processes or objects (Cho et al., 2014). To achieve natural and intuitive interactions within the metaverse, researchers emphasize the importance of responsive and realistic interaction modalities like voice commands, gestures, touch, and haptic feedback (Park & Kim, 2022). The difficulty lies in designing and implementing these interactions in accordance with user expectations and mental models, thereby fostering a sense of presence and immersion.

Resource Management

Integrating digital twins into the metaverse requires the efficient allocation, utilization, and optimization of computational resources, network-bandwidth and storage (Van Huynh et al., 2022). The dynamic nature of the metaverse, coupled with the increasing complexity and inter-connectedness of digital twins, poses unique challenges for the effective management of these resources. In a diverse and distributed metaverse ecosystem, dynamic resource allocation, processing power optimization, and efficient data storage and retrieval pose challenges (Chang et al., 2022). Prior research has also demonstrated the significant relationship between resource management and data security (Ali et al., 2023). Privacy and security measures must be incorporated into resource management practices (Liu et al., 2011; Yang et al., 2022). In addition, previous research indicates that resource management is intrinsically linked to interoperability, highlighting the importance of coordinated resource allocation and standardized protocols to facilitate communication and data exchange between digital twins (Buhalis et al., 2023).

Interoperability

Integrating digital twins into the metaverse presents considerable challenges in terms of interoperability and standards (Naderi & Shojaei, 2023). Interoperability in the environment of the metaverse refers to the communication, exchange of data, and operation of various digital twin models and platforms (Mourtzis et al., 2022; Ocker et al., 2021). Standardization is required for the establishment of interoperable protocols, interfaces, and frameworks (da Rocha et al., 2022). Without interoperability, digital twin systems may function in isolation, hindering collaboration, data sharing, and the realization of the metaverse's potential (Yang et al., 2022). There have been efforts, such as the Asset Administration Shell, to develop interoperability standards and frameworks (Platenius-Mohr et al., 2020). Studies also suggest that interoperability is believed to accelerate scalability by facilitating efficient data exchange and communication (Teisserenc & Sepasgozar, 2021). In addition, it ensures real-time synchronization via frameworks and protocols that are standardized.

Data Privacy and Security

Integrating digital twins into the environment of the metaverse presents significant data privacy and security challenges. As digital twins collect, analyze, and share data from physical objects or processes, concerns arise regarding the confidentiality, integrity, and accessibility of this data (Suhail et al., 2021). Prior research has emphasized the importance of incorporating data privacy and security measures into resource management and interoperability frameworks (Dagher et al., 2018; Lampropoulos & Siakas, 2022). By considering data privacy and security throughout the integration process, organizations can protect sensitive data, build trust, and maximize the benefits of integrating digital twins into the environment of the metaverse (Alcaraz & Lopez, 2022; Lee et al., 2021; Liu et al., 2022). Moreover, the dependence of digital twins on real-time data from a variety of sources, such as sensors and IoT devices, highlights the significance of protecting the privacy and security of this data within the metaverse environment (Parmar et al., 2020). To maintain the privacy and security of data in the metaverse, it is essential to implement rigorous data protection measures and address potential vulnerabilities.

Scalability

As the number and complexity of digital twins increases, various scalability considerations come into play (Scime et al., 2022). First, it is essential to manage the massive amount of data generated by digital twins in the metaverse environment. The integration of multiple digital twins generates huge amounts of information that must be processed, stored, and analyzed in real-time (Aloqaily et al., 2022). Digital twins require computational resources to perform real-time simulations, process data, and render virtual representations (Cao et al., 2022). It is crucial to ensure that the system can scale its computational resources to meet the needs of a growing ecosystem of digital twins. Past studies also highlight that scalability is intrinsically linked to the responsiveness and real-time nature of metaverse digital twins (Aloqaily et al., 2022). As the number of interconnected digital twins increases, it becomes increasingly difficult to maintain real-time synchronization and responsiveness. In order to ensure seamless interactions within the metaverse environment, scalable solutions that prioritize real-time synchronization are necessary (Zhang et al., 2022).

Real-Time Synchronization

In the management context of integrating digital twins into the metaverse environment, real-time synchronization poses a significant challenge (Lv et al., 2022). Real-time synchronization becomes more difficult to manage in a metaverse environment with a growing number of interconnected digital twins. Organizations must ensure that the virtual representation of digital twins remains up-to-date and synchronized with their physical counterparts in order to facilitate accurate and responsive interactions within the metaverse (Lattanzi et al., 2021). Real-time synchronization requires addressing crucial data flow and network infrastructure factors (Kherbache et al., 2021). Past studies suggest that organizations must establish robust communication protocols and infrastructure to guarantee the reliability and efficacy of data transmission, particularly in distributed metaverse environments (Semeraro et al., 2021; Tang et al., 2022). Organizations should establish efficient mechanisms for capturing, processing, and transmitting data from sensors, actuators, and other sources in real time.

In this study, we utilized the M-TISM methodology (Sushil, 2017; Dhir et al., 2021; Rajan & Sushil, 2022; Sindhwani et al., 2022) to examine the challenges associated with integrating digital twins into the metaverse environment. The M-TISM method extends the TISM (Sushil, 2012) and enables the development of a hierarchical model of the identified research domain challenges. The M-TISM methodology's step-by-step process is outlined below.

Step 1: Identifying the challenges: We conducted a comprehensive literature review in order to identify the key challenges associated with integrating digital twins into the metaverse.

Step 2: Defining contextual relationships: The next step involves describing the contextual relationships between the identified challenges. For instance, we determine the direct or indirect impact of Challenge C3 on Challenge C4. This procedure is carried out for each challenge and serves as the foundation for the M-TISM model.

Step 3: Interpreting relationships: We analyze the contextual connections between the identified challenges. For instance, if resource management (C3) has an effect on interoperability (C4), we explain the relationship between C3 and C4.

Step 4: Pairwise comparison: We perform pairwise comparisons of the challenges to develop an "Interpretive logic knowledge base" matrix. Each comparison indicates whether a relationship exists between the identified challenges, denoted by "Y" (Yes) or "N" (No).

Step 5: Reachability matrix and transitivity check: We construct a reachability matrix that depicts the significant and influential relationships between the identified challenges. A value of '1 - (Yes)' signifies a robust link, whereas a value of '0 - (No)' specifies a less prominent connection, and 1* indicates transitive relationships between two challenges.

Step 6: Hierarchical level partition: We evaluate the reachability set, antecedent set, and intersection set of each challenge to determine its level within the hierarchy. The challenges with same reachability and intersection sets are considered to be in Level I and positioned on the top of the hierarchical level in the ISM based model, and this process is repeated to assess the same value for the reachability and antecedent sets until all the challenges are scanned.

Step 7: Building the digraph: We construct a digraph consisting of nodes and links, representing the established relationships between the identified challenges. Arrows are used to indicate the direction of these relationships, and the challenges are arranged in a level-wise manner within the digraph.

Step 8: Validating the digraph: We validate the developed digraph by seeking the opinions of a panel of experts. The M-TISM model is further developed by logically interpreting each relationship between the identified challenges in the digraph.

Step 9: The M-TISM hierarchical structural model: Finally, we develop the M-TISM model by incorporating the insights gained from the digraph and interpretive matrix.

Through the utilization of the M-TISM methodology, this study aims to gain a comprehensive understanding of the hierarchical relationships and interdependencies between the challenges associated with integrating digital twins into the metaverse environment.

M-TISM for this Research

We have identified seven key challenges through an extensive literature review. These challenges have been divided into four main categories: technical, user experience, operational, and data management (see Table 1).

Table 1: The key challenges with their broader categories

Challenge Code	Challenges	Category	References
C1	Virtual-Physical Integration	Technical Challenges	Jiang et al., 2021; Luo et al., 2020; Mi et al., 2021
C2	User Experience and Interaction	User Experience Challenges	Buhalis et al., 2023; Cho et al., 2014; Lv et al., 2022
C3	Resource Management	Operational Challenges	Ali et al., 2023; Buhalis et al., 2023; Yang et al., 2022
C4	Interoperability	Technical Challenges	Mourtzis et al., 2022; Naderi & Shojaei, 2023; Ocker et al., 2021
C5	Data Privacy and Security	Data Management Challenges	Alcaraz & Lopez, 2022; Dagher et al., 2018; Lampropoulos & Siakas, 2022
C6	Scalability	Technical Challenges	Aloqaily et al., 2022; Cao et al., 2022; Zhang et al., 2022
C7	Real-time Synchronization	Technical Challenges	Lv et al., 2022; Semeraro et al., 2021; Tang et al., 2022

The comparison digraph in Figure 1 illustrates the successive pairwise comparison of the identified challenges. Due to the unknown hierarchy of challenges initially, the comparisons have been conducted in a sequential manner. The comparisons are based on a review of the literature. Additionally, transitive links have been verified concurrently. For example, if there is a relationship between C2 and C3, and between C3 and C4, then a transitive link between C2 and C4 is established. This transitivity checking process continues until all transitive links are established. The digraph includes dotted lines to represent the transitive links, while direct lines indicate the direct relationship between two challenges.

Figure 1: Successive Pairwise Comparison of Identified Challenges.

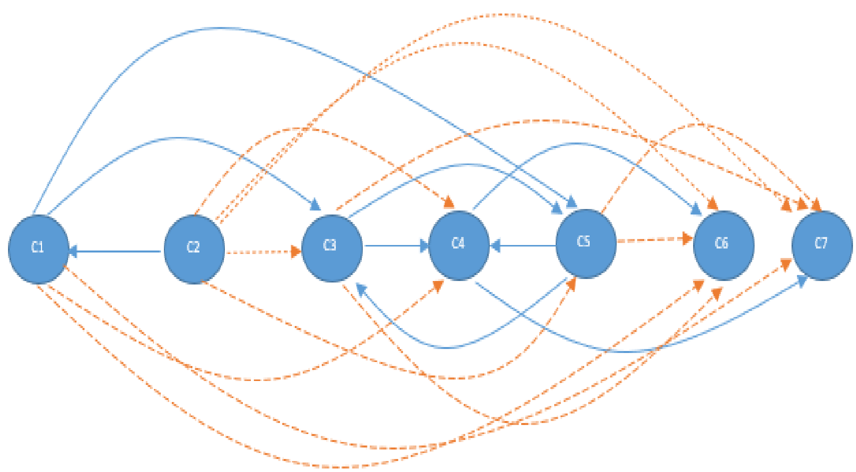


Table 2 presents the reachability matrix, which was developed based on the information in Figure 1. Each challenge is represented in the reachability matrix, indicating its direct relationship with other challenges. The reachability matrix employs a binary format, where a value of '1' indicates a direct relationship, while a value of '0' denotes no direct relationship between the challenges. Transitive relationships between two challenges are denoted as 1* in the matrix.

Table 2: Reachability Matrix with Transitivity (*Transitive Links).

Challenges	C1	C2	C3	C4	C5	C6	C7
C1	1	0	1	1*	1	1*	1*
C2	1	1	1*	1*	1*	1*	1*
C3	0	0	1	1	1	1*	1*
C4	0	0	0	1	0	1	1
C5	0	0	1	1	1	1*	1*
C6	0	0	0	0	0	1	0
C7	0	0	0	0	0	0	1

Table 3 presents the level partition of the challenges. At each iteration, the reachability set, antecedent set, and intersection set were sorted from the final reachability matrix. Challenges that shared similar reachability and intersection sets were grouped together at the topmost level (Level I group) as shown in Table 4. Subsequently, these top-level components were removed in the subsequent iterations, and the process was repeated until all levels of each challenge were determined.

Table 3: Iterations and Level Partitioning.

Challenges	Reachability Set	Antecedent Set	Intersection Set	Level
		(a): Iteration 1		
C1	1, 3, 4, 5, 6	1, 2	1	
C2	1, 2, 3, 4, 5, 6	2	2	
C3	3, 4, 5, 6	1, 2, 3, 5	3, 5	
C4	4, 6	1, 2, 3, 4, 5	4	
C5	3, 4, 5, 6	1, 2, 3, 5	3, 5	
C6	6	1, 2, 3, 4, 5, 6	6	I
C7	7	1, 2, 3, 4, 5, 7	7	I
		(b): Iteration 2		
C1	1, 3, 4, 5	1, 2	1	
C2	1, 2, 3, 4, 5	2	2	
C3	3, 4, 5	1, 2, 3, 5	3, 5	
C4	4	1, 2, 3, 4, 5	4	II
C5	3, 4, 5	1, 2, 3, 5	3, 5	
		(c): Iteration 3		
C1	1, 3, 5	1, 2	1	
C2	1, 2, 3, 5	2	2	
C3	3, 5	1, 2, 3, 5	3, 5	III
C5	3, 5	1, 2, 3, 5	3, 5	III
		(d): Iteration 4		
C1	1	1, 2	1	IV
C2	1, 2	2	2	
		(e): Iteration 5		
C2	2	2	2	V

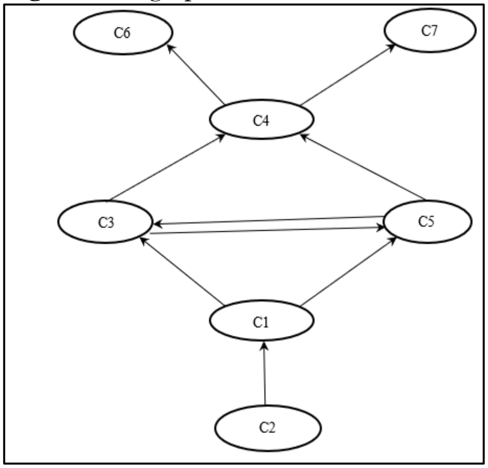
The level of identified challenges has been shown in Table 4.

Table 4: Challenges and Their Levels to Develop The M-TISM Model.

Challenge Code	Challenge	Level
C7	Real-time Synchronization	I
C6	Scalability	I
C4	Interoperability	II
C3	Resource Management	III
C5	Data Privacy and Security	III
C1	Virtual-Physical Integration	IV
C2	User Experience and Interaction	V

After the level partition of the challenges, the directed ISM digraph (Figure 2) has been constructed to illustrate the relationships between the challenges based on their respective levels. The digraph represents both direct relationships (indicated by solid lines) and transitive relationships (indicated by dotted lines). Only significant transitive links have been included in the digraph to provide a clear depiction of the interconnections between the challenges.

Figure 2: Digraph After Hierarchical Partitioning of Challenges Using ISM.



Assessment of the Developed Model Through Experts' Opinion

The interrelationships among the challenges pertaining to digital twins in the metaverse environment were identified through a comprehensive literature review. To validate the developed structural model, insights from expert managers were sought to review their perceptions and consider their decisions based on the links between key challenges. The existing gap in the literature indicates a lack of understanding regarding the connections and relationships among the identified key challenges. A panel of nine experts, comprising five industry professionals and four academic experts, with a minimum of ten years of experience in the domains of virtual reality, digital twins, IoT, human-computer interaction, and user experience design, were selected for the assessment of the developed M-TISM model. The opinions of the experts were gathered through direct interaction at academic and industrial workshops as well as through personal contacts. The selected experts, who held senior positions in their respective industries and reputed institutions, provided valuable insights. Details of the selected experts are presented in Table 5.

Table 5: Profile of Selected Experts.

Expert	Experience (Years)	Expertise	Domain
EX1	10	Virtual reality, augmented reality, and digital twins	Academic
EX2	12	Immersive virtual environments	Industrial expert
EX3	16	Smart cities and IoT	Industrial expert
EX4	15	Human-computer interaction and user experience design	Industrial expert
EX5	16	Blockchain technology and decentralized systems	Industrial expert
EX6	13	Computer science and virtual reality	Academic
EX7	14	Internet and society	Academic
EX8	14	Space technology and satellite systems	Industrial expert
EX9	15	Intersection of design, technology, and the metaverse	Academic

The experts were surveyed using a questionnaire based on the links of the digraph (Figure 2) and they were informed of the background of the study and the hierarchical structural model developed through the M-TISM approach. The digraph was shared with the designated experts where they were asked to rank the relationships between challenges in the sketched digraph. The experts were asked to assign scores on a scale of [1-5] where '1' represented 'strongly disagree' and '5' 'strongly agree', indicating their agreement with the linkages between the challenges. Links that received an average score of three or higher were deemed acceptable and included in the digraph. Through this process, the panel of experts accepted each link in the digraph. The overall average score for the entire proposed digraph was was found to be 3.90, as represented in Table 6. Thus, based on the consensus of the expert panel, the proposed digraph was accepted.

Table 6: Validation of Proposed Digraph.

Link	EX1	EX2	EX3	EX4	EX5	EX6	EX7	EX8	EX9	Average score	Average score for digraph
C2-C1	4	4	3	5	4	5	4	5	4	4.22 [A]	3.90 [A*]
C1–C3	4	5	4	4	2	5	5	4	3	4.00 [A]	
C1–C5	3	3	4	2	4	5	4	5	5	3.88 [A]	
C3–C4	5	5	4	3	3	5	2	3	4	3.77 [A]	
C3–C5	5	3	4	2	4	3	3	5	4	3.66 [A]	
C5–C3	2	5	3	4	5	2	5	4	4	3.77 [A]	
C5–C4	4	4	3	5	3	4	5	2	5	3.88 [A]	
C4–C6	2	3	5	5	4	4	5	4	5	4.11 [A]	
C4–C7	4	3	4	4	5	4	4	3	3	3.77 [A]	

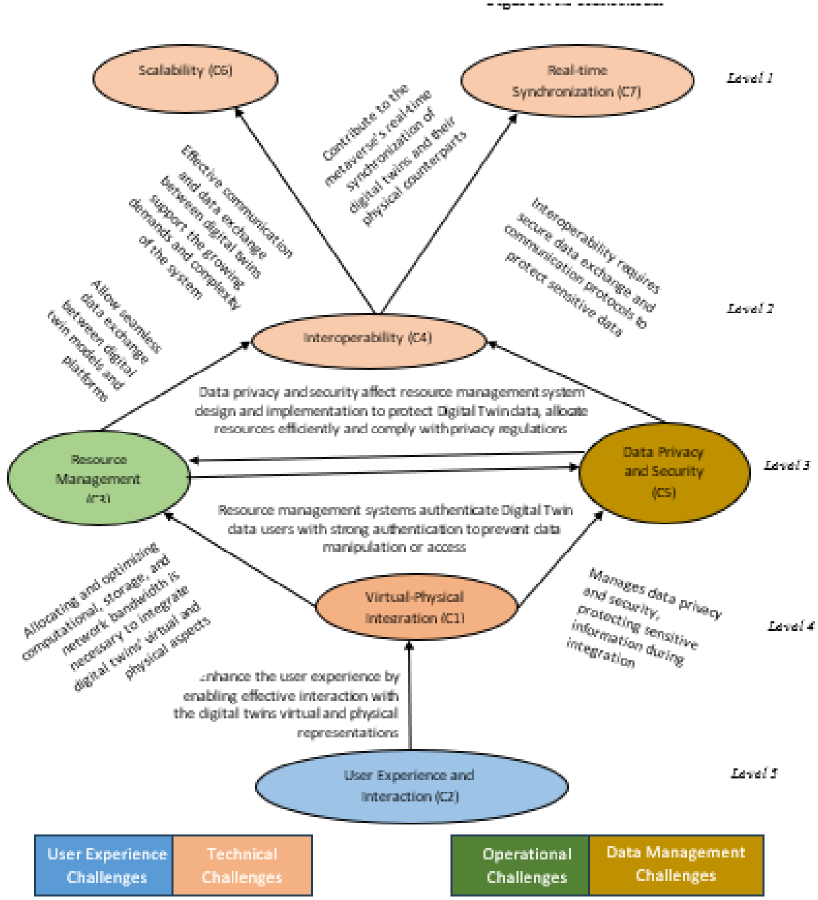
[Note: A: Accept this link, A*: Accept the ISM digraph]

An "Interpretive Logic Knowledge Base" matrix has been constructed to facilitate the comparison of identified challenges in pairs (Table 7). It provides a detailed interpretation of the validated links between the challenges, supported by the existing literature. Subsequently, an M-TISM model has been developed based on the "Interpretive Logic Knowledge Base" matrix (Table 7) and the proposed digraph (Figure 2). The M-TISM model provides an interpretation for each link, offering insights into the relationships among the challenges. The M-TISM hierarchical structural model serves as a framework for understanding the interconnections and dependencies among the challenges related to digital twins in the metaverse environment

Table 7: Interpretive logic - Knowledge Base.

Link	Interpretation	Supporting literature
C2-C1	Enhance the user experience by enabling effective interaction with the digital twins virtual and physical representations.	Buhalis et al., 2023; Mi et al., 2021; Park & Kim, 2022
C1–C3	Allocating and optimizing computational, storage, and network bandwidth is necessary to integrate digital twins' virtual and physical aspects.	Chang et al., 2022; Luo et al., 2020; Mi et al., 2021
C1–C5	Manages data privacy and security, protecting sensitive information during integration.	Alcaraz & Lopez, 2022; Dagher et al., 2018; Lee et al., 2021; Lv et al., 2022
C3–C4	Allow seamless data exchange between digital twin models and platforms.	Buhalis et al., 2023; Mourtzis et al., 2022; Yang et al., 2022
C3–C5	Resource management systems authenticate digital twin data users with strong authentication to prevent data manipulation or access.	Chang et al., 2022; Dagher et al., 2018; Van Huynh et al., 2022
C5–C3	Data privacy and security affect resource management system design and implementation to protect digital twin data, allocate resources efficiently, and comply with privacy regulations	Lampropoulos & Siakas, 2022; Lee et al., 2021
C5–C4	Interoperability requires secure data exchange and communication protocols to protect sensitive data.	Alcaraz & Lopez, 2022; Mourtzis et al., 2022; Teisserenc & Sepasgozar, 2021
C4–C6	Effective communication and data exchange between digital twins support the growing demands and complexity of the system	Aloqaily et al., 2022; Yang et al., 2022; Zhang et al., 2022
C4–C7	Contribute to the metaverse's real-time synchronization of digital twins and their physical counterparts	Ocker et al., 2021; Semeraro et al., 2021; Teisserenc & Sepasgozar, 2021

Figure 3: M-TISM Model.



Results and Discussion

We have identified seven major challenges in this research that have a significant impact on the integration of digital twins into the metaverse environment. Using the M-TISM methodology, we constructed a hierarchical model depicting the interrelationships between these challenges. The results indicate that "User Experience and Interaction" (C2) plays a crucial role as the driving challenge, influencing the integration of digital twins into the metaverse. "Virtual-Physical Integration" (C1) has a substantial impact on "Resource Management" (C3) and "Data Privacy and Security" (C5), while C3 and C5 also influence one another. In addition, C3 and C5 have a direct influence on "Interoperability" (C4), which in turn influences "Scalability" (C6) and "Real-time Synchronization" (C7). The challenges have been divided into distinct categories, such as technical, user experience, operational, and data management. Technical challenges include the seamless integration of digital representations with physical objects and processes within the metaverse, as well as virtual-physical integration, interoperability, scaling, and real-time synchronization. Creating immersive and engaging experiences for metaverse users through intuitive interfaces, natural interaction modalities, and responsive interactions are user experience challenges (Buhalis et al., 2022). The operational challenges associated with digital twins include the efficient management of resources, processes, and workflows, as well as resource allocation, and the implementation of robust operational frameworks. Challenges in data management include the collection, storage, analysis, and security of the vast quantities of data generated by digital twins, as well as data quality, integration, and governance.

By understanding and addressing these challenges, organizations can overcome challenges and maximize the potential of digital twin integration in the metaverse environment. This necessitates inter-disciplinary collaboration, the creation of innovative solutions, and the adoption of best practices from a variety of domains in order to create a seamless and transformative metaverse experience. Our study fills a gap in the literature by providing a detailed interpretation of the M-TISM model, supported by prior research, and validating it through the opinions of industry and academic experts.

Conclusions, Limitations and Future Research

The study examines the key challenges associated with integrating digital twins into the metaverse, shedding light on the critical factors for supporting strategic management decisions. Using the M-ISM methodology, a hierarchical model was developed to systematically classify the challenges into four distinct areas: user experience, technical, operational, and data management. This classification was derived from a comprehensive literature review and consultations with industry managers and academic experts who provided valuable insights into the interrelationships between the identified challenges. The results highlight the significance of User Experience as a significant challenge, highlighting the need to prioritize and improve the user's interaction and immersion within the metaverse. Another significant challenge is virtual-physical integration, which emphasizes the seamless integration of digital representations and physical objects and processes. Moreover, the study identifies real-time synchronization, scalability, interoperability, resource management, and data privacy and security as significant challenges requiring careful consideration. Through a comprehensive examination of these challenges and their interdependencies, this study provides valuable insights for practitioners and researchers seeking to overcome challenges to the integration of digital twins into the metaverse. The findings emphasize the importance of addressing user experience and virtual-physical integration, while also acknowledging the significance of other challenges to achieving successful integration.

While this study has made significant contributions to our understanding of the challenges of integrating digital twins into the metaverse environment, there are a number of limitations that must be taken into account. First, the selection of significant challenges was based on a specific literature review, which may contain inherent biases and limitations. Future research could expand on this by conducting a more comprehensive and methodical literature review to ensure a more representative set of challenges. Second, the study relied on the knowledge of participants from a particular region, India, limiting the generalizability of the findings. To improve the reliability and applicability of the results, it would be advantageous to include experts from a variety of geographic locations and cultural backgrounds. This would allow for greater comparisons and understanding of the challenges faced in various contexts. In addition, the sample size of experts included in this study was relatively small. Future research could include a larger, more diverse sample size in order to validate the developed model and ensure its reliability. To evaluate the model's validity and applicability, statistical analysis techniques could be employed. In conclusion, while this study focused on identifying challenges, future research could build on this by developing a comprehensive framework of critical success factors and barriers for implementing digital twins in the metaverse environment. This would provide a broader understanding of the factors that contribute to the successful integration of digital twins.

By addressing these limitations and conducting additional research, we can gain a better understanding of the barriers and possibilities associated with integrating digital twins into the metaverse environment.

This will contribute to the development of effective strategies and frameworks for organizations seeking to capitalize on the potential of digital twins in the evolving technological landscape.

Recommendations and Implications for Practice and Policy

In the context of integrating digital twins into the metaverse environment, this study makes a number of theoretical and practical contributions. This study is the first of its kind to systematically investigate and identify the challenges associated with digital twins in the metaverse from a theoretical standpoint. Using the M-TISM methodology, a hierarchical structural framework has been developed that provides a thorough understanding of the interrelationships between these challenges. This framework can serve as a helpful framework for future empirical research, allowing researchers to empirically test the proposed model. This study provides practitioners and managers with valuable insights into the challenges they may face when implementing digital twins in the metaverse. By understanding these challenges, practitioners can proactively plan for and address potential challenges, thereby increasing the likelihood of successful integration. The identified challenges can also be used to develop strategies and best practices for overcoming these challenges and thereby facilitating the effective use of digital twins in the metaverse environment.

Recommendations for Future Researchers

The following research questions are proposed for future academic research based on the findings of this study and the identified challenges associated with integrating digital twins into the metaverse environment: [i] What are the main factors affecting the scalability of digital twins in the metaverse, and how can organizations ensure scalability as the number and complexity of digital twins increase? [ii] What strategies and best practices can organizations use to overcome the challenges identified in this study and successfully integrate digital twins into the metaverse? [iii] How can data privacy and security challenges be effectively managed in metaverse integration? [iv] How do cultural and regulatory factors affect digital twin integration in the metaverse across regions and countries? [v] What ethical issues arise from integrating digital twins into the metaverse, and how can organizations ensure ethical use of digital twin technology? [vi] What are the critical success factors to metaverse digital twin adoption and implementation, and how can organizations leverage the success factors? [vii] How can user experience and interaction challenges be addressed to make metaverse digital twins more immersive and engaging?

Implications for Managers and Practitioners

The following suggestions are made for improving strategic management decisions for industry managers and practitioners based on the findings of this study and the challenges identified in integrating digital twins in the metaverse environment: [i] Implement robust data privacy and security measures to safeguard sensitive data, [ii] Invest in infrastructure that can be scaled to meet the growing needs of digital twins in the metaverse, [iii] Promote interoperability and standardization to facilitate communication and data exchange, [iv] Prioritize user experience design in order to develop immersive and engaging metaverse experiences, [v] Promote inter-disciplinary collaboration and the exchange of knowledge among experts in fields such as virtual reality, the IoT, human-computer interaction, and user experience design.

Implications for Policymakers

By implementing these recommendations, policymakers in an emerging economy like India can create an environment conducive to the successful integration of digital twins into the metaverse. These efforts will contribute to economic growth, technological progress, and societal development, while addressing the challenges and maximizing the benefits of digital twin integration in the context of the metaverse. Following are suggested recommendations for policymakers: [i] Promote a regulatory environment conducive to the incorporation of digital twins into the metaverse, [ii] Promote a startup-friendly environment by providing entrepreneurs and businesses in the digital twin sector with financial incentives, tax breaks, and regulatory support, [iii] Encourage the research and development of digital twin technologies by providing funding and incentives to academic institutions and the private sector, [iv] Implement data protection and privacy regulations that ensure the secure handling and storage of digital twin data, [v] Encourage collaboration and strategic partnerships between government agencies, industry, and academia to promote innovation and knowledge sharing in the digital twins field, and [vi] Promote the adoption of open standards and interoperability frameworks to facilitate the integration and exchange of data between various digital twin systems.

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