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Industrial Metaverse design methodologies: a comprehensive literature review

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ABSTRACT

XR-based industrial Metaverse is a new paradigm for manufacturing, a fully immersive virtual space that interacts with the physical space to enhance manufacturing efficiency. This cyber-physical system integrates technologies such as digital twins, IoT, blockchain, and NFT to build a Metaverse that contains a virtual replica of the physical system, connecting people, machines, processes, and environments within the product design, production planning, manufacturing, and predictive maintenance process. By performing industrial process simulations and taking advantage of augmented reality (AR) or virtual reality (VR) technology, industrial Metaverse has great potential in applications such as collaborative workspaces, virtual factories, digital management, and employee training. However, the design process and methodologies related to industrial Metaverses lag behind when compared to the architectures and applications of industrial Metaverses. Through digging into existing literature, this paper mainly focuses on the design of industrial Metaverses, including frameworks, methodologies, and techniques related to the design of an industrial Metaverse with an XR perspective. The paper also analyses the technologies that form the system, elaborates the challenges and opportunities in various applications, and finally provides insights for the future.

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Industrial metaverse; design methodology; e-manufacturing; virtual manufacturing; industrial dataspace; AR/VR applications

1. Introduction

The industrial Metaverse is a trending concept following the transition towards Industry 4.0, Industry 5.0 and the Web3 era. As a relatively new field, theories, principles or methods are scattered across different literature and have not yet been fully summarised. This literature review aims to create an initial conceptualisation or theoretical model of the design of XR-based Industrial Metaverses by collecting literature related to industrial Metaverse design principles, the technology and components of industrial Metaverses, and applications or use cases of industrial Metaverses. This literature places an emphasis on the design methodologies.

Following the purpose of this review, the search strategy is devised. The literature search is split into three sections, a search focusing on design principles that are related to XR/Metaverse, a search focusing on components and technologies that can be used in the design of industrial Metaverses, and a search on applications and use cases of industrial Metaverse. The search is mainly conducted on IEEE, Elsevier, ACM, and Google Scholar, aiming for papers no older than 5 years unless necessary. The search keywords are a combination of 'Industrial Metaverse' and respective keywords of the different fields, such as *Design Principles, design methodology, …* in the first section; *Digital Twins, Blockchain, NFT, …* in the second section; and specific applications or use cases of Industrial Metaverses in the third place. Papers are first collected, and then screened for relevance.

This literature review is organised into eight main sections. The first section introduces the background of industrial Metaverse and the related technologies. The second section explains the Metaverse and its components in detail while comparing different categories and types of Metaverses. The third section elaborates on the categorisation of design methodology applicable to industrial Metaverse design, organising, comparing, and summarising key Metaverse design methodologies. The fourth section provides a detailed discussion of challenges and limitations. The fifth section provides insight and prospects for future industrial Metaverse development. Finally, the last section concludes the paper.

1.1. Analysis on research trends

An analysis on keyword trend was performed to obtain insights on how research on Metaverse is performing. A tool called Dimensions was used to obtain yearly publication data and perform analysis ('Dimensions AI | The Most Advanced Scientific Research Database' 2024).

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Two sets of keywords were chosen for comparison: 'Metaverse AND Design', and 'Industrial Metaverse AND Design'. The main sources of the publications were arXiv, IEEE, Electronics, and related journals and conferences.

Metaverse and the industrial Metaverse are relatively new fields that have emerged in the past 4 years. As shown in Figure 1, before 2021 only a couple hundred papers related to Metaverse were being published every year, but in the following year of 2022, the publication number has rose to around 5000. Following the trend of Metaverse, the publication number of industrial Metaverse-related design has risen to slightly more than 2000 papers in 2022. This trend kept rising in 2023, with more than 12,000 Metaverse design-related papers published. From this trend diagram, Metaverse and industrial Metaverse are very hot and popular titles, with more than 8000 papers for Metaverse and 4000 papers for industrial Metaverse already published within the first half of the year 2024, which is expected to double at the end of the year.

Research fields also span widely in terms of Metaverse and industrial Metaverse publications. As shown in Figure 2, around half of all industrial Metaverse publications are in computer science, while the other half are in management, engineering, business, and marketing fields, mostly focusing on applications and use cases of the industrial Metaverse in their respective fields.

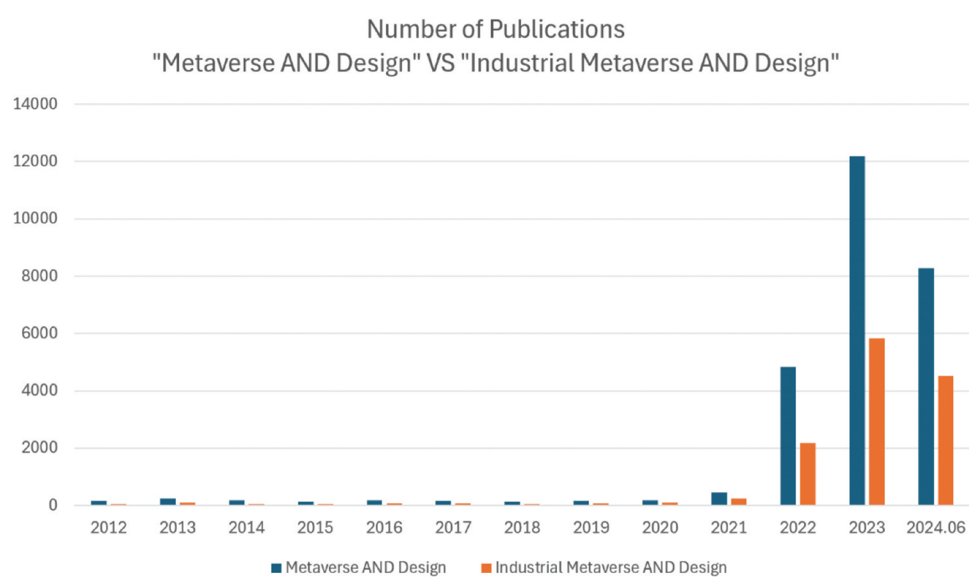

Figure 1. Yearly number of publications.

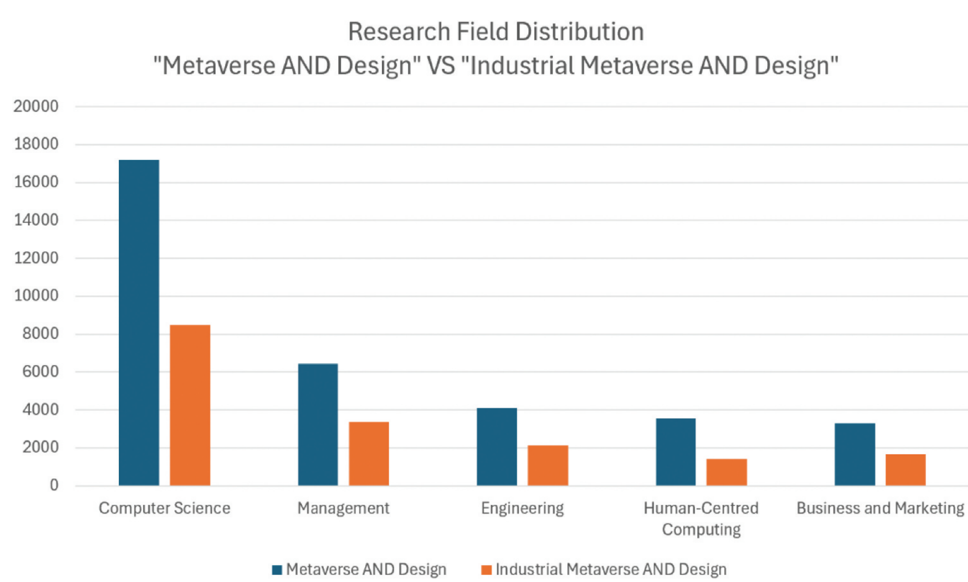

Figure 2. Number of publications sorted by research fields.

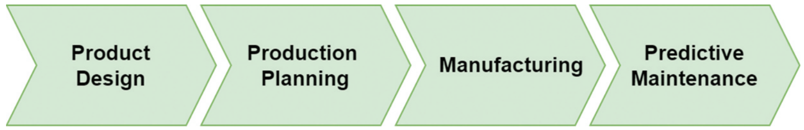

Figure 3. The four related processes of industrial Metaverse.

The contribution of this paper is in the collecting, organising, categorising and summarising of the various industrial Metaverse design methodologies scattered across literature. This paper aims to introduce more systematic design theories into the design process of the industrial Metaverse, standardise the design processes and methods, and provide reference design methods for different types of industrial Metaverses.

This will enable:

(1) Design researchers to gain a more comprehensive and extensive understanding of available design methods through organised Metaverse design methods, literature, and sources.
(2) Computer scientists to understand designers' perspectives, ensuring they choose appropriate technologies to support designers and the design process.
(3) Industrial Metaverse designers to better understand the characteristics, functions, and limitations of various methods, and how these methods impact future practices. They will be more capable of integrating human-centred design thinking with the current technology- and engineering-driven industrial Metaverse.
(4) Developers to better understand their roles in the process and the best practices for implementation.

1.2. Different definitions of Metaverse

Metaverse is a concept that has multiple definitions. The first mention of Metaverse comes from a science fiction novel, 'Snow Crash', published in 1992, and describes Metaverse as a realistic virtual world (H. Wang et al. 2023). The term 'Metaverse' is derived from the fusion of 'meta' and 'verse'. "meta" originates from Greek, serving as a prefix suggesting transcendence, while "verse" refers to the concept of the universe (H. Wang et al. 2023). In Encyclopedia, the Metaverse is defined as'the post-reality universe, a perpetual and persistent multiuser environment merging physical reality with digital virtuality' (Azar, Barretta, and Mystakidis 2022).

In a more practical definition, Metaverse is a digital economic system built upon the redefinition of value through internet platforms, the transformation of identity into assets, the appreciation of content, and the promotion of open interoperability. It is a new form of networked society that expands the scope of real-world social interactions and interpersonal connections across temporal and spatial boundaries (Chi et al. 2023).

As the metaverse rapidly advances, its definition continually evolves. As community members – including designers, engineers, researchers, policymakers, and users – gain a deeper understanding of its potential and challenges, the definition of the metaverse will be further refined (Zallio and John Clarkson 2022b). However, in this paper discussing the metaverse, including the exploration of the methodology for designing the metaverse, the term 'metaverse' adopts Felix et al.'s viewpoint, namely a fully immersive three-dimensional environment that can integrate the physical world or virtual world and can be accessed through XR interfaces such as VR and AR (Dwivedi et al. 2022). It is not synonymous with 3D virtual platforms like Decentraland, Sandbox, or Roblox, which themselves do not capture the essence of the metaverse, namely fully immersive 3-dimensional environments accessible through VR and AR.

1.3. Industrial Metaverse

1.3.1. Definition

Industrial Metaverse is a specific application of Metaverse used in an industrial setting. According to Jie Cao et al., the industrial metaverse is a fully immersive virtual space that interacts with the physical space in real time to enhance operational efficiency (Cao et al. 2023). Liu et al. state that the industrial metaverse is a part of the metaverse that aims to promote high-quality industrial development by breaking through the constraints of space and time (S. Liu, Xie, and Wang 2023). According to Cai et al., the industrial metaverse is the combination of virtual reality and other technologies in the industrial field, connecting people, machines, materials, processes, and environments within a virtual space (H. H. Cai, Xiao, and Shen 2023). Zheng et al. further specify that the Industrial Metaverse is introduced as a novel digital twin system for the real-world industrial economy. This system enables seamless interaction between humans and machines, facilitates industrial process simulations, and supports transactions related to industrial value (Zheng et al. 2022). As Figure 3, a basic process of manufacturing with cyber-physical integration is product design, production planning, manufacturing, and predictive maintenance (Qi and Tao 2018).

Chi et al. proposed a reference architecture of an industrial Metaverse consisting of the real world, a virtual world, an industrial Metaverse infrastructure bridging the real and virtual world, and the new models and applications that extend from the virtual world (Chi et al. 2023). The real world consists of the interior and exterior of a factory, which interfaces to the industrial Metaverse infrastructure through networks, computing and storage. Within the industrial Metaverse infrastructure, a platform lies at its core, integrating experience, identity, assets, and different systems such as social systems, governance systems, etc. The infrastructure supports the virtual world, which provides new models and applications. The entire framework is security and privacy protected.

1.3.2. Technologies in an industrial Metaverse

Industrial Metaverse builds upon various technologies, which are core to the distinctive functionalities that an industrial Metaverse provides. As summarised by Chi et al, an industrial Metaverse is built upon four major technology foundations: network, computing and storage, perception, and control. Network such as Wi-Fi, ethernet, 5 G etc. underlays the connection within Metaverse; Cloud computing and datacentres provide computational power to support the data and computation expensive simulations; Perception summarises how data is acquired through sensors and measurements; and control summarises the hardware used to control, monitor and drive the industrial Metaverse (Chi et al. 2023). These foundational technologies support the advanced technologies used in industrial Metaverses.

Typical technologies used in the industrial Metaverse include blockchain, digital twins, Internet of Things and NFT. Digital twins, blockchain, IoT, and NFT, work together to form basic functions and roles, which are then integrated seamlessly to form Metaverse (Kshetri 2023; Zheng et al. 2022). A basic technological architecture is shown in Figure 4. Blockchain is the foundation of secure authentication, providing trust for NFT-based asset authentication and identity management. Physical assets are digitally replicated into digital twins, with IoT and sensors providing data to through cloud. Together with the simulations of digital twins, data is visualised and displayed either through augmented reality or virtual reality. In augmented reality, data is overlayed on physical machines and assets, providing intuitive information. In virtual reality, stakeholders can

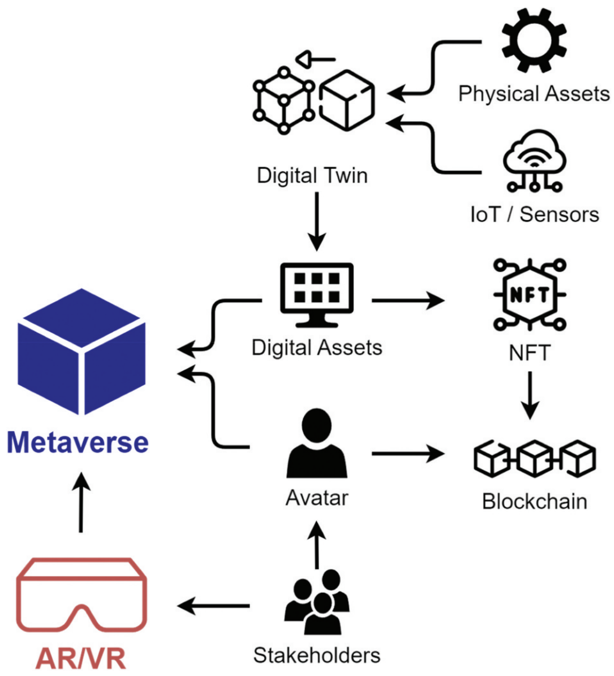

Figure 4. Diagram of Metaverse and its components.

join the virtual world through avatars. These technologies form the foundation of an industrial Metaverse.

2. Components and categories of industrial Metaverse

2.1. Components of industrial Metaverse

The industrial metaverse can be seen as a seamless integration of the cyber/digital and physical worlds. Its core components include assets, stakeholders, technology, User-Experience Design (UXD), interactions, environment, security, and ethics, each extending to distinct functions, use cases, and applications (Chi et al. 2023; Nleya and Velempini 2024; J. Wang et al. 2023; Zheng et al. 2022). A detailed structure of an Industrial Metaverse can be seen in Figure 5, which at its core is a cyber-physical system within Industry 5.0 (J. Lee and Kundu 2022). It demonstrates how components are grouped within the Metaverse structure, for example equipment and infrastructure are categorised as assets, whereas privacy and accessibility are grouped within ethics (Fernandez and Hui 2022; White Paper - The IEEE Global Initiative on Ethics of Extended Reality Report–Metaverse and Its Governance' 2024). One core aspect of the industrial Metaverse is the Interaction. Different from recreational Metaverses, the large number of digital twins brings more rigid requirements for human-software-hardware interactions (Y. Wang et al. 2021). The interactive design of the metaverse also creates

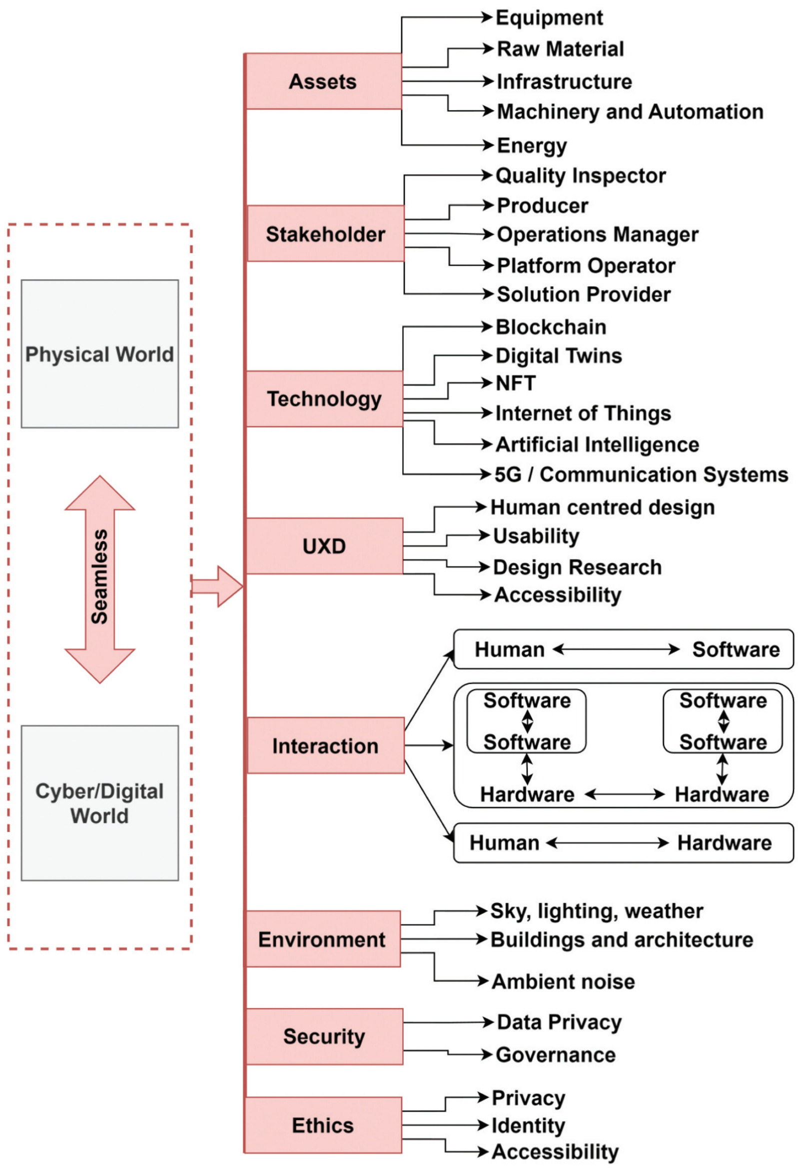

Figure 5. Structure and components of an industrial Metaverse.

a seamless integration of the physical and virtual worlds, allowing users to engage with visual elements, navigate the metaverse freely, and experience an immersive digital environment (Zhao et al. 2022). Hardware (asset) data are visualised through software, and humans could control software and hardware through the Metaverse. Therefore, the interaction between the three parties is tightly intertwined.

2.2. Categories of industrial Metaverse

In this section, the different types of industrial Metaverses are explored for their similarities and differences in an industrial setting.

Industrial metaverse is highly based on its relationship between cyber world and physical world. Although there is a lack of detailed classifications based on the perspective of manufacturing processes, Himavamshi et al. (2024) and other researchers have reviewed studies on the application of AR/VR technologies in manufacturing and industry (S et al. 2024). While some of these use cases may not strictly qualify as part of the 'industrial metaverse', their work serves as a solid foundation for further exploration. Building on this foundation, we propose a categorisation that aligns with the natural flow of industrial production. Rather than classifying use cases based solely on technology or industry sector,

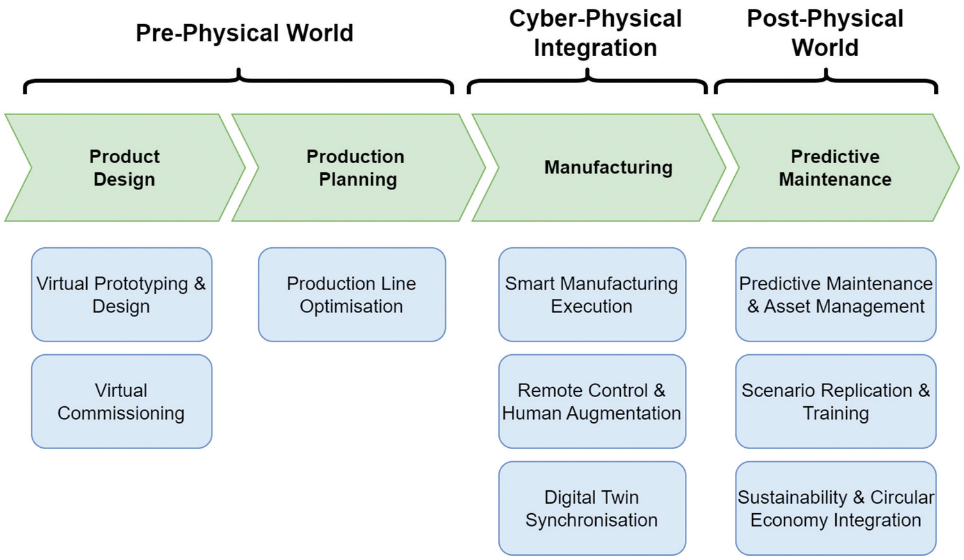

Figure 6. Categorisation of the industrial Metaverse based on the stages of industrial production.

our approach follows the sequence of industrial processes: from pre-production optimisation to real-time cyber-physical integration and post-production lifecycle management.

The Industrial Metaverse serves as a bridge between the digital and physical worlds. Based on the types and use cases of the industrial metaverse, the process of manufacturing with cyber-physical integration outlined in Section 1.3.1 has been further expanded. Following a production-order-based logic, the industrial metaverse is categorised into three major stages aligned with the natural flow of industrial production, as depicted in Figure 6.

(1) Before – Encompassing design and planning
(2) During – Focusing on real-time operations
(3) After – Covering maintenance, training, and optimisation

This structured framework ensures that metaverse applications are mapped directly to the stages of industrial production. This classification framework serves as a valuable reference for future users seeking to define their specific industrial metaverse environments and identify appropriate design methodologies.

Based on the categorisation of industrial Metaverses, a few typical industrial Metaverse use cases are summarised in Table 1, which brings a clearer understanding of different types of industrial Metaverses. Only papers that clearly represent the field with typical use cases focused on their corresponding categories.

3. Design principles for Metaverse and industrial Metaverse

3.1. Literature search methodology

This literature review is focused on industrial Metaverses and its design methodology. As illustrated in Figure 7, the process of literature search was conducted as follows: ***Step 1:*** The related keywords that are used to perform the search were listed below:

- Industrial Metaverse
- Metaverse Design Methodology
- Metaverse Design Framework
- Metaverse Design Principles
- XR metaverse Design
- XR industrial Design
- Metaverse Design Theory
- Metaverse Design Ethics

Based on these keywords, multiple search queries were formed for use in online databases such as Google Scholar, ScienceDirect, IEEE, Elsevier and ACM. The main query 'Industrial Metaverse AND Design' was used in searching digital libraries with additional restrictions on showing results only published after 2019. The additional queries added to the main query were 'Design Methodology OR Design Framework OR Design Principles OR Design Theory' was used in ACM digital library. This initial search resulted in 2650 articles in total.

After a certain design methodology is collected, a secondary search using the query '[Methodology name] AND Industrial Metaverse' was performed.

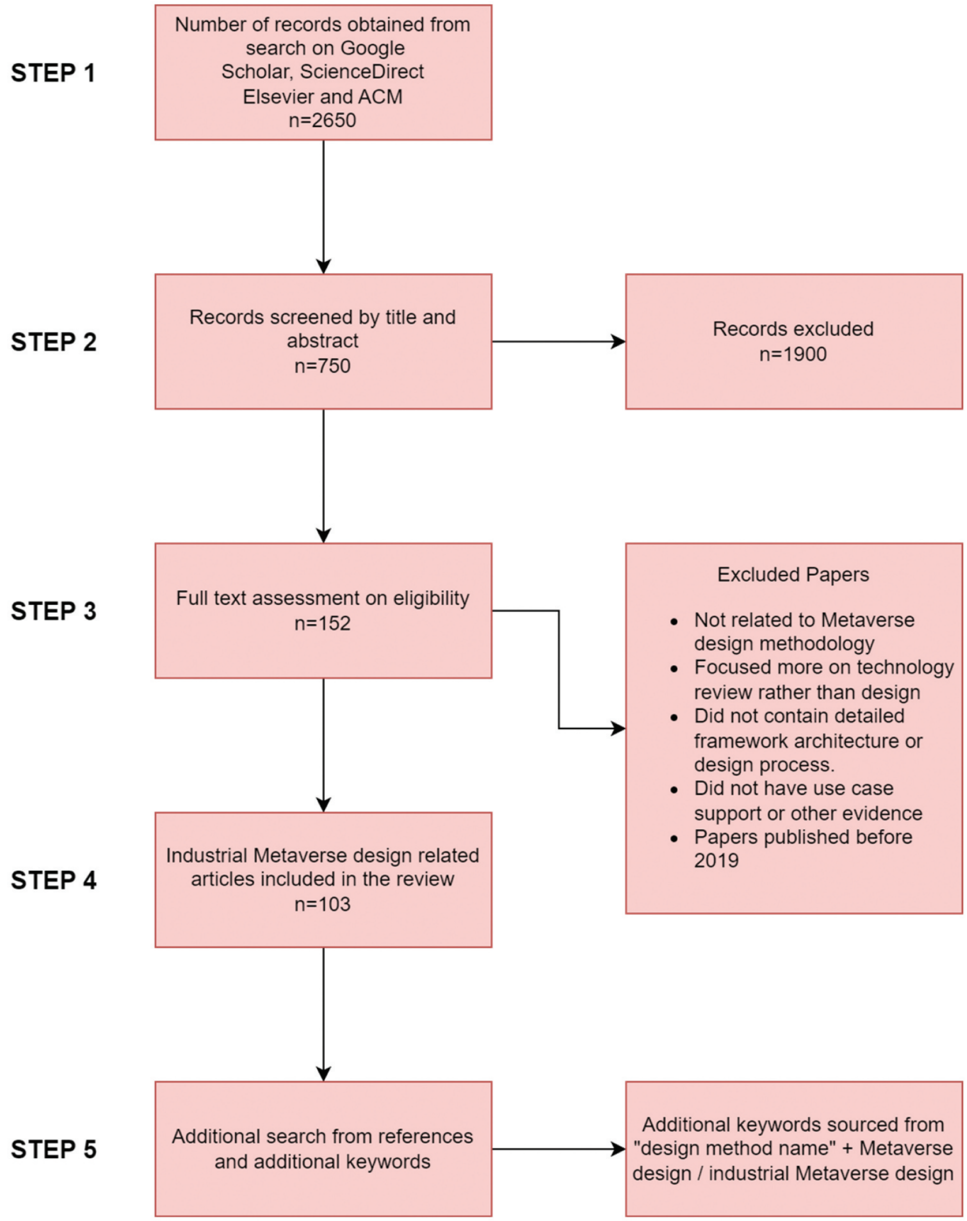

Figure 7. The literature search process.

Step 2: The second step is to determine the inclusion criteria for the literature so that papers out of scope are discarded. The title and abstract of the papers are then scanned by the inclusion criteria. The inclusion criteria are as shown.

- Language: only articles written in English
- Types of articles: journals, conference papers, books; literature review papers are excluded
- Themes: methodology and design of industrial Metaverse; industrial Metaverse frameworks, applications and use cases; Industrial Metaverse components and related design methodology of the components.
- Field: Engineering, Design
- Additional criteria for industrial Metaverse design are as follows:
  a. It should be applied and demonstrated using industrial examples.
  b. It should be published in peer-reviewed journals and adequately cited in the literature.
  c. All design methods mentioned must apply to the Metaverse as defined in before.

Around 750 articles were screened by their title and abstract, of which 152 are included for the next step.

Step 3: A more detailed full-text assessment is carried out in this step to further narrow excluded irrelevant papers. Out of the 152 papers, 103 papers were selected.

Table 1. Categorisation of Metaverse use cases.

Stage	Key Areas	Use Case	Reference
Pre-Physical World (Digital-First Optimisation & Planning)	Production Line Optimisation	AI-driven layout planning	(Arkouli et al. (2024); Choi et al. (2024); Gu et al. (2023a); Hovanec et al. (2023); Kour et al. (2022); Mourtzis, Panopoulos, and Angelopoulos (2022); Schranz, Strohmeier, and Damjanovic-Behrendt (2020); Y. Wang et al. (2021); Xie et al. (2024)
		Logistics flow analysis	(Gu et al. (2023a); Hovanec et al. (2023); Michalos et al. (2018))
		Energy efficiency simulation	(Alahmad et al. (2011); Lie et al. (2022))
	Virtual Prototyping & Design	Digital twin-based simulation	(Kent et al. 2021; Rane, Choudhary, and Rane (2023); Gruenefeld et al. (2022); Krauß et al. (2022); Grego, Nenna, and Gamberini (2024); Keshavarzi, Bidgoli, and Kellner (2020); Oppermann, Buchholz, and Uzun (2023); Pelliccia et al. (2021); Malik, Masood, and Bilberg (2020); Jagatheesaperumal and Rahouti (2022); Kuts et al. (2019); Xie et al. (2024); Yao et al. (2024); Yildiz, Møller, and Bilberg (2020); Adamenko, Kunnen, and Nagarajah (2020); Kour et al. (2022); Mourtzis, Panopoulos, and Angelopoulos (2022); Schranz, Strohmeier, and Damjanovic-Behrendt (2020); Silva et al. (2023); Tao et al. (2018); Y. Wang et al. (2021); Cecconi et al. (2020); Dimitropoulos et al. (2020); J. Lee and Kundu (2022); Lim et al. (2021); Y. Wang et al. (2022a); Zambiasi et al. (2023); Khanna, Karim, and Kumari (2024); Nikolakis et al. (2019); Bujari et al. (2023))
		Generative design	(Dong et al. (2023); Gruenefeld et al. (2022); Kent et al. (2021); Krauß et al. (2022); Rane, Choudhary, and Rane (2023); Yigitbas, Nowosad, and Engels (2023))
		Collaborative VR/AR design reviews	(Kent et al. (2021); Rane, Choudhary, and Rane (2023); Gruenefeld et al. (2022); Krauß et al. (2022); Dong et al. (2023); Ens et al. (2019); Fathianathan, Panchal, and Nee (2009); Krauß et al. (2021), S. Liu et al. (2023); Oppermann, Buchholz, and Uzun (2023); Pelliccia et al. (2021); Tian et al. (2023); Malik, Masood, and Bilberg 2020; Kour et al. (2022); Y. Wang et al. (2021); Dimitropoulos et al. (2020); Jagatheesaperumal and Rahouti (2022); J. Lee and Kundu (2022); Xie et al. (2024); Khanna, Karim, and Kumari (2024))
	Virtual Commissioning	Simulated testing of automation systems	(Kuts et al. (2019); Pelliccia et al. (2021); Xie et al. (2024))
		Robotics validation before deployment	(Kour et al. (2022); Malik, Masood, and Bilberg (2020); Xie et al. (2024))
Cyber-Physical Integration (Real-Time Industrial Operations & Monitoring)	Smart Manufacturing Execution	IoT-enabled production tracking	(Bujari et al. (2023); Kang et al. (2022); Khanna, Karim, and Kumari (2024); Mourtzis, Panopoulos, and Angelopoulos (2022); Rane, Choudhary, and Rane (2023); Schranz, Strohmeier, and Damjanovic-Behrendt (2020); Silva et al. (2023))
		AI-assisted quality control	(Bordegoni and Ferrise (2023); Danylec et al. (2022); Khanna, Karim, and Kumari (2024); Y. Wang et al. (2022a))
		Cyber-physical automation	(Rane, Choudhary, and Rane (2023); Malik, Masood, and Bilberg (2020); Xie et al. (2024); Kour et al. (2022); Mourtzis, Panopoulos, and Angelopoulos (2022); Schranz, Strohmeier, and Damjanovic-Behrendt (2020); Silva et al. (2023); Y. Wang et al. (2021); Jagatheesaperumal and Rahouti (2022); J. Lee and Kundu (2022); Lim et al. (2021); Y. Wang et al. (2022a); Cheng and Bateman (2008); Khan, Raouf, and Cheng (2011))
	Remote Control & Human Augmentation	AR-assisted machine operation	(Aivaliotis et al. (2024); Avalle et al. (2019); Green et al. (2010); Jagatheesaperumal and Rahouti (2022); Khan, Raouf, and Cheng (2011); Kour et al. (2022); Masoni et al. (2017); Oppermann, Buchholz, and Uzun (2023); Romero and Stahre (2021); Truong, Le, and Niyato (2023); Xie et al. (2024))
		Robotic telepresence for hazardous environments	(Aivaliotis et al. (2024); Avalle et al. (2019); Bavelos et al. (2025); Green et al. (2010))
	Digital Twin Synchronisation	Real-time data streams mirroring physical assets	(Bavelos et al. (2025); Jagatheesaperumal and Rahouti (2022); Nikolakis et al. (2019); Rane, Choudhary, and Rane (2023); Tao et al. (2018); Y. Wang et al. (2022a); Xie et al. (2024); Yao et al. (2024))
		Predictive analytics for operational efficiency	(Karki and Porras (2021); Khanna, Karim, and Kumari (2024); Lim et al. (2021); Mourtzis, Panopoulos, and Angelopoulos (2022); Schranz, Strohmeier, and Damjanovic-Behrendt (2020); Silva et al. (2023); Tao et al. (2018); Y. Wang et al. (2021); Yao et al. (2024))

(*Continued*)

Table 1. (Continued).

Stage	Key Areas	Use Case	Reference
Post-Physical World (Lifecycle Management & Continuous Optimisation)	Predictive Maintenance & Asset Management	AI-powered failure prediction	(Gu et al. (2023b); Lim et al. (2021); Tao et al. (2018))
		AR-guided repairs	(Avalle et al. (2019); Bordegoni and Ferrise (2023); Kour et al. (2022); J. Lee and Kundu (2022); Masoni et al. (2017); Zambiasi et al. (2023); Gavish et al. (2015); Joshi et al. (2021); H. Lee, Woo, and Yu (2022))
		Real-time condition monitoring	(Carreira et al. (2018); Cecconi et al. (2020); J. Lee and Kundu (2022); Lim et al. (2021); Romero and Stahre (2021); Gu et al. (2023b))
	Scenario Replication & Training	Digital twin-based industrial training	(Hovanec et al. (2023); Ren et al. (2024); Yildiz, Møller, and Bilberg (2020); Bordegoni and Ferrise (2023); Karki and Porras (2021); J. Lee and Kundu (2022); Masoni et al. (2017); Romero and Stahre (2021); Almeida et al. (2023); Danylec et al. (2022); Gavish et al. (2015); Joshi et al. (2021); H. Lee, Woo, and Yu (2022); Sacks, Perlman, and Barak (2013); Wolfartsberger et al. (2023))
		VR safety simulations	(Kuts et al. (2019); Apostolopoulos et al. (2022); Zambiasi et al. (2023); Almeida et al. (2023); Danylec et al. (2022); Gavish et al. (2015); Gu et al. (2023b); Joshi et al. (2021); H. Lee, Woo, and Yu (2022); Sacks, Perlman, and Barak (2013); Wolfartsberger et al. (2023))
		Remote skill development	(Bordegoni and Ferrise (2023); Kour et al. (2022); Mourtzis, Panopoulos, and Angelopoulos (2022); J. Lee and Kundu (2022); Masoni et al. (2017); Romero and Stahre (2021); Zambiasi et al. (2023); Almeida et al. (2023); Danylec et al. (2022); Gavish et al. (2015); Joshi et al. (2021); Khanna, Karim, and Kumari (2024); H. Lee, Woo, and Yu (2022); Sacks, Perlman, and Barak (2013); Wolfartsberger et al. (2023))
	Sustainability & Circular Economy Integration	Resource tracking	(Cecconi et al. (2020); Hovanec et al. (2023); Karki and Porras (2021); Truong, Le, and Niyato (2023))
		Lifecycle analysis	(Adamenko, Kunnen, and Nagarajah (2020); Cecconi et al. (2020); Karki and Porras (2021); Lim et al. (2021); Ren et al. (2024); Silva et al. (2023); Tao et al. (2018); Truong, Le, and Niyato (2023); Yao et al. (2024); Yildiz, Møller, and Bilberg (2020))
		End-of-life digital twin modelling	(Adamenko, Kunnen, and Nagarajah (2020); Silva et al. (2023))

Step 4: The retrieved papers were further assessed and categorised. Snowballing and citation searches are performed on these papers, increasing the number of selected papers. The papers are used in the following analysis.

3.2. Framework of industrial Metaverse

Before discussing the design methods for the industrial metaverse, finding an appropriate framework to divide the overall structure of the metaverse can help clarify thoughts and plan the levels that need to be considered in the design. Therefore, the authors reviewed the design frameworks for both the entire Cyber-Physical System (CPS) and the software aspects.

According to Dimitris Mourtzis, the industrial metaverse is a digital ecosystem where people and organisations work together using a human-centred approach to generate personalised value (Mourtzis 2023b). Within Cyber-Physical Systems, the architectural framework of the 3C (Connection, Conversion, Cyber) and 5C (Connection, Conversion, Cyber, Cognition, Configuration) CPS and self-adaptive CPS plays a crucial role, particularly in intelligent decision-making processes within complex production environments (Kayan et al. 2022; Mourtzis, Panopoulos, and Angelopoulos 2022; Petrovska et al. 2022). With the rapid advancement of spatial computing, the design of software platforms for the industrial metaverse, according to Mourtzis et al.'s summary, is divided into five stages: (1) enabling platforms; (2) content platforms; (3) human-centred platforms; (4) utility platforms; and (5) platforms for applications (Mourtzis 2023a, 2023b). It is worth noting that this structural foundation encompasses industrial technologies and communication protocols, ranging from user experience to the technologies involved in the industrial metaverse. This comprehensive consideration makes this framework highly applicable in the design of the industrial metaverse. Based on this five-layer framework, the authors can obtain a standardised design approach and summarise the relevant methodology accordingly.

Mourtzis thoroughly practised this framework in another study, fully integrating Digital twins, product lifecycle, and XR to design and develop a framework involving customers in the design phase of new products within the mass personalisation paradigm (Mourtzis, Angelopoulos, and Panopoulos 2022). The application of co-design can be identified, providing inspiration and insight for the XR design process. Ren et al. derived the industrial Metaverse model and architecture for smart manufacturing (Ren et al. 2024). They designed the industrial metaverse by dividing it into three parts: the network universe, the physical universe, and the social universe, all supported by an industrial AI brain. Additionally, they divided the industrial metaverse into eight architectures based on the different technologies needed.

From a technological perspective, the technology framework of a Metaverse can be summarised into five sections: (1) Communications and Computing Infrastructure; (2) Management Technology; (3) Basic Technological Foundations; (4) VR Object Connection; (5) VR Space Integration (H. Wang et al. 2023). These frameworks, based on the industrial metaverse, standardise its structure and provide an excellent conceptual model for the designers to consider when designing the industrial metaverse.

The authors classified the metaverse frameworks based on their applicability and scope, such as whether they consider both hardware and software design, focus solely on software platforms, or concentrate on technological design. The authors also summarised the hierarchical levels within these frameworks and the specific types of industrial metaverse they address. The selected frameworks should have logical reasoning or analysis behind each component they choose to use. The frameworks are shown in Table 2.

3.3. Categorising design methodologies in the Metaverse

Numerous design methods have been applied in the Metaverse and industrial Metaverse. When reviewing the design methods in the Metaverse, the authors found that methods from the fields of design science, social science, computer science, and industry are widely used. However, when the scope is limited to the industrial Metaverse, the mention and application of design methodologies significantly decrease.

Design methodologies for industrial applications have been classified along two axes: 'concrete vs. abstract' and 'individual vs. general'. The study by Tomiyama et al. identifies four main categories (Tomiyama et al. 2009).

'Concrete and Individual' methodologies focus on specific product classes, such as procedural knowledge for designing jet engines.

'Concrete and General' methodologies generalise design methods to be applicable across various products, including prescriptive design methodologies like those by Pahl and Beitz and DfX (Design for X) strategies.

'Abstract and Individual' methodologies use mathematical abstractions and computational methods for optimisation and engineering computation, targeting

Table 2. Frameworks of industrial Metaverse.

Type	Framework/Model	Description	Key Stages/Elements	Focus	Ref.
CPS	3C CPS	Cyber-Physical Systems framework focusing on Connection, Conversion, and Cyber.	Connection, Conversion, Cyber	Basic CPS architecture for intelligent decision-making.	(Kayan et al. (2022); Mourtzis, Panopoulos, and Angelopoulos (2022); Petrovska et al. (2022))
	5C CPS	Enhanced CPS framework adding Cognition and Configuration to the 3C model.	Connection, Conversion, Cyber, Cognition, Configuration	Advanced CPS with adaptive capabilities.	
	Self-Adaptive CPS	CPS with the ability to adapt to changing conditions autonomously.	Connection, Conversion, Cyber, Cognition, Configuration, Self-adaptation	Dynamic adaptation for complex environments.	
	Industrial Metaverse Model by Ren et al.	Industrial metaverse model divided into Network Universe, Physical Universe, and Social Universe, supported by an Industrial AI Brain.	Network Universe, Physical Universe, Social Universe, Industrial AI Brain	Integrative approach for smart manufacturing.	(Ren et al. (2024))
	Industrial Metaverse Architectures	Eight architectures based on different technologies required for the industrial metaverse.	1. Sensor and Actuator Network, 2. Communication Network, 3. Data Processing, 4. AI and Machine Learning, 5. XR, 6. Security, 7. Human-Machine Interaction, 8. Application Development	Comprehensive technological framework	(Ren et al. (2024))
	Three-layer Industrial Metaverse Architecture	System architecture of industrial metaverse from the perspective of new information and communication technologies	Infrastructure, core, and application layers	System Architecture	(Wenzheng (2023))
Software	Mourtzis' Five Stages	Framework for industrial metaverse design divided into five stages.	Enabling Platforms, Content Platforms, Human-Centred Platforms, Utility Platforms, Platforms for Applications	Comprehensive platform design approach.	(Mourtzis (2023b))
	Three layer framework from Duan et al.	A three-layer metaverse architecture from a macro perspective.	Infrastructure, interaction, and ecosystem	Macro perspective architecture for platform development	(Duan et al. (2021))
Technology	Five Section Technology Framework of a Metaverse	Structural model from a technological perspective	Communications and Computing Infrastructure; Management Technology; Basic Technological Foundations; VR Object Connection; VR Space Integration	Technological foundation framework	(H. Wang et al. (2023)).

specific design goals like the Taguchi method for quality design.

'Abstract and General' methodologies, such as Yoshikawa's General Design Theory (GDT), conceptualise design processes and activities as knowledge operations. Across these methodologies, the design process is commonly seen as a logical sequence of phases, although differences in model scope and iterations exist. The ultimate goal is to advance toward a universal design theory, though intermediate forms exist that are either more general or more abstract but still concrete or individual.

In short, methods categorised in 'general' should be applicable to all kinds of Metaverse design, whereas 'individual' methods are not applicable to all types of Metaverses; Methods in 'abstract' are more loosely defined, whereas methods in 'concrete' should have a more robust theory or implementation procedure.

Based on this classification standard, the authors attempted to categorise the design methods used in Metaverse and industrial Metaverse. The methods appear in two forms: one is the existing methods that authors use when designing the Metaverse, and the other is new frameworks and methods summarised or proposed through empirical research and other means.

3.4. Design methodologies in the industrial metaverse

The authors have summarised the usage and application cases of these methods in the metaverse, as shown in Table 3.

Compared to the design methods for the broader Metaverse, the methods here have three additional criteria:

- The keywords must include 'industrial Metaverse'.
- They belong to a category described in section 3.2 of the industrial Metaverse.
- The methodologies should be applicable in business-to-business environments where product and service development is complex and influenced by numerous factors.

Table 4 distinguishes between methods that are generally applicable in the Metaverse ('General') and those that are only applicable to specific types of Metaverses ('Individual').

3.4.1. General design methodologies in the industrial Metaverse

Based on the summary above, several general methods can be applied to the design process of all types of Metaverses. These methods have been structured according to the design steps of Design Thinking, as summarised in Figure 8. Based on the summary above, several general methods can be applied to the design process of all types of Metaverses. These methods have been structured according to the design steps of Design Thinking, as summarised in Figure 8.

Design Thinking, as a formal method for problem-solving and innovation, has gained significant attention in various fields and is widely used in metaverse design and industrial metaverse design (Menon and Menon 2023; Pintado et al. 2023; Sisamud, Chatwattana, and Piriyasurawong 2023). Based on the table above, the authors attempt to summarise the general design methods (including both abstract and concrete) in the Metaverse and industrial Metaverse and applies them to the different design stages in Design Thinking.

Table 3. Classifying the design methods used in the Metaverse.

General Metaverse	Abstract	Concrete
General	**Phenomenology** (S. K. Kim et al. (2023); B. Wang, Gao, and Shidujaman (2024)), **Design thinking** (Menon and Menon 2023; Pintado et al. 2023; Sisamud, Chatwattana, and Piriyasurawong 2023), **Empirical case study** (Kour et al. (2022); Meng et al. (2023a); Sisamud, Chatwattana, and Piriyasurawong (2023); Song, Yoon Shin, and Seong Shin (2023)), **Human-centred design** (Ricci, Scarcelli, and Fiorentino (2023); Singla et al. (2023); R. Yang et al. (2023)), **Modular-based framework** (Fernandez and Hui (2022)), **Affordance-based design** (Singla et al. (2023)), **Universal Design Principles** (Singla et al. (2023)), **Three kinds of visual elements and the two graphical construction methods** (Zhao et al. (2022)), **Multidisciplinary Approach** (Ricci, Scarcelli, and Fiorentino 2023), **Ethical design** (Fernandez and Hui (2022); Prillard, Boletsis, and Tokas 2024)	**Double diamond** (Cobben (2024); Rian, Triayudi, and Diana Sholihati 2024; Z.; Z. Liu et al. (2022)), **Quantitative analysis method** (Chen, Jin, and Chen (2024); Ricci, Scarcelli, and Fiorentino (2023); Zhang and Wang (2023)), **Qualitative analysis method** (Chen, Jin, and Chen (2024); Singla et al. (2023); Thomas et al. (2023); Zallio and John Clarkson (2022b)), **Ethnographic study** (Zallio and John Clarkson (2022a)), **Storytelling** (Zhang and Wang (2023); S.; S. Yang (2023)), **Co-design** (Garcia et al. (2023); Meng et al. (2023a); Nickerson et al. (2022)), **Participatory design** (Abramov et al. (2024)), Meng et al. (2023)), **Prototyping** (Kent et al. (2021))
Individual	**A framework for gamification** (Thomas et al. (2023)), **Block technologies framework** (Ali et al. (2023)), **Hyper-connected meta-environment framework** (Guan and Morris (2023)),	**Pilot study** (T. Kim, Planey, and Lindgren (2023))

Table 4. Classifying the design methods used in the industrial Metaverse.

General Metaverse	Abstract	Concrete
General	**Integrating Systems Thinking** (Menon and Menon (2023)), **Industrial foundation models (IFM)** (J. Wang et al. (2023)), **Framework of the industrial metaverse** (Chi et al. (2023)), **IM's driving technologies framework** (Nleya and Velempini (2024)), **Design thinking** (Ricci, Scarcelli, and Fiorentino (2023)), **Empirical case study** (Rane, Choudhary, and Rane (2023)), **Human-centred design** (Grego, Nenna, and Gamberini (2024); Mourtzis (2023c))	**Co-Design** (Almeida et al. (2023)), **Prescriptive design** (Kang et al. (2022); Pelliccia et al. (2021))
Individual	**Co-design framework for minimising communication load in the metaverse** (Meng et al. 2023b), **Method for developing immersive metaverses for industrial training** (Almeida et al. (2023)), **Toolbox in industrial setting** (Oppermann, Buchholz, and Uzun (2023)), **Service-oriented architecture in conjunction with metaverse-enabled platforms** (J. J. Lee and Kundu (2022)), **System framework with a mixed reality (MR) on-site assessment tool, concept of Industrial Metaverse for smart manufacturing systems** (J. J. Lee and Kundu (2022)), **Co-design of sensing communication control and computing in Industrial Metaverse** (Meng et al. (2023a)), **Service-oriented digital twin architecture with Metaverse-enabled platforms** (Mourtzis (2023a)), **Micro-service architecture based modular collaborative system** (Dong et al. (2023)), **WYSIWYG (What You See Is What You Get) editor** (Gruenefeld et al. (2022)), **Mass Collaborative Product Realisation (MCPR) platform** (Fathianathan, Panchal, and Nee (2009)), **Knowledge-based decision support system** (Gleadall et al. (2016))	**A bottom-up inspection device development workflow** (Y. Wang et al. (2022b)), **Specific optimisation methods for industrial MR applications** (S. Liu, Xie, and Wang (2023)), **Fuzzy analytic hierarchy process** (S. Liu, Xie, and Wang (2023)), **Hybrid AI Optimisation** (Xie et al. (2024)), **Heatmaps & Spaghetti Charts** (Arkouli et al. (2024); Michalos et al. (2018)), **Proposed systematic methodology with proof-of-concept case study** (Hosseini et al. (2024)), **Process Simulation** and **Lean Analysis and Reconfiguration** (Hovanec et al. (2023)), **Graph matching**, and **case-based reasoning** (Dong et al. (2023)), **Computer-aided participatory design** (Pelliccia et al. (2021)), **Deep reinforcement learning** and **Agentic AI** (Ali et al. (2023); Choi et al. (2024))

In the user-centred metaverse design process, many general design principles and methods can be used to ensure a positive user experience. These principles are widely applied in UX design, and due to the importance of UX and the universality of these principles, they hold significant value in metaverse design. However, in the design process of the industrial metaverse, there are not many cases of using these methods to design the user experience.

Therefore, following a user-centred design process and referencing the design process can improve the user experience of the industrial metaverse. This approach can shorten the learning curve, improve efficiency, and increase user adoption of the industrial metaverse.

Participatory and collaborative design are methods for collecting creativity and innovation from different participants, including various stakeholders. While participatory design has a structured process emphasising participant input and feedback, design decisions primarily rest with the organiser. Co-design on the other hand, is an extension of participatory design with a broader scope, is more flexible and iterative, and focuses more on creativity and innovation. Participatory design has been used in the design of Metaverse and industrial systems, including use cases in designing a changeable manufacturing system, design methods for digital photogrammetry and Gaussian splatting in the metaverse, and computer-aided participatory design sessions for developing industrial workplaces and processes (Abramov et al. 2024; Andersen et al. 2018; Pelliccia et al. 2021). Participatory design and collaborative design methods align well with the design process requirements of industrial Metaverses, where many stakeholders are involved with different needs and requirements. The two design methods allow stakeholders to communicate their needs directly with the designers, allowing a smoother and more efficient design process.

Storytelling has been used in Metaverse to create innovative and enriching cultural Metaverses, improving user engagement in an immersive cultural experience (S. Yang 2023). 3D storytelling has also been used for users to create and explore virtual environments, control characters and cameras, perform actions from context-generated options, and automatically generates storyboard panel descriptions based on user activities (Manuri, Sanna, and De Pace 2023), which would be a hugely beneficial to user experience in industrial Metaverses. The above use cases show storytelling as a powerful tool for the industrial Metaverse due to its ability to convey complex information, engage users, and enhance learning experiences. Whether assisting designers in gaining a more intuitive understanding of complex industrial scenarios during user research or providing a more visual representation of ideas to users unfamiliar with industrial environments or the metaverse before beginning prototyping, storytelling excels at simplifying complex concepts and enhancing user engagement.

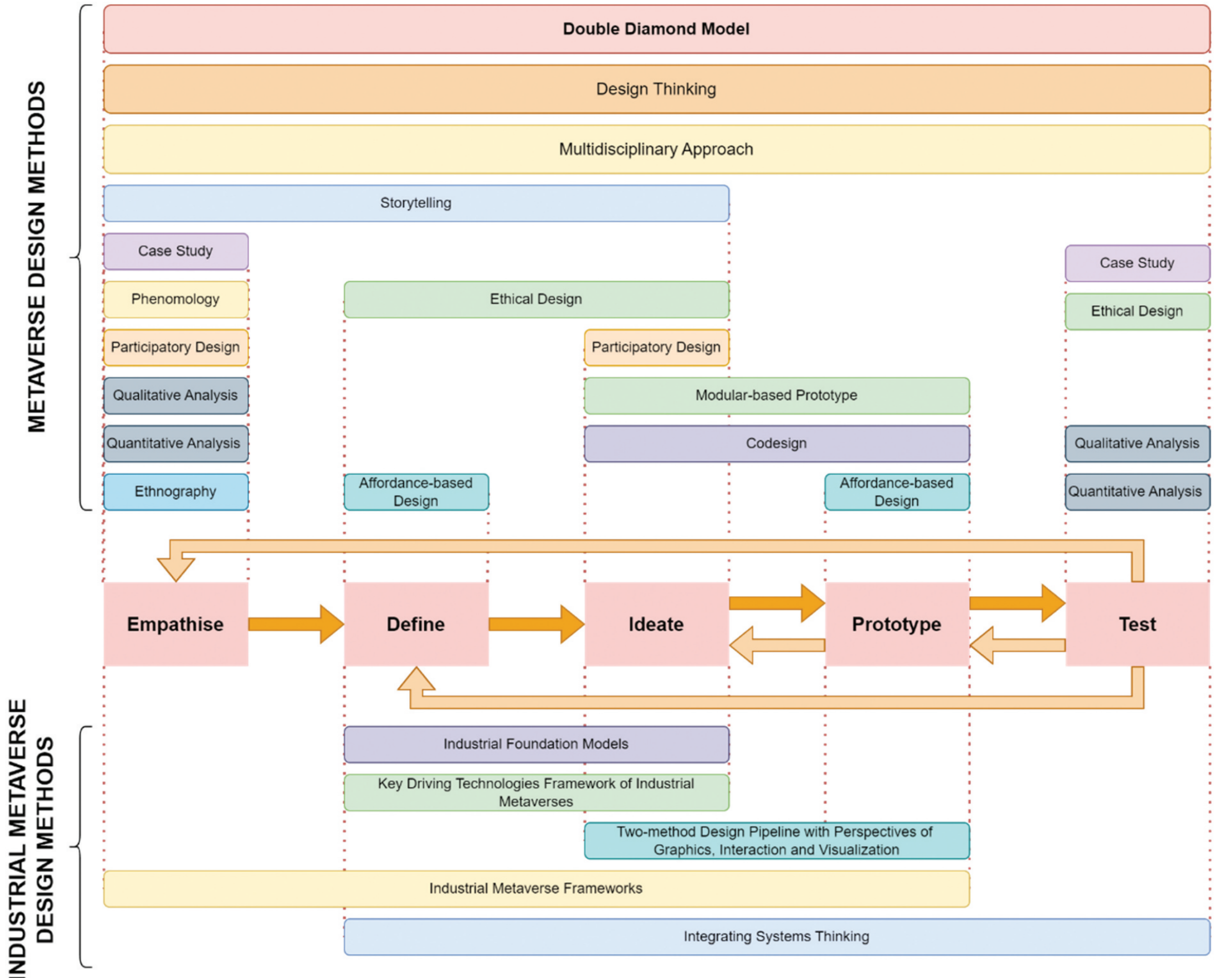

Figure 8. Summary of the design methodologies that can be applied to different design steps during the development of an industrial Metaverse.

Ethical design in the metaverse is a critical consideration as virtual environments become more integrated into daily life and industry practices (Fernandez and Hui 2022). Prillard et al. documented privacy challenges in the user onboarding process of Meta Horizon Workrooms, and proposed a set of ethical design approach such as informed user interfaces, privacy icons, anonymisation, and enhanced consent procedures to address issues of data privacy awareness and transparency (Prillard, Boletsis, and Tokas 2024). Compared to the general Metaverse, which emphasises social, entertainment, and cultural experiences, the Industrial Metaverse focuses on business and industrial applications such as manufacturing, logistics, and workforce training. Consequently, it prioritises data security, workplace safety, and operational efficiency. Therefore, ethical design methods, while addressing fundamental concerns like privacy, inclusivity, and security, are particularly valuable and need further development at every stage of Industrial Metaverse design.

3.4.2. Individual methodologies in the industrial Metaverse

Regardless of the type of industrial metaverse being designed, the design steps within high-level design methodologies remain applicable. Moreover, certain specialised design approaches could potentially be applied to similar types of industrial metaverse designs that are within the same stage of industrial production. After reviewing articles on the industrial metaverse and based on the industrial process framework and classification outlined in Section 2.2, the applicable methodologies for specific industrial metaverses have been summarised in Figure 9 below.

3.4.2.1. Pre-physical world.

In the pre-physical world, the industrial Metaverse serves as a planning, optimisation, and design tool for previewing the physical world. It aims to provide an intuitive representation of plans within a virtual environment without committing resources to physical production. At this stage, different

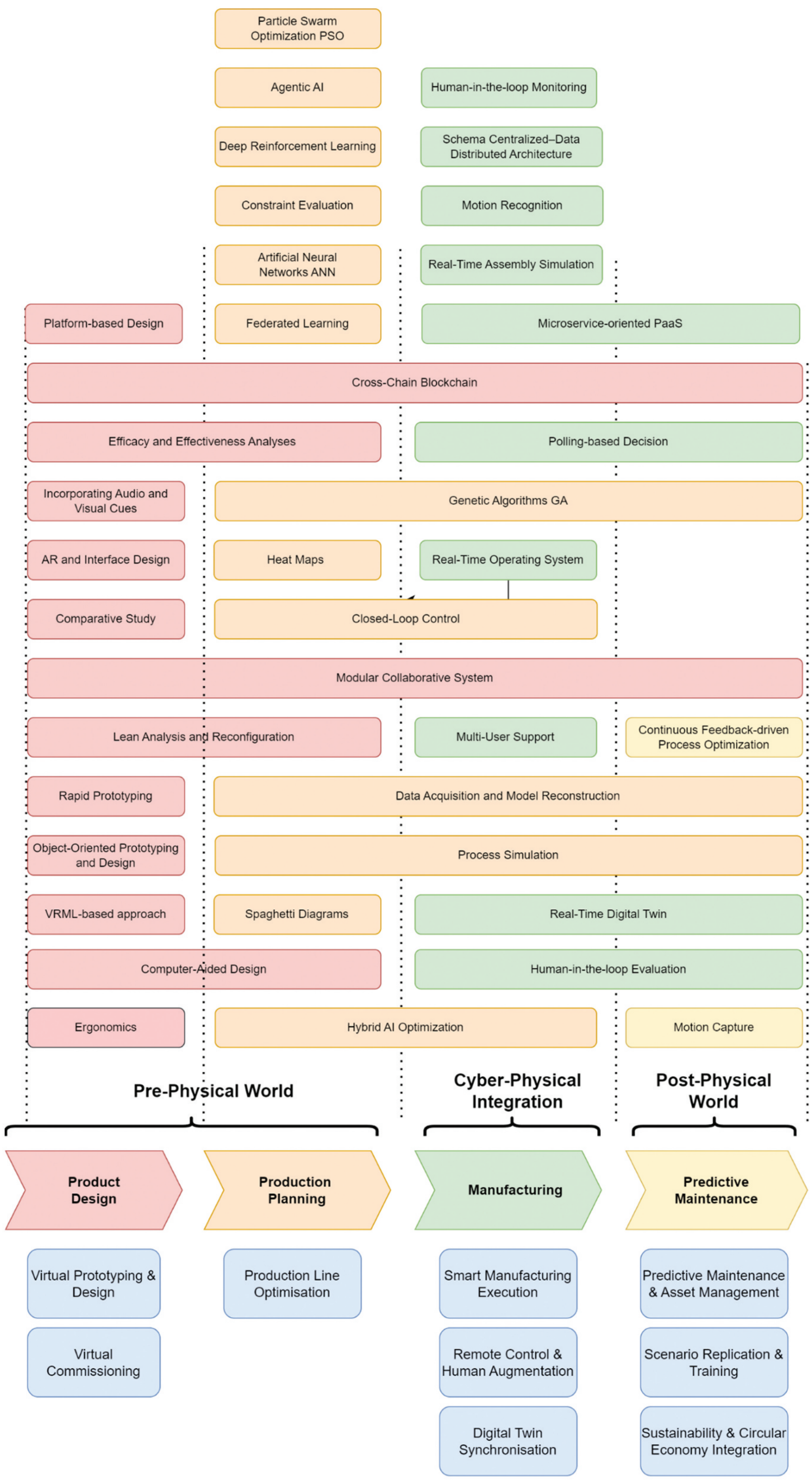

Figure 9. Methodologies found in different steps within a CPS design process.

simulation methods are needed depending on the object being simulated.

For example, Hybrid AI Optimisation can be used to automate layout generation, Human-in-the-loop Evaluation in virtual reality can help simulate, assess, and refine designs. Motion capture and ergonomics can be applied to generate visualisations such as spaghetti diagrams and heat maps (Arkouli et al. 2024; Dimitropoulos et al. 2020; Michalos et al. 2018; Xie et al. 2024)

For the optimisation of factory layouts, several general design methodologies, such as Genetic Algorithms (GA), Particle Swarm Optimisation (PSO) techniques, and Artificial Neural Networks (ANN), have been used. However, depending on the specific type of optimisation, different design approaches are also be considered. For instance, when utilising the industrial metaverse for energy efficiency, a Virtual Reality Modelling Language (VRML)-based approach can be employed for the 3D visualisation of energy-efficient buildings (Alahmad et al. 2011; Lie et al. 2022). For optimisation based on material flow and production processes, Process Simulation and Lean Analysis and Reconfiguration are two commonly used design methodologies. Process simulation helps identify inefficiencies within the system, while lean manufacturing concepts are applied to pinpoint and eliminate waste in the production process (Hovanec et al. 2023). For repetitive layouts or parametric layouts, generative design is an efficient approach to reduce repetitive workload. Approaches include traditional mathematical methods such as graph matching, and also AI-powered methods such as case-based reasoning (Dong et al. 2023).

Real-Time Assembly Simulation allows operators to follow step-by-step assembly sequences in a virtual environment. Although this approach is more commonly used as a component of digital twin systems, it provides engineers with the opportunity for rapid feedback and iterative design before the physical assembly sequence is fully implemented. This enables engineers to refine designs and optimise processes without the need to build physical prototypes. Computer-Aided Design (CAD) plays a crucial role in industrial metaverse design, enabling simulation-based testing before physical deployment. Physical robots, industrial equipment, and factory layouts are first designed in CAD software.

The use of CAD such as computer-aided participatory design (PD) for industrial workplaces (Pelliccia et al. 2021) emphasises the need for collaborative industrial Metaverse design methods. In industry-level projects, collaboration is crucial since designs tend to be big and complex, requiring many designers and maintainers over a period of time. With collaborative design methods, design processes could be parallelised, increasing efficiency. Numerous collaborative design approaches have been suggested for industrial Metaverses, including the use of micro-service architecture to build a modular collaborative system (Dong et al. 2023). Another approach is implementing a WYSIWYG (What You See Is What You Get) editor, which is a toolkit that allows multi-user collaboration and remote prototyping (Gruenefeld et al. 2022). The Mass Collaborative Product Realisation (MCPR) platform provides another solution by implementing mechanisms on community-based team members, broadcasted message information sharing, managerial assignment of task assignments, and a polling-based decision mechanism (Fathianathan, Panchal, and Nee 2009), which has the scalability to realise mass collaborations.

Data Acquisition and Model Reconstruction are widely applied in the simulation of factories and office spaces. This process involves utilising resources such as CAD drawings and floor plans to ensure that the simulated environment accurately represents the factory workshop layout. The use of a '5 W +2 H' method (what, when, why, who, where, how, and how much) helps in pre-planning and iterative optimisation of assembly tasks (Xie et al. 2024).

When the design focus shifts to object-based prototyping and design (e.g. machines), in addition to using traditional 3D design software such as NX, CAD, SolidWorks, and Rhino, other approaches like rapid prototyping and multi-user support can also be considered to enhance the design process.

3.4.2.2. Cyber-physical integration. In the Cyber-Physical Integration stage, the industrial metaverse serves as the interface between the physical and digital worlds, with the virtual environment used for monitoring, optimising, and controlling real-world industrial operations. It is tightly connected to real-world industrial assets, functioning as a real-time digital twin. This implies that numerous design methodologies are required to support the development of the industrial metaverse at this stage, including data collection, processing, and transmission, as well as design and validation methods to ensure cyber-physical system (CPS) consistency. In practice, the design of the Physical Integration Stage focuses on how to execute the manufacturing operations (using digital twins), how to (remotely) control the manufacturing operations, and how to synchronise the digital twins.

A digital twin architecture based on Apache Kafka, an open-source distributed event streaming platform for high-performance data pipelines, streaming analytics, data integration, and mission-critical applications, has been proposed by (Schranz, Strohmeier, and Damjanovic-Behrendt 2020). The proposed architecture focuses on providing scalable data streaming and event processing, while also distinguishes between two types of stakeholders: applications running on CPSs for sensor data management and multi-end-users interacting via web or mobile interfaces with dedicated APIs. This proposal was tested on a prototype that collects smart vehicle's sensor data and exchanges these data between multiple stakeholders along the vehicles' lifecycle phases. IoT is used in many industrial Metaverse applications as a means of obtaining data. Several Frameworks on IoT have been published, including a privacy-preserving framework for industrial metaverses using federated learning and cross-chain blockchain technology on Industrial IoT (IIoT) nodes to selectively upload non-sensitive data to the virtual space for learning-based tasks while keeping sensitive data in the physical space. It maintains data freshness with an Age of Information (AoI) metric and preserves privacy (Kang et al. 2022). The integration of Industrial IoT (IIoT) with the Metaverse is also poised to enhance smart manufacturing by enabling real-time, intelligent, and flexible production processes. A study proposes a layered architecture integrating Industrial IoT (IIoT) with the Metaverse to enhance smart manufacturing. Digital Twins enable human-in-the-loop monitoring, ensuring system stability. Middleware technology supports QoS needs for operational monitoring, while a virtual layer processes data for Metaverse applications via a microservice-oriented Platform as a Service (PaaS) layer. The approach is demonstrated through two proof-of-concept applications: real-time network monitoring and visual asset inspection (Bujari et al. 2023).

With data obtained from digital twins and IoTs, industrial Metaverses allow users to remotely control and perform operations. (Paper3) proposes an AR framework integrated with a robot controller, real-time operating system (ROS), and OpenFlow for seamless interaction between virtual and physical components in an industrial setting. OpenFlow acts as the main information hub for the AR application, delivering real-time updates on tasks assigned to human operators and seamlessly incorporating data from the Digital Twin. This framework was tested on two case studies from the automotive and white good industries, showcasing its ability to provide assembly guidance, robot control, interaction with tools, resilience to robot action failures, and awareness of quality inspection results.

Since behaviour simulation is a crucial component of the digital twin framework, accurate real-time data collection is crucial, done often in combination with sensor fusion technologies and internet and cloud capabilities. Additionally, Closed-Loop Control is a key design methodology to ensure that the digital twin remains continuously updated with real-world data. A digital twin-based closed-loop CPS is proposed by Nikolakis et al., integrating a physical system with a cyber system via a digital twin within a closed-loop control system to optimise assembly operations (Nikolakis et al. 2019). The physical system, modeled as a discrete event LTI system, interacts with a cyber counterpart that simulates processes, refines inputs, and optimises outputs based on real-time sensor data. Motion recognition and constraint evaluation enhance simulation accuracy, improving efficiency. By bridging physical and virtual components, the CPS enables continuous, feedback-driven process optimisation in manufacturing.

For remote control, achieving realistic manipulation relies on an interaction manager, which listens for user input and manages seamless and intuitive user interactions within the industrial metaverse. A study presents an Industrial Dataspace for Machining Workshop (IDMW) to manage the increasing complexity of machining processes and data, supporting machining operation control in virtual manufacturing. The three-layer IDMW framework follows a Schema Centralised – Data Distributed architecture, utilising a Process-Workpiece-Centric knowledge schema and decentralised data storage. Industrial case studies demonstrate IDMW's effectiveness in managing heterogeneous data, interconnecting resources, and enhancing machining operations control (Li et al. 2022).

3.4.2.3. Post-physical world. At the Post-Physical World stage, after physical production is completed, the industrial metaverse functions as an extended support system, integrating asset management, predictive maintenance, and workforce training within one platform, while continuously enabling interactions between the physical and virtual worlds. Moreover, ensuring scalability and interoperability is crucial for the future development of the industrial metaverse.

To enhance security and privacy-preserving model training across Industrial IoT (IIoT) nodes in both the physical and virtual domains, a layered blockchain or private blockchain architecture can be employed (Abramov et al. 2024; Ali et al. 2023; Kang et al. 2022; Z. Liu et al. 2022).

Predictive maintenance usually requires real-time data analysis, and the system is expected to make dynamic decisions based on the analysis results. Therefore, Deep reinforcement learning and Agentic AI are widely considered for decision-making and continuous path optimisation (Ali et al. 2023; Choi et al. 2024).

For manual maintenance, AR and interface design can provide users with more intuitive guidance. AR can overlay real-time instructions onto physical components, reducing cognitive load and improving task efficiency. Additionally, interactive interfaces can enhance user experience by integrating visual cues, step-by-step guidance, and real-time system feedback. Future research should explore how AI-driven adaptive interfaces can further optimise user interactions and improve maintenance accuracy (Himavamshi et al. 2024; Aivaliotis et al. 2024).

When replicating physical-world scenarios for training or teaching purposes, the accuracy of scene replication and the realism of interactions directly impact training outcomes, unlike pre-created virtual environments. Incorporating audio and visual cues to guide users through the training process can enhance the user experience, creating a more intuitive and immersive training environment (Joshi et al. 2021; H. Lee, Woo, and Yu 2022). However, systematic validation methods for ensuring model accuracy still require further exploration and research.

For validating scenario-based training models, comparative studies between VR and traditional training methods are commonly used to assess training effectiveness. These studies determine the superiority of VR-based training using metrics such as knowledge acquisition, retention, and user engagement. Efficacy and effectiveness analyses are conducted to evaluate the performance of VR training modules (Joshi et al. 2021; H. Lee, Woo, and Yu 2022; Sacks, Perlman, and Barak 2013; Wolfartsberger et al. 2023)

Whether for training or maintenance, teamwork and communication are crucial aspects of the industrial Metaverse. The inclusion of multiple roles and multi-user interaction in virtual environments allows multiple users to engage in the same virtual space, enabling training sessions (H. Fathianathan, Panchal, and Nee 2009; H. Lee, Woo, and Yu 2022; Oppermann, Buchholz, and Uzun 2023)

Platform-based design is an approach in engineering and software development that focuses on creating a set of common components or platforms, which can be reused and adapted to develop a variety of products or applications (Sangiovanni-Vincentelli et al. 2004). It has been widely used in the automobile industry, where car platform refers to the evolution of automobile design, development, production, form, and use that is reliant on increased connectivity, programmability, modularity, integration, and data collection within, between, and among vehicles (Hind, Kanderske, and van der Vlist 2022). In the industrial metaverse, this approach has the potential for entirely new applications, shortening the construction time of the industrial metaverse and improving the efficiency of the industrial metaverse. Unfortunately, there isn't any literature that uses this concept in industrial metaverse. However, there are still some projects that have integrated the idea of platform-based design in manufacturing. For example, they have reused existing technologies or elements, or modularised design components. A typical car platform could have six levels of platforms that could be summarised as from the aspects of vehicle hardware and materials to software development and engineering, as well as connectivity and urban infrastructure considerations (Hind, Kanderske, and van der Vlist 2022). This idea of 'car platform design' could also be used in the design of industrial Metaverses, where the Metaverse platform is designed with hardware to software to connectivity and to user experience in mind. Although this concept is yet to be seen in Metaverse design methodology, there are a few use cases of platform-based design in manufacturing.

Gleadall et al. contribute a knowledge-based decision support system focusing on product design and process chain selection in hybrid manufacturing platforms. This system integrates manufacturing expertise into the design process (Gleadall et al. 2016). Napoleone et al. revisit the concept of reconfigurable manufacturing systems (RMS) and propose a four-step design methodology, emphasising the necessity of tools to support each step. Although the solutions for specific problems differ, they are all based on production steps, cost savings, and improving production efficiency. Although the solutions for specific problems are different, they are all based on production steps, aiming to save costs and enhance production efficiency.

Moussa and ElMaraghy developed a non-linear model for designing optimal multi-period additive/subtractive product platforms. Their model manages inventory considering changing customer demands and utilising partially completed platforms (Moussa and ElMaraghy 2022). This approach focuses on enhancing production flexibility. Similarly, addressing this aspect is the concept by Riesener et al., which aims at interdisciplinary module design within mechatronic modular product platforms. This concept optimises product variety by considering component interfaces across different disciplines (Riesener et al. 2023). In an industrial metaverse, the ability to integrate and modify different components swiftly is vital. Simultaneously, providing component interfaces across different disciplines offers expanded possibilities for integrating manufacturing expertise and technologies such as AI, and DT, among others.

3.5. Interoperability and integration

By comparing the design methods used in the metaverse and the industrial metaverse, the authors identified significant differences. In the metaverse, more than 10 concrete methods are applied alongside abstract methodologies. However, when focusing on the industrial metaverse, the use of general and concrete methods is significantly reduced, while many abstract frameworks specifically for the industrial metaverse emerge. These frameworks often lack specific content; they describe their concepts without providing concrete, practical methods. As a result, the design process and methods remain unclear and lack broader application scenarios. Notably, numerous abstract and individualised frameworks have been developed.

Just as no single tool solves every real-world problem, no single input device, concept, or interaction technique suits all XR applications (Hillmann 2021). While consistent interaction metaphors are generally preferable, they are not always appropriate. Interaction designers should consider the specific task when choosing, modifying, or creating new interactions.

Looking back at existing research, it's evident that the methodologies of AR, VR, and the Metaverse, when applied in the field of the industrial metaverse, tend to be rather one-sided and fragmented, addressing only specific stages of the process. Therefore, in attempting to establish a systematic methodology for the Industrial Metaverse, the authors can base it on human-centred design concepts and design thinking. By integrating and reconstructing these methods across various stages of product development, a new set of methodologies can be formed.

4. Challenges and limitations in designing the industrial Metaverse

4.1. Technical challenges

4.1.1. Lack of standardised and scalable metaverse design methodologies

Since the boom of Metaverse and Metaverse-related research, the authors have seen implementations of Metaverse across a vast variety of use cases and applications. Since the birth of Metaverse, one of the most successful applications is in games such as Roblox ('Roblox' 2024). However, as far as the industrial metaverse is concerned, it is still in its early stages of development and has several limits (Ren et al. 2024). Companies in the game industry tend to develop their version of Metaverse, as such that two Metaverses of different companies are completely incompatible with each other. Unlike gaming, where companies develop independent and often incompatible Metaverse solutions, industrial applications require interoperability, scalability, and adaptability to complex manufacturing environments.

This paper has presented numerous studies with proposed Metaverse design methodologies and frameworks; however, these solutions are mostly tailored to specific industrial use cases and lack generalisability. Many are validated only within a limited scope, making it difficult to assess their scalability across a wide range of manufacturing environments. Addressing this gap requires a systematic approach to developing industrial Metaverse architectures that are capable of adapting to new manufacturing environments while also retaining compatibility with existing manufacturing systems.

4.1.2. Strict specifications for data throughput, latency, accuracy, reliability, and storage

Industrial use has strict requirements for data throughput, latency, accuracy, and reliability (Cao et al. 2023), which could be hard to account for in a general design methodology. The more complex the manufacturing operations are, the more IoT sensors are needed, and the more data is generated and transferred per second, the more processing power is required (Chi et al. 2023). For example, in semiconductor inspection lines, a throughput of approximately 2x10^9 pixels are captured each second, requiring high-speed and reliable data transfer and processing (1999). Digital twins also have high data transfer and low latency requirements, as low as 1 ms latency requirements. Industrial applications require reliable hardware and software, which can be difficult to achieve considering the complexity of a Metaverse system. However, Blockchain technology, digital avatars, and digital asset transactions, etc, will pose further constraints, as transaction times for these technologies often exceed seconds to minutes, which is incompatible with real-time process control (Chi et al. 2023).

4.1.3. Challenges in sustaining long-term software maintenance and support

Industrial Metaverse implementations rely on diverse software ecosystems, including physics-based simulation engines (e.g. Siemens NX, Ansys) and proprietary middleware. However, technology stacks in the field of computer science evolve rapidly, with new software, languages, and platforms gradually replacing older software, languages, and platforms (Madhavji, Fernandez-Ramil, and Perry 2006). Most industrial software vendors provide long-term support cycles in the range of 5–10 years. However, after these support cycles, legacy manufacturing systems face challenges in renewing outdated software that are no longer maintained. This issue becomes even more severe as Metaverses typically rely on many software stacks from different providers, making long-term support management cumbersome and challenging. To make matters worse, long-term support for this software is crucial as industrial Metaverses require high stability and reliability.

4.1.4. Issues with cross-technology and cross-platform compatibility

Compatibility in Metaverse can be described in two aspects, there are compatibility issues between Metaverses created by different companies or platforms, as well as challenges in ensuring compatibility between Metaverses and the real world (H. Wang et al. 2023). The technologies used in industrial Metaverse, such as blockchain, digital twins, and IoT follow different communication and data protocols, APIs, speed, and architecture. Their respective core intellectual property is held by different companies, for example, Siemens has the capability to build one of the world's most comprehensive digital twin ('The Role of Digital Twin in Advanced Manufacturing - Siemens US' 2024), whereas blockchain is entirely decentralised. This cross-technology compatibility challenges the integration of different technologies into the Metaverse while maintaining mutual data communications. The collaborative nature of industrial Metaverses also requires designers to take extra care in cross-platform compatibility. Users will expect to be able to access their industrial Metaverse not only through XR headsets but also from their computers, servers, and phones. This poses a challenge for cross-platform Metaverse development as reliability cannot be compromised not on one but on all platforms, which increases costs and time.

4.1.5. Complexity in balancing customisability and modularity within industrial Metaverses

Building a functional industrial system is complex, but companies across various industries can effectively manage complexity by modularising product architectures and implementing targeted platform and module strategies ('Platforming and Modularity: Smart Answers to Ever-Increasing Complexity | McKinsey' 2024). Considering the complexity of industrial processes, it is logical to pre-build the most common building blocks used in the Metaverse. However, even with modularity, the building blocks are still required to be highly customisable. This additional modularity and flexibility come at the cost of increased complexity and vulnerability. Because of the inherent qualities of the metaverse, several fundamental issues with security provisioning might develop, including scalability and interoperability (Y. Wang et al. 2023). One of the solutions comes from the concept of car platforms, where car manufacturers reuse the same chassis design for different car series. Cars from different series are differentiated by which components are used (e.g. engine, transmission system etc), but the chassis remains the same. Carefully designed chassis makes modular assembly possible in car platforms, reducing the time and cost of redesigning chassis for different car series (Boldt, Linnéusson, and Rösiö 2021). This concept could also be implemented in industrial Metaverse. The so-called platform-based industrial Metaverse provides a platform for rapid modular Metaverse construction.

4.2. Practical challenges (user/organisation perspective)

4.2.1. Digital identity and digital asset protection

In industrial Metaverses, protecting proprietary CAD designs, process parameters, and DT models is a major concern. These industrial Metaverses contain corporate secrets that shareholders want them to be absolutely secured. For users of industrial Metaverses, digital identity and data protection is crucial, especially when industrial Metaverses exist mostly in the digital realm. Digital identity and assets management in industrial Metaverses have been implemented with blockchain. However, although blockchain provides a solution for industrial applications, its implementation remains costly. Blockchain typically charges a transaction fee for putting information on the block as a reward to the miner. This fee is typically calculated as an amount per kilobyte of data ('Bitcoin Block 844920' 2024). In recent year, however, novel blockchain developments such as Layer-2 blockchains and private blockchains have shown better adaptability in industrial uses but have yet to see large-scale adoption.

4.2.2. Safety and risk management

Managing safety and risk in the industrial Metaverse is complex. Due to the nature of integrating different technologies, the weak point lies in the weakest technology. Therefore, during the design of an industrial Metaverse, a thorough evaluation of the technologies to be used should be conducted to ensure that there are no weaknesses in the system. Safety concerns in the industrial Metaverse also arise from real-time control dependencies and rigorous data synchronisation requirements, where low-latency and exceptional reliability are of paramount importance to ensure production safety, such as operating large industrial robots using AR.

4.2.3. Accessibility and inclusivity

Accessibility is a measure of whether a product, virtual or not, is available to as many people as possible. As industrial Metaverses aim to build a virtual world, it should be a universal design that is accessible to all users (Y. J. Y. J. Lee 2024). For disabled people, Metaverses provide a potential solution to extending their life and experience (Radanliev et al. 2023). Industrial Metaverses would allow disabled people to work in roles that were not possible before, helping them connect with society. Decisions about the Metaverse concerning the disabled should involve them directly. Their perspectives, experiences, and skills must be central to its development, as it is their space as well (Gupta et al. 2024). Therefore, accessibility and inclusivity should be considered during the design process.

4.3. Adoption and acceptance challenges (economic perspective)

4.3.1. Complexity and scale of implementation

The adoption of industrial Metaverse scales with real industrial operations. Due to the intertwining technologies, industrial Metaverses tend to become complex. The Metaverse will encompass not only transitions between immersive virtual experiences but also seamless transitions between physical and virtual experiences (Seidel et al. 2022). Designing and developing interfaces, software, and hardware for such complexity can be challenging. The resources, workforce, and training needed to operate within the industrial Metaverse also scale with complexity.

4.3.2. Software licensing and powerful hardware required

Software licences are required for each third-party technology that the industrial Metaverse uses. Licensing costs could be extremely high, considering the diverse types of technology used. Operating an industrial Metaverse is also computationally expensive, as high-end processors are required to process substantial amounts of data, render and/or overlay the virtual world with the real world, and perform simulations with the digital twins. The real-time interactive nature and high demands on data storage, streaming rates, and processing power of Metaverse applications will even accelerate the integration of the cloud into the network (Y. Cai et al. 2022). Similarly, Metaverses scale and grow in complexity following the physical industrial processes.

4.3.3. Realising shareholder expectations and creating value

The adoption of industrial Metaverse should create value for the company, including but not limited to increasing production efficiency, reducing maintenance time, reducing design effort with easier collaboration, reducing management overhead, integrated management of assets, remote virtual control, aiding decision-making, more efficient employee training etc. These functions are expected to meet shareholder's needs and create more value for the company.

4.4. Legal and regulatory considerations (government perspective)

4.4.1. NDA and intellectual property issues

Industrial Metaverses provide service to industry clients. The nature of industrial Metaverse has decided that it needs to be integrated into the core products of companies. For example, data sharing is inevitable if digital twins were to be used. For data sensitive industries such as defence and aerospace, it is difficult to control confidentiality while sharing sensitive data. As different technologies provided by different parties are used, protecting the rights of the client is of utmost importance. Typically, non-disclosure agreements or NDAs are signed by all parties to provide legal protection. However, following the rapid development and adoption of Metaverse, new regulations and laws need to be put into place, including laws that protect intellectual property rights. Defining clear intellectual property rights is crucial for encouraging growth and investment in the metaverse, which holds significant financial potential. However, securing intellectual property in the metaverse is challenging due to its unique characteristics. To develop a legal framework that protects digital assets and stimulates innovation, scholars need to study the evolution of metaverse and intellectual property rights (Gupta et al. 2024).

4.4.2. Data security and privacy

The importance of user privacy cannot be understated. In the Internet era, multiple different mechanisms, protocols, and encryption algorithms have been developed to keep user data private. Breached data could not only be used to exploit the users in unlawful acts but may even bring danger to the user itself. As the Internet evolves towards AR, VR and Metaverse, it has brought up many new challenges for maintaining privacy.

The use of Metaverse is usually accompanied by massive amounts of data transferred. It is estimated that Metaverse could stimulate video data traffic, causing current data usage to increase 24 times in the next decade (Y. Cai et al. 2022). With massive amounts of data transferred, Gavrilov et al. summarise potential Metaverse security problems into three categories: confidentiality, integrity, and availability (Gavrilov 2023). Confidentiality is the cornerstone of privacy, ensuring no access to Metaverse by unauthorised parties. The integrity of Metaverse ensures all users send and receive data as a whole and without corruption, ensuring a smooth Metaverse experience. Availability of Metaverse ensures a seamless integration of virtual and physical worlds accessible anywhere and anytime.

4.4.3. Identity privacy of users

Privacy is important in all 4 stages: product design, production planning, manufacturing, and predictive maintenance. This included privacy for user avatars, requiring Metaverse platforms to both implement avatar-user authentication systems and prevent impersonation or avatar thefts. One example of avatar exploitation is the use of AI and Generative Adversarial Networks (GAN) to generate a person's voice, impersonating not only the pitch and sound characteristics of the person but also the person's speaking style (Gao, Singh, and Raj 2018). This makes Metaverse very prone to impersonation. One of the solutions is to implement biometric authentication within the VR/AR headsets (Huang, Joy Li, and Cai 2023). The management and authentication of distinct roles and stakeholder avatars in industrial Metaverse is also important. The example illustrates that privacy in Metaverse is also application-specific, making it very difficult to consider everything for the users. In the Industrial Metaverse, the requirements for privacy are stricter compared to the Metaverse for personal use. This specialised Metaverse must offer robust support for safeguarding patents and intellectual property, including procedures to protect models of physical assets. The importance cannot be understated as a complete set of information on these assets is stored in Metaverse. However, there is a current gap in research and implementation of security measures and procedures in industrial Metaverse to address these privacy demands.

5. Future directions and opportunities

Industrial Metaverse's development brings a new paradigm for intelligent and conscious manufacturing. From the technology itself to the various fields linked to the industrial Metaverse, a future where XR and Metaverse tightly integrate into our everyday work and life is prominent. Establishing and refining the design processes and methodologies for the industrial Metaverse is challenging, yet it opens exciting possibilities for future research and development.

In this section, the authors discuss emerging trends in developing industrial Metaverse design methodologies and identify research opportunities that warrant further exploration.

5.1. Standards development and interoperability in the industrial Metaverse

5.1.1. Structured and detailed industrial Metaverse design methods

Based on the summary and statistics regarding design methodologies presented in previous sections, current industrial Metaverse design methods in literature are dominantly conceptual frameworks or individualised approaches, with a noticeable lack of general, step-by-step guidelines and corresponding use cases. Therefore, there is a significant potential in future research to develop a comprehensive design methodology for the design of industrial Metaverse by systematically abstracting design methods and structuring design steps.

5.1.2. Platform-based design approach in industrial Metaverses

The platform-based design approach has great application potential in the design process of the industrial metaverse, ensuring that the metaverse applications provide seamless, high-quality experiences that enhance productivity, safety, and collaboration across various industrial sectors. For example, cross-platform content standardisation, adaptive user interfaces, modular content design, etc., to support the reuse of design elements, thus enhancing content creation efficiency within the industrial metaverse. Additionally, this approach has the potential to enhance platform interoperability, promoting seamless integration and communication between different industrial Metaverse platforms.

5.2. Integrating emerging technologies into the industrial Metaverse design process

5.2.1. Cognitive decision-making in industrial Metaverses

The industrial metaverse is closely related to digital twins, making it crucial to apply the correct design methods to ensure that digital twins and their development processes are effectively integrated into the industrial metaverse. Additionally, when users use digital twins for decision-making, they may need to employ advanced technologies such as automation algorithms and artificial intelligence. Future design methods might take into account the thoughtful integration and application of these technologies for informed decision-making.

As Smart (2022) demonstrates, mixed reality devices, virtual objects like holograms, and online computational routines can be integrated into human cognitive processes (Smart 2022). This constitutes the first stage of decision-making, where metaverses support human cognitive processes. In the second stage, automation algorithms can handle decision-making for non-critical operations, such as asset maintenance management, allowing for more efficient and effective processes.

5.2.2. Blockchain integration for digital asset and identity Management

During the design of industrial Metaverses, designers or users will often add, modify, or manage a large number of digital assets. If Digital Twins is involved, the management of digital assets becomes ever more important as Digital Twins are expensive and are crucial to industrial processes. The consistency, authentication, and security of digital assets is important to keeping the industrial Metaverse and the physical world it interacts with safe. Special attention should also be taken for improving reliability and preventing single point of failures when using digital assets. On the other hand, users utilise industrial Metaverses through avatars, which would inevitably involve identity authentication. Blockchain with its decentralised and immutable characteristics provide an excellent tool for managing digital assets and the identity of avatars. The distributed and decentralised characteristics of blockchain prevents it from being prone to single point of failures, providing a very secure way of digital asset and identity management in industrial Metaverses.

As designers aim to enrich the industrial metaverse with various technologies, the selection and integration of these technologies become particularly important. Additionally, when one technology requires the support of others, it is crucial to present them effectively. By doing so, the designers can ensure that users with diverse abilities and backgrounds can understand these technologies, thereby reducing their learning curve, unleash the enormous development potential of technology in the industrial metaverse.

5.3. Human-Centric design and user experience

5.3.1. Innovative and interdisciplinary use of design methods

Industrial Metaverse does not only have a technological aspect but also a user experience aspect, particularly in AR/VR. It is crucial to incorporate design theories and methodologies from user experience design and related fields when developing Metaverse design methodologies. Therefore, future research needs to incorporate more general methods from not only metaverse design, platform design, mechanical design, but also broadly defined design principles into the design process of industrial Metaverse to improve user experience. This highlights the need for innovative and interdisciplinary approaches to be applied to the design of industrial Metaverses.

5.4. Ethical considerations and regulatory frameworks

With the rapid advancement of the industrial metaverse, there is a pressing need to address ethical considerations and establish regulatory frameworks to guide its development and deployment. Future research should focus on systematically developing ethical design approaches, ensuring that ethical issues such as data privacy and digital rights are integrated into every step of the industrial metaverse's design process.

6. Discussions

Compared to other comprehensive reviews on the industrial metaverse, this paper does not rely on bibliometric clustering (Abbate et al. 2022), nor does it simply list technologies and case studies (Nleya and Velempini 2024; S et al. 2024) s. Instead, it adopts a structured and inductive approach to classify and synthesise key insights, offering practical design recommendations for the future development of industrial metaverses.

The main contribution of this paper lies in its novel classification method based on a production-order-driven logic, which allows for a more intuitive understanding of industrial metaverse applications across different stages of the production lifecycle. It also proposes a design framework that can guide practitioners, categorising both universal and individualised methods for industrial metaverse development.

By mapping specific design methods to distinct phases of the production process, this research offers tailored guidance that helps standardise the design process and make it more pragmatic, accessible, and implementation-oriented.

Reflecting on the categorisation and the challenges mentioned in this review, the authors have found the following challenges and limitations in current research:

(1) While many works demonstrate their proposed methodologies in case studies, most lack connection to well-defined design methodologies and many still require further research before they can be considered practically feasible.
(2) Each approach reviewed has shown academic merit and potential value, but it remains uncertain to what extent these benefits can be translated into real-world industrial settings. Nonetheless, these works have provided researchers and practitioners with a variety of potential methodologies, only requiring further validation of merit in different industrial settings.
(3) Understanding when and where different models or methodologies of the industrial Metaverse are applicable is a challenge, especially facing a diverse field of applications each with their own individual specifications and requirements.
(4) Complex implementation challenges also arise from the fact that the field continues to evolve rapidly with new hardware and software stacks emerging monthly, outdating previous technologies. This poses a risk for both a lengthened learning curve for practitioners, and for the validation of methodologies through limited opportunities to be implemented within real-life industrial settings.
(5) This article primarily draws on academic literature, which inevitably means that some developments and reports from industry may have been overlooked (i.e. marketing). In addition, to maintain a clear scope, the review focuses mainly on literature related to design and technology. As a result, valuable contributions from other fields may not be fully captured or discussed in depth.

Moving forward, the classification and frameworks in this review are expected to serve as a foundational reference for researchers and practitioners seeking to systematically build industrial metaverses, bridging the gap between fragmented technical solutions and cohesive design methodologies. Future work may involve validating these frameworks through real-world case studies, especially in Small and Medium-sized Enterprises (SMEs), and refining them based on feedback from industry experts and end users.

7. Conclusions

This paper conducted a comprehensive literature review around design methodologies applied to the design of industrial Metaverses. However, in analysis of current Metaverse development, particularly within industrial contexts, most do not follow a structured design methodology. Instead, most industrial Metaverse design processes are unstructured and ad hoc, lacking common design methodologies that could be applied to general design. This tendency reflects the novelty of Metaverse technology, where innovation often overshadow formalised processes and universally accepted theories are yet to be formed. This also highlights the importance of developing structured design methods for industrial Metaverses to enhance the consistency, efficiency, and scalability of industrial Metaverse projects.

In current literature, most papers demonstrate their industrial Metaverse designs through frameworks and architectures, which could be classified as abstract design methods. Although frameworks and architectures show how a complex industrial Metaverse system is designed, it does not provide structured steps for the design process.

This review differs from previous work in three key ways. First, it connects the emerging field of industrial Metaverse with well-researched design methodologies, which was not present in previous works. Second, it categorises frameworks and architectures from recent works on Metaverse/industrial Metaverse based on the implemented design methodology through a four-quadrant categorisation method: 'abstract vs concrete' and 'individual vs general', providing a structured overview of the diverse methodologies employed in emerging research. Third, it emphasises the importance of design methodologies in industrial Metaverses to achieve rapid prototyping, accelerating future research and implementation for both researchers and practitioners.

Despite the availability of various methodologies, their adoption in industrial Metaverse projects remains limited. Analysis from the literature review shows several key challenges that hold back the development of general structured design methodologies for industrial Metaverses. The first and foremost reason is that Metaverse and industrial Metaverses are still early in development. Although it is a hot trend for research, a widely accepted general design methodology for industrial Metaverse does not yet exist. Another challenge lies within the complexity and uniqueness of industrial Metaverse applications, where companies must highly customise their Metaverse solutions. These designs are tailored to a specific application, and are only tested in one use case, lacking general proof of concept. The integration of multiple advanced technology within a digital space also poses challenges, including compatibility, scalability, modularity and upgradability. Considering the different technological specifications that different Metaverse components are built on, developing a generally accepted design methodology is challenging.

Under the above challenges, two main future research directions stand out: First, there is a need to integrate innovative and interdisciplinary design methods, drawing from user experience design, AR/VR, platform-based design, and engineering design. This approach aims to enhance the overall user experience and encourage novel design practices within the industrial Metaverse. Second, researchers should focus on developing structured and detailed design methodologies. This involves creating comprehensive, step-by-step guidelines and corresponding use cases, moving beyond the current reliance on conceptual frameworks and individualised approaches. By systematically abstracting and structuring design methods, future research can establish robust methodologies that significantly advance the field of industrial Metaverse design.

List of acronyms

Acronym	Description
AI	Artificial Intelligence
ANN	Artificial Neural Networks
AR	Augmented Reality
CAD	Computer-Aided Design
CPS	Cyber-Physical System
DfX	Design-for-X Strategy
DT	Digital Twins
GA	Genetic Algorithm
GAN	Generative Adversarial Networks
GDT	General Design Theory
IDMW	Industrial Dataspace for Machining Workshop
IIoT	Industrial Internet of Things
IoT	Internet of Things
MCPR	Mass Collaborative Product Realisation
NDA	Non-Disclosure Agreement
NFT	Non-Fungible Tokens
PaaS	Platform as a Service
PD	Participatory Design
PSO	Particle Swarm Optimisation
RMS	Reconfigurable Manufacturing Systems
ROS	Real-time Operating System
SMEs	Small and Medium-sized Enterprises
UX	User Experience
UXD	User-Experience Design
VR	Virtual Reality
WYSIWYG	What You See Is What You Get
XR	Extended Reality

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