Manufacturing in the Metaverse

Systematic literature review

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Manufacturing in the Metaverse: a systematic review of the literature

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The future of manufacturing will be underpinned by two elements: digital technologies and collaboration. The industrial metaverse is the epitome of these elements, using extended reality to blend the physical and digital worlds to transform how businesses design, manufacture, and interact with objects. This report presents a coherent summary of established knowledge from academia and practice on the drivers, risks, enablers, and barriers of the industrial metaverse for manufacturing through a systematic literature review. These aspects are explored at three levels of granularity: the individual, the firm, and the manufacturing ecosystem. We conceptualise a prototype of an industrial metaverse implementation using a case of cocoa manufacturing.

1. Introduction

'Metaverse' has become a buzzword in the technology industry [1] to describe three-dimensional virtual space facilitating user interaction. Despite various evidence of metaverse experiments, the consultancy materials, industrial press and company reports do not agree on defining the *industrial metaverse*. For example, automakers like Renault conceptualise the Metaverse as applying digital twin technology to their production line [2]. In contrast, the policymakers (e.g., World Economic Forum) describe an abstract moment when digital lives become more important than physical ones [3]. Complex terms and concepts are used interchangeably, resulting in misinterpretation, lack of clarity, and uncertain evidence of the applicability to manufacturing.

So far, the benefits lack context and systematisation. Figure 1 depicts the aggregated benefits of the industial metaverse suggested in consultancy and manufacturing company reports.

Figure 1: Benefits of industrial metaverse as seen from the consultancy and manufacturing company reports.

While the benefits paint an optimistic picture of the impact of the industrial metaverse, the social elements of adoption, including the drivers, risks, enablers, and barriers for employees, firms, and the manufacturing ecosystem, are yet in shadow[19]. For example, risks include online harassment, cyberattacks, data protection issues, non-fungible token (NFT) fraud, and novel IP rights issues. Risks that were once purely digital can also directly impact physical production via IoT connectivity and remote control. Other barriers may include constrained access to XR technologies, digital twin technologies, distributed ledger technologies, and AI. In addition, the lack of sufficiently strong communication networks, legislation, and cooperation between companies is concerning. Lastly, how to overcome them and enable the industrial metaverse is unclear. At the same time, the academic literature is dominated by technological considerations related to the practicalities of deploying industrial metaverse as a concept. Hence, to support its deployment for the ecosystem, firm and individual (employee worker) levels, there is a need for a systematic review of academic and industrial literature to achieve a balanced and coherent understanding of the possible impacts of the industrial metaverse on the future of manufacturing.

So, is Metaverse for manufacturing systems a hype or a future reality[1]?

[1] https://interact-hub.org/2023/09/04/industrial-metaverse-for-manufacturing-systems-a-hype-or-future-reality/ (accessed 20.10.2023)

In response to this question, we systematically assess drivers, risks, enablers, and barriers to metaverse adoption for individuals, firms, and the manufacturing ecosystem and conceptualise manufacturing in the Metaverse. Hence, we focus on answering three questions:

RQ1. *What are the drivers of the industrial metaverse*?

RQ2. *What are the risks of the industrial metaverse?*

RQ3. What are the technological, organisational, and environmental factors that aid or hinder the implementation of the industrial metaverse?

The drivers and risks of the industrial metaverse are presented separately and are structured according to whether they affect individuals, firms, or entire manufacturing ecosystems. The enablers and barriers are presented together and are structured according to whether they relate to technological, organisational, or environmental factors (TOE model).

2. Research approach – Systematic Literature Review

This project has deployed a research design based on the PRISMA guidelines for reporting systematic reviews [13]. This approach will allow other researchers to replicate the systematic literature review (SLR) and extend the findings. The process of systematically finding and screening academic articles is illustrated in the PRISMA flowchart in Figure 2. In parallel, industrial literature sources were found to investigate how the industrial metaverse is being conceptualised and deployed outside academia, as shown in Figure 2.

Systematic identification of academic studies

A search string was identified to investigate the Metaverse in the context of manufacturing: *"industrial metaverse" OR (Metaverse AND (industr* OR production OR manufacturing)).* Searching two databases (Web of Science and Scopus) yielded 605 unique sources that matched the search string criteria in the source title, abstract or keywords.

Eligibility and screening

The entries were restricted to include only articles (i.e., not conference proceedings) as standard systematic review practice [14]. This yielded 342 papers to be manually reviewed.

Inclusion/exclusion into review

342 papers were manually reviewed by reading the titles and abstracts. Inclusion was based on articles discussing the Metaverse in a manufacturing context. Of the 61 articles meeting the inclusion criteria, five articles could not be retrieved (one paper had no access option, and four had no available English version). The remaining 56 papers were assessed for eligibility by reading the full text, during which 27 papers were excluded. Exclusion reasons include papers not being relevant for an industrial context

(e.g., focusing on the consumer metaverse), papers purely about the underlying technologies of the Metaverse (such as blockchain), and papers examining digitalisation in general rather than the Metaverse specifically. Based on these criteria, 29 papers were included in the academic SLR from the initial search.

Identification of sources via other methods

In parallel, 54 industrial literature sources were identified, including company reports and consultancy material. During screening, five were excluded as not specific to the industrial metaverse. Therefore, the total number of sources contributing to the analysis in this report is 78, inc. 29 from academic literature and 49 from industrial literature.

Data extraction

Data were extracted from 29 academic papers and 49 industrial sources that met the review's inclusion criteria. Two researchers extracted data from each source to identify the industrial metaverse's drivers, enablers, risks, and barriers.

Analysing and reporting the data

Thematic analysis was performed on the extracted data to classify the drivers, risks, enablers, and barriers into themes. The academic sources and industrial literature were analysed separately to facilitate comparison between the findings. The drivers and risks are reported in the following section according to the level of analysis (individual, firm, or ecosystem). During analysis, we found a large overlap between the enablers and barriers – some sources posited factors as enablers, whilst others viewed them as barriers. For example, some sources explained that developments in communication network technologies enabled the industrial metaverse; other sources reported that the current performance of communication network technologies was acting as a barrier to industrial metaverse deployment. Therefore, the enablers and barriers are presented together according to whether they are technological, organisational, or environmental.

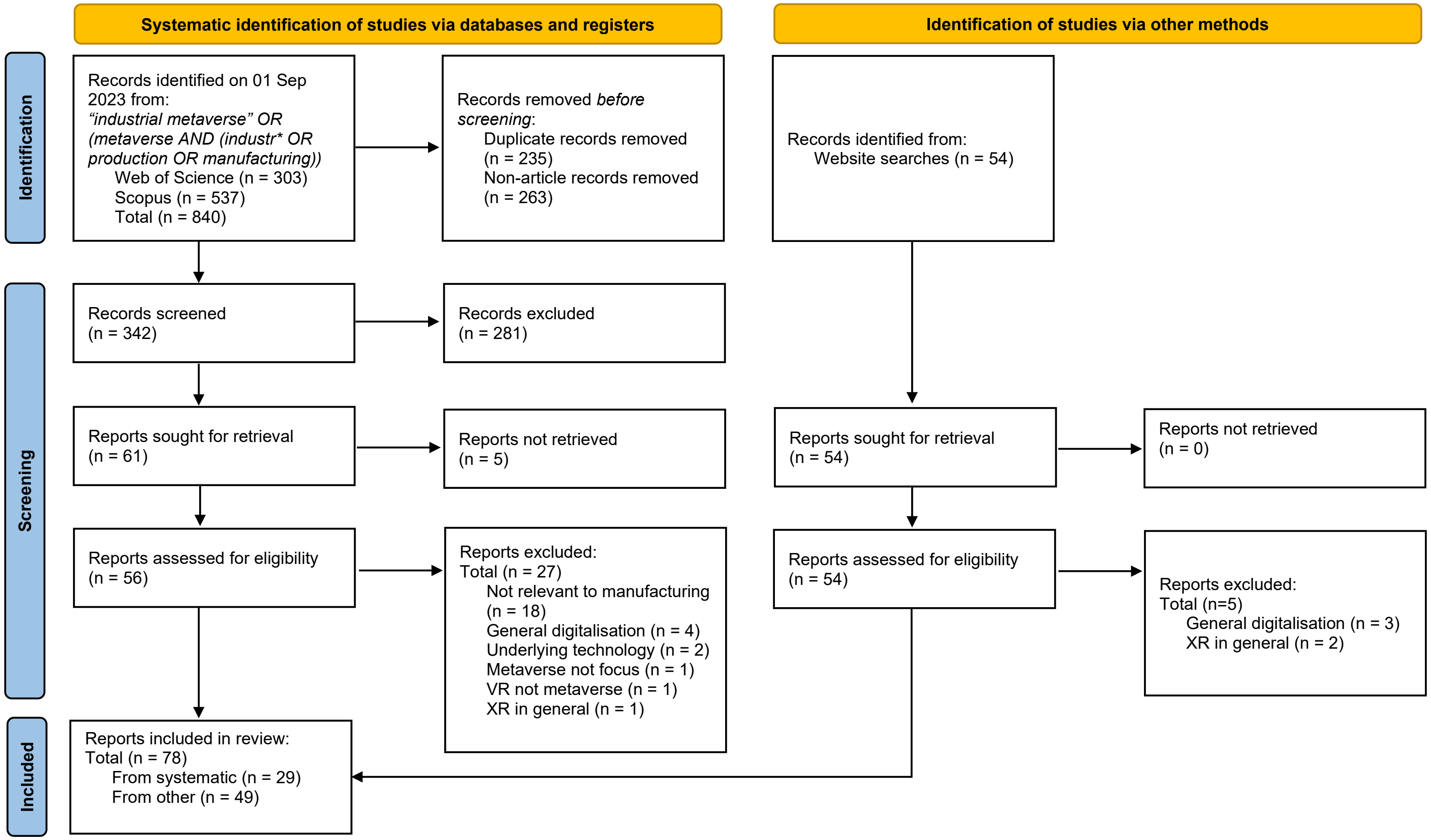


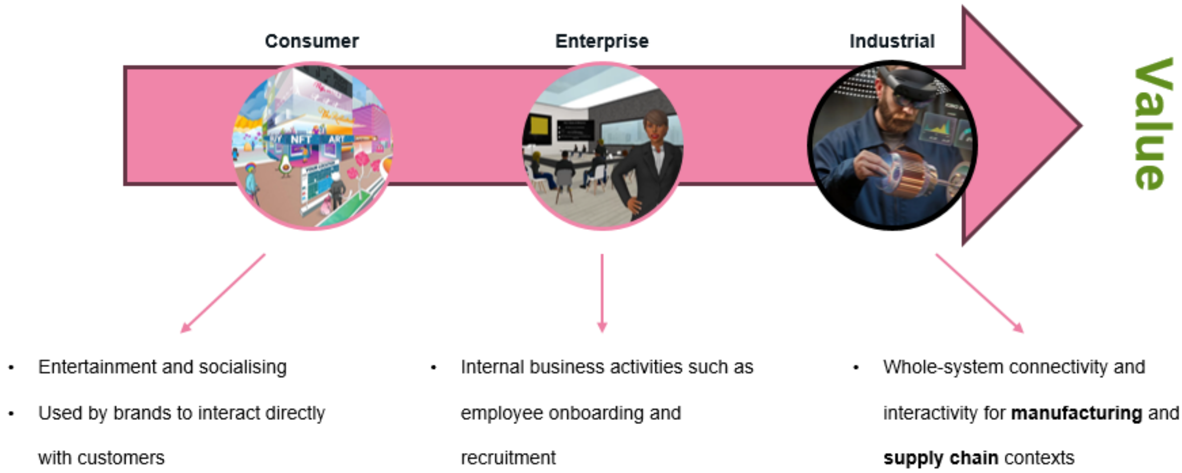
Figure 2: PRISMA diagram from the PRISMA 2020 Statement [13].

3. Findings from the systematic literature review

The fourth industrial revolution (Industry 4.0) and the digital transformation imply significant changes in how individuals, firms, and entire industries operate [4]. Industry 4.0 is the integration between manufacturing operations systems and information communication technologies (ICT) to form cyber-physical systems (CPS) [5]. Although deploying Internet of Things (IoT) devices, robotics, and big data analytics are essential for connected manufacturing systems, other pillars of Industry 4.0 include simulation and extended reality [6]. Extended reality (XR) is an umbrella term that encapsulates technologies that blend the real with the virtual, including virtual reality (VR), augmented reality (AR), and mixed reality (MR). VR fully immerses users into a virtual environment[1], whereas AR focuses on augmenting physical objects with enhanced information. If XR spans a 'virtuality continuum' between an authentic and completely virtual environment [9], MR sits between VR and AR to combine the digital and physical so that real and virtual elements interact. XR can be achieved using various technologies, from desktop- and projection-based systems to handheld devices and head-mounted displays. The choice of technology depends on the user's desired level of immersion and interaction, which can go as far as impacting the senses and feelings of a user. For example, sensory marketing uses experience stimuli [16] to convey brand messages and trigger purchasing intention. Coherent immersive experiences in Metaverse include sight, sound, taste and smell**.** In particular, smell is considered to be the most potent attractor for purchasing decisions.

Hence, Metaverse is the further development and convergence of simulation and XR technologies into a sensory environment that blends the physical and digital worlds, thus we define industrial metaverse *as "a sensory environment that uses extended reality to blend the physical and digital worlds to transform how businesses design, manufacture and interact with objects"*. Metaverse represents an evolution from **data-based** decision-making to **experience-based** decision-making.

There are three types of Metaverse: consumer-bounded, enterprise-bounded, and industrial-bounded, which differ in scope, complexity and the expected benefits for individuals, firms and manufacturing ecosystems. Implementing the two former types has a solid foundation based on shared data, norms, rules and regulations. The *consumer metaverse* represents an additional virtual reality sales channel focusing on entertainment and socialisation [7]. For example, Nike uses a consumer metaverse to interact directly with consumers [8]. The Metaverse for *enterprises* extends the collaboration platform, but its scope includes internal business activities only, such as employee onboarding and recruitment. The *industrial metaverse* is distinct from other conceptualisations of the Metaverse, as it focuses on whole-system connectivity and interaction within a manufacturing and supply chain context(e.g., from “farm-to-fork”), supported by a range of digital technologies. The activities embraced by the industrial metaverse cross the boundaries of firms, countries, or even continents, implying high installation and maintenance complexity. However, simultaneously, it promises the most benefits for the economy, society and environment by providing a coherent experience for decision-making in complex multi-dimensional environments.



The rise in simulation complexity will either blur the boundary between artificial and real or create a replica of a physical object through exploratory modelling [10]. For example, industrial metaverse can immerse a user into a virtual representation of a manufacturing system, enabled by near real-time synchronisation between the virtual and the physical space (also referred to as digital twin) - it facilitates simulation, testing, predicting and anticipating scenarios, and optimisation [11], [12], [21]. Specifically, such an advanced industrial metaverse can be used for stress testing [2] production in virtual reality, thus revealing the responses and recovery characteristics after supplier disruption or demand shocks, such as pandemics or natural catastrophes.

[2] https://hbr.org/2020/04/we-need-a-stress-test-for-critical-supply-chains (6 december 2023)

What are the drivers of the industrial metaverse for individuals, firms, and manufacturing ecosystems? How the UK can enable these drivers?

The drivers for the industrial metaverse have been grouped into themes, which are presented in Figure 3 according to the level that the drivers primarily affect.

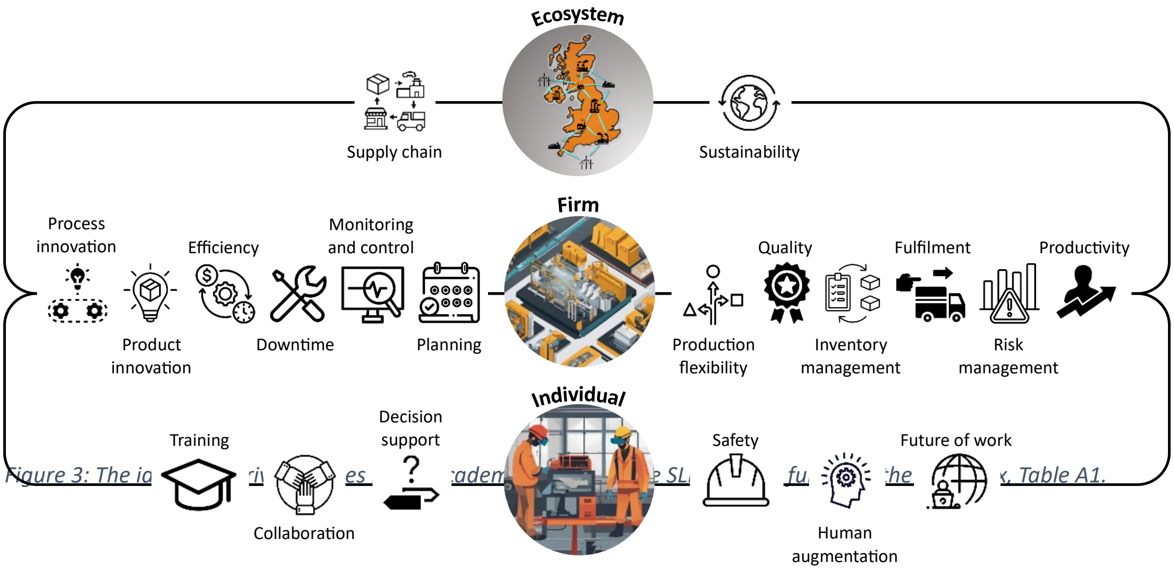


Figure 3: The i… … es … adem… SL… fu… the … x, Table A1.

Recommendations for increasing drivers at three levels:

- At the **individual level**, employees must be engaged in pilot augmented reality and simulation projects that can support their daily work activities. This can include identifying opportunities to improve decision-making, training or safety issues. Employees can flag any training needs and become early adopters of AR/XR.
- At the **firm level**, based on the above, executives are advised to identify 'quick wins' for the Metaverse in their organisation. What pilot projects are for deploying aspects of the industrial Metaverse to improve the existing KPIs and performance targets?
- At the **ecosystem level,** based on the above, the policy-makers are advised to enable legal framework to govern collaboration on industrial metaverse across the existing supply chains[19,20]. This also requires communication throughout industrial sectors to help improve data transparency, awareness, risk simulations, and mutual impacts on sustainability.

What are the risks of the industrial metaverse for individuals, firms, and manufacturing ecosystems? How the UK can reduce these risks

Following the same structure as the drivers presented above, the potential negative consequences for individuals, firms, and manufacturing ecosystems are presented in Figure 4 below. Security, privacy, integrity, and pressure are discussed at multiple levels due to the different impact scales.

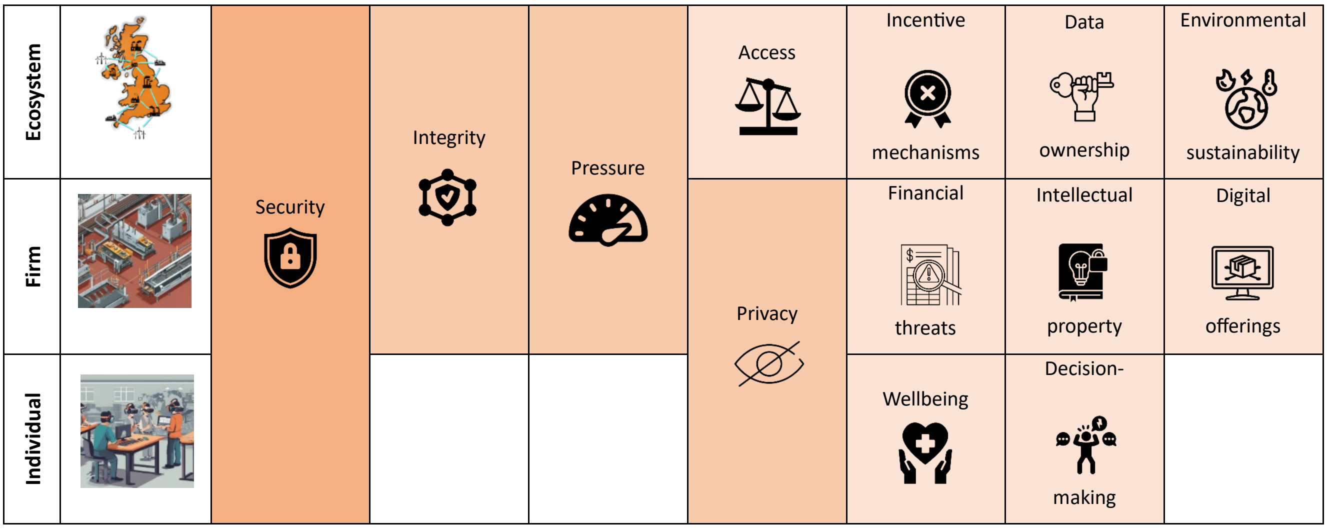


Figure 4: The identified risk themes from the academic articles in the SLR, the full list is in appendix, Table A2.

Recommendations to mitigate risks for industrial metaverse:

- At the **individual level**, we suggest reducing the risk of information overload by considering how people view and interact with data. This will ensure that the implementation of industrial metaverse will not risk people's physical safety (for example, by being distracted by digital elements rather than focusing on their physical surroundings)
- At the **firm level**, we suggest that cyber security is taken seriously. Organisations must consider how digital products and services interact with existing goods and services.
- For **the ecosystem**, we suggest starting with a cross-industrial governance framework focusing on security and privacy – ensuring that the licenced devices are secure against cyber-attacks. The related purpose is to ensure that data being shared between firms is authentic and strive to align incentives between supply chain actors to encourage 'good' behaviour. Clear agreements about data ownership and robust mechanisms are necessary to ensure data confidentiality.

What are the opportunities for implementation of the industrial metaverse?

The opportunities for metaverse implementation are represented as a balance between enablers and barriers. Whilst enablers aid the implementation of the industrial metaverse, barriers hinder or prevent adoption. The enablers and barriers were identified separately during data extraction; however, it became clear that the lack of an enabler represents a barrier. The themes are presented in Figure 5 below, clustered according to the technology-organisation-environment (TOE) framework [15]. This framework describes how technological, organisational, and environmental factors enable or hinder technology adoption and implementation.

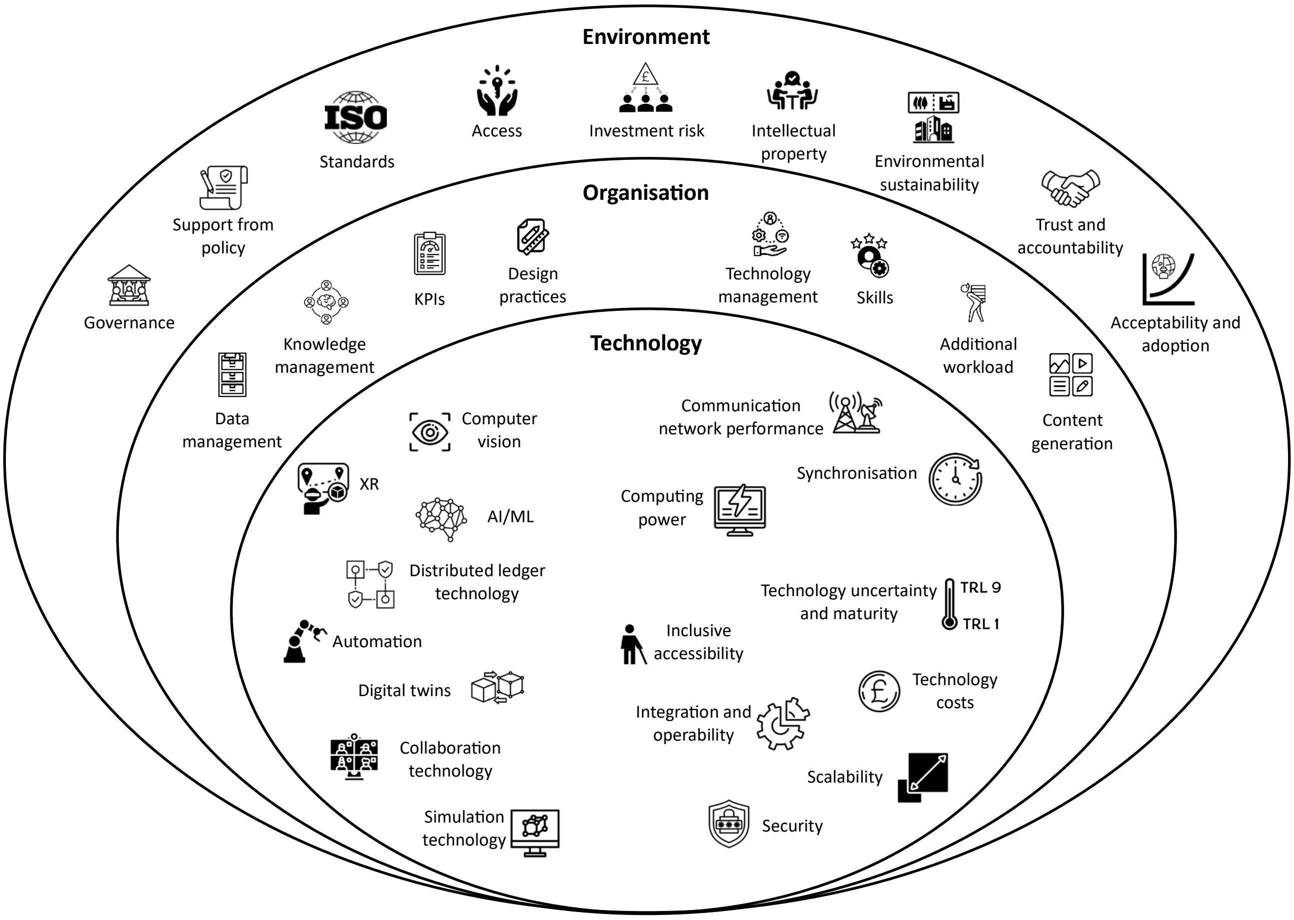


Figure 5: The Technological, organisational, and environmental factors that aid or hinder the implementation of the industrial metaverse, as conceptualised from the SLR, the full list is in the appendix, Table A3.

Discussion

After completing the systematic literature review, the team discussed the demo for an immersive experience for the manufacturing system. For this demo, we assume that data sharing along supply chains (e.g., 'from farm-to-fork') is regulated so the industrial metaverse can link real manufacturing processes and supporting functions to final product delivery and customer interaction. For this purpose, we focus our efforts on food manufacturing, where more supply chain data is available after the recent horsemeat scandal, and the Metaverse can provide an experience for every decision-making level.

Interactive prototype of *Industrial Metaverse* for *manufacturing*

One of the critical challenges of sustainable development is decision-making that does not consider social and environmental concerns. Immersive experiences in the Metaverse can interpret and target real-world data sources about production conditions for the buyer, potentially increasing demand for sustainability when purchasing manufactured goods. For example, displaying the impact of unethical manufacturing practices that help cut costs (such as using child labour, fossil fuel energy sources, and increased CO_2 emissions) will decrease demand for unethically manufactured products while validating the origin and ethics of the production process will expand the market for this purpose-led business.

We conceptualise an industrial metaverse that

> *activates several senses (sight, sound, temperature, and smell) to represent production and supply chain conditions, where buyers cannot easily make an informed choice based on multiple criteria like carbon footprint and social norms, often hidden in the secondary data.*

We integrated a prototype using an augmented reality headset (Meta Quest 3) and a smell generator (Olorama) to make a demo. We developed software based on off-the-shelf Unity Engine to develop extended experience showing the difference between cost-efficient and sustainable manufacturing systems. The concept is illustrated in Figure 6. This prototype created an immersing experience to answer two key questions about the product**:**

1) Where was this product made? How far its components/raw materials were sourced? How much carbon was released into the atmosphere?
2) What were the production conditions along the product's supply chain?

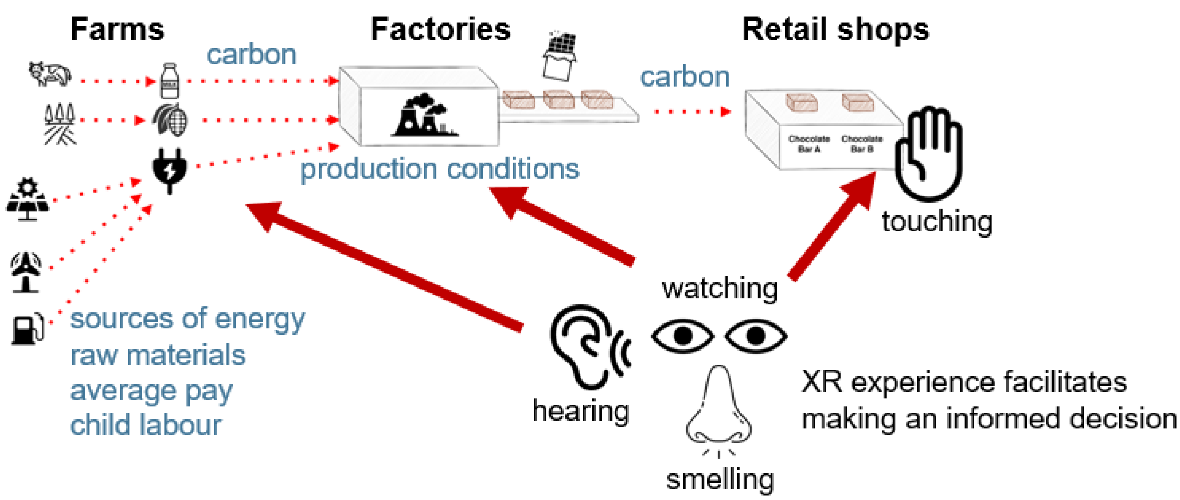


Figure 6: The conceptualisation (acknowledgement: Dr Bang Yong Min)

Case study: Immersive experiences for consumers of cocoa *supply chains*

The leading chocolate brands have been criticised for a long time for neglecting ethical standards in cocoa procurement. About six in 10 cocoa-growing households in Ghana upstream cocoa supply chain are estimated to use child labour[3], Figure 7.

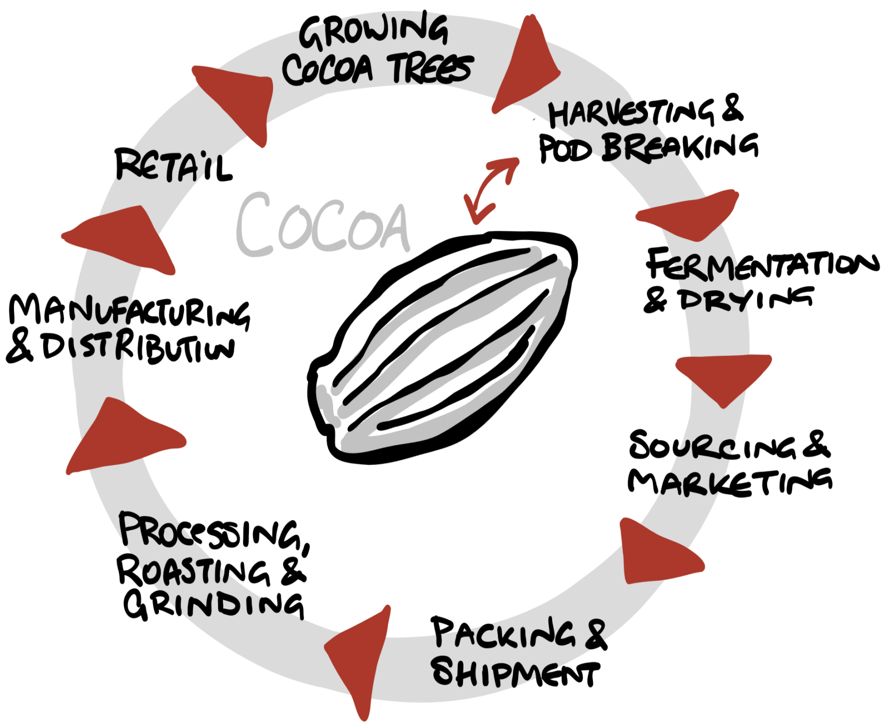


Figure 7: The cocoa supply chain (acknowledgement: Drawnalism)

[3] https://www.theguardian.com/food/2023/dec/02/brands-to-avoid-mars-cadbury-chocolate-firms-criticised-ethics-report

Due to farmers' low market power, their cocoa sales are below profitability. Being limited in hiring professional workers, farmers may take children out of school to work on the farm. While European and UK consumers are the main market for harvesting cocoa; hence, they have market power to improve conditions for farmers in West Africa. To end forced labour and enable children to access schools, chocolate-importing countries must ensure consumers know each brand's production conditions. For example, Tony Chocoloney[4] created "Bean Tracker" using technology to trace the entire supply chain from "bean to bar"[5]. For our demo we envisioned an industrial metaverse to interpret this data source, explain data better and improve the sustainability of purchases along supply chains. First, we plan experimental research using three phases. First, a participant faces a selection between £0.39 and £3.20 chocolate, where they can buy expensive (option A) or cheap (option B). In the second phase, the participant gets immersed into production conditions behind this chocolate bar and again can make two choices A or B, and this time decide not to buy at all(C), or buy expensive (C) but less often (D). Finally, in the third phase, we will ask the participant to explain their choice, Figure 8.

Figure 8: Immersion into the cocoa supply chain (acknowledgement: Dr Bang Yong Min)

[4] https://hbr.org/2023/09/how-tonys-chocolonely-created-a-purpose-driven-and-profitable-supply-chain
[5] https://www.youtube.com/watch?v=tU5jB72MQC4

Conclusion

We define industrial Metaverse *as "a sensory environment that uses extended reality to blend the physical and digital worlds to transform how businesses design, manufacture and interact with objects"*.

Key project result for academics

The existing industrial cases reveal technological barriers such as immaturity, lack of sufficiently strong communication networks and sustainability concerns. Other cases include cybersecurity risks like cyberattacks and data protection/privacy issues. The social barriers include jurisdictional and legislative difficulties, lack of cooperation between companies necessary to achieve interoperability and the need to change worker and user mindsets.

Key project results for manufacturers

Manufacturers could gain many potential benefits from adopting the industrial metaverse. At the **individual** level, firms can engage employees in using XR and simulation technologies and identify opportunities for improvement in their daily work: current operations, training processes, or safety issues. One should consider how people interact with data and manage possible information overload to support decision-making efficiency and well-being. Specifically, the area where employees will be in the Metaverse should be cleared from physical surroundings for safety reasons.

At the **firm level,** manufacturers must **i**dentify quick wins for the Metaverse and deploy their aspects in pilot projects to improve existing KPIs and performance targets. Manufacturers must take cyber security seriously and consider how digital products and services interact with existing goods and services. There are also concerns about increased performance pressure on firms and the negative impacts of digital offerings.

Finally, at the **ecosystem level**, firms must agree on a legal framework for supporting collaboration across the existing supply chains and industrial sectors and establish data-sharing practices to help improve supply chain transparency, risk awareness, and risk mitigation. There should be a focus on security and privacy, ensuring that the licenced devices are secure against cyber-attacks, data ownership and confidentiality, the authenticity of data shared between the actors, and the incentives for sustainable purchasing and manufacturing behaviour.

Key project result for technology providers

There are technological enablers and barriers to the industrial Metaverse. Enabling technologies include XR, distributed ledgers, computer vision, AI and ML, automation, and digital twins. Developments in computing power, communication network performance, simulation technology, collaboration technology and synchronisation are needed. Further technological barriers include technology uncertainty and maturity, integration and interoperability, costs, user accessibility, scalability, and security.

Key project result for policymakers

The operating environment will play a role in supporting industrial metaverse adoption. Financial risks and environmental sustainability concerns act as barriers. However, governance, support from policy, and standards will facilitate adoption. Furthermore, ubiquitous access, intellectual property protection, trust and accountability, and acceptability and mass adoption are necessary to deploy the Metaverse into manufacturing successfully. Finally, risks include unequal access to the Metaverse, negative effects of incentive mechanisms, data ownership questions, and negative environmental impact. By affecting both judgements and feelings, industrial metaverse will support the narrative as a driving force for policy advancement towards carbon neutrality and raise chances for sustainable development goals to be achieved. For example, the simulation of consumer demand patterns will increase awareness of available responses, particularly regarding energy consumption and carbon costs.

Limitations

While energy required to power the industrial Metaverse may be considered a risk to environmental sustainability and a barrier to adoption, Metaverse may also enable manufacturers to use resources and energy more efficiently, thus acting as a positive driver for adoption. Without further research, whether the potential benefits outweigh the risks and barriers is unclear. The economic development and educational level of stakeholders arguably will play a moderating role and are still under investigation. Still, we argue that the industrial metaverse can enable substantial support for experience-driven decision-making towards sustainability. It is unclear if being informed in real-time will trigger sustainable decision-making by manufacturers and policymakers. For example, would the smell of burning Amazon forests make decision-making more sustainable than the abstract carbon footprint number?

Future work

Metaverse is likely to increasingly move from merely representing reality (digitally) to shaping reality (in the case of business models and industrial architectures). One of the benefits of our experimental prototype is that it is likely to change how and what people buy and influence the value creation and capture processes. Specifially, it is advised to run an experiment to test the feasibility of shifting decision-making towards more expensive but more sustainable production along the food manufacturing supply chain. Hence, future research is expected from a business model innovation perspective.

We expect the experimental prototype to be further explored as a spin-off or start-up for other funding initiatives. For example, underpinning the industrial metaverse with digital twins of factories, products, and processes will increase the precision of the simulation of demand shocks and disruptions caused by the "black swan", such as the next pandemic. The generated immersive experience can inform about the existing responses of production systems that can feedback to policy-making. For example, what are the bottlenecks in supply chains responding to the next pandemic? What is the impact of removing them?

All following-up projects will contribute to the Made Smarter Innovation (MSI) goal of achieving a 30% carbon emission reduction, provided that political and legislation challenges that can constrain the scale-up of the prototype for international supply chains are resolved.

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Appendices

Table A1: Drivers of the industrial Metaverse identified through SLR of academic literature.

Level	Driver	Description
Individual	Training	Immersive and engaging training using extended reality (XR) technologies beneficial for simulating dangerous training environments virtually.
	Collaboration	Real-time remote collaboration with an enhanced sense of presence through XR.
	Decision support	Real-time data to inform decision-making and simulations to understand potential outcomes and consequences.
	Safety	Reduced physical access to dangerous operating environments through virtual testing and operation.
	Human augmentation	Enhanced human abilities through 3D visualisations of complex systems, more intuitive programming of robots, provision of information hands-free, and reduced physical and mental workload.
	Future of work	Shifts to workplace norms include remote work, AI-based and IoT-based virtual assistants, and the creation of new jobs.
Firm	Process innovation	Accelerated planning and design of new production layouts, faster and cheaper innovation through virtual iterations and testing, and system optimisation through simulation.
	Product innovation	Collaborative new product design environment for stakeholder involvement, including modelling user needs. Faster design iterations using virtual prototypes and testing.
	Efficiency	More efficient production cycles, material efficiency gains through system optimisation, and improved resource efficiency through scenario modelling. All contributing to reduced production costs.
	Downtime	Reduced planned downtime (predictive maintenance, virtual testing of process changes) and unplanned downtime (virtual fault detection, remote troubleshooting, system simulations)
	Monitoring and control	Remote real-time monitoring linked to continuous simulations. Remote control of production machinery and process automation.

	Planning	More accurate planning processes through demand forecasting informed by market data. Optimised peak load planning using simulations for scenario planning.
	Production flexibility	Enhanced adaptability for changing operating conditions and variable production inputs. Capabilities for mass customisation of products.
	Quality	Automated quality inspection and control, resulting in less scrap and rework. Optimised quality of fresh products through dynamic routing.
	Inventory management	Optimised inventory management, warehouse design, and logistics.
	Fulfilment	Improved traditional fulfilment dependability, efficiency, and customer service. New opportunities for online services and goods, facilitating enhanced customer interaction and engagement.
	Risk management	Simulation of potential problems before they arise or become critical. Risk management based on real-time data.
	Productivity	Automation of production aspects, optimisation of production buffers for higher throughput and/or reduced labour costs.
Ecosystem	Supply chain	Reduced lead times through supply network simulation, seamless digital finance and smart contracts with suppliers, enhanced production transparency (adherence to sustainability standards and laws), improved global traceability, real-time supply chain updates for monitoring supply chain disruptions, and increased resilience through supply chain scenario simulations.
	Environmental sustainability	Reduced environmental impacts of manufacturing due to efficiencies throughout production and the supply chain. Opportunities for more circular production (and business models) thanks to enhanced connectivity of the manufacturing ecosystem. Immersive experiences could help to overcome behavioural barriers to climate action.

Table A2: Risks of the industrial Metaverse identified through SLR of academic literature.

Level	Risk	Description
Individual	Wellbeing	Cyber-sickness due to use of XR technologies, and other physical impacts of technology over-use such as head and neck strain. Risks to physical safety of operators whilst immersed in virtual reality due to lack of awareness of physical surroundings and diverted attention. Mental health risks such as digital addiction, and social impacts such as reduced interpersonal skills and social isolation.
	Security	Security of users' data and content linked to individuals. Security of users' devices against interference and cyber-attacks. Risks of identity theft.
	Privacy	Personal privacy violations and issues surrounding conditional privacy.
	Decision-making	Information overload may hinder decision-making performance, in addition to unknown behavioural effects and exacerbated cognitive biases.
Firm	Security	Security of confidential data about physical production systems and firms' core competencies. Security of the production system and network against interference and cyber-attacks. Risks of unauthorised users accessing the system (identity verification risks) or authorised users unable to access the system.
	Privacy	Privacy concerns around data sharing between firms, and concerns about government monitoring.
	Integrity	Risks of fraudulent data being used or released, issues about information authenticity, and risks of unauthorised augmentations being displayed in virtual production systems.
	Financial threats	Risks of financial scams, ransomware, and money laundering.
	Intellectual Property	Risks of intellectual property rights violations.
	Pressure	Exacerbated pressure for shorter lead times of products in the digital age.

	Digital offerings	Cannibalisation of physical goods or services for digital ones, and risk of disputes caused by differences between real and virtual products.
Ecosystem	Security	Confidentiality during data sharing, and risks of industry-wide cyber-attacks.
	Integrity	Risks of inauthentic data shared between firms in the manufacturing ecosystem.
	Access	Unequal access to the industrial Metaverse could aggravate already existing social and economic inequalities.
	Pressure	Supply chain relationships and trust put under strain due to constant monitoring of activities.
	Incentive mechanisms	Risks that incentive mechanisms for metaverse adoption inadvertently encourage negative practices or behaviours.
	Data ownership	Issues of data ownership at each stage of the manufacturing ecosystem.
	Environmental sustainability	Potential increases in energy consumption due to computing power requirements.

Table A3: Enablers and barriers of the industrial Metaverse identified through SLR of academic literature.

Level	**Barrier/ Enabler**	**Description**
Technology	Extended reality (XR) technologies	XR technologies (including virtual, augmented, and mixed reality) blend the physical and digital worlds and will act as an interface between users and the industrial Metaverse. High levels of realism for virtual scenes have been linked to higher performance.
	Distributed ledger technology	Monetary infrastructure, smart contracts, and Blockchain will enable secure and traceable financial transactions throughout supply chains.
	Computer vision	Computer vision is a field of computer science which enables machines to identify objects and people from camera data. This is essential for process monitoring and automation and human communication through XR technologies.

	Artificial intelligence (AI) and machine learning (ML)	AI and ML enable the processing and use of large amounts of data. However, training models require sufficient volumes and quality of data.
	Automation	Automation, Internet of Things (IoT), and robotics enable data exchange between systems and reduce the need for human intervention in processes. These attributes enable remote monitoring and control of systems. Current barriers include sensitivity of sensors and requirements for more IoT devices.
	Computing power	Improvements in computing power, including edge computing, cloud computing, and compression algorithms. Demands and costs of computing power are barriers to adoption.
	Communication network performance	Developments in communication network technologies, such as 5G and ultra-reliable and low-latency communication (URLLC) are essential for real-time data exchange. Current bandwidth, latency and network reliability are barriers for the industrial Metaverse.
	Digital twins	Digital twin technologies are virtual representations of real systems. Digital twins are acting as a first step towards firms' adoption of the industrial Metaverse.
	Simulation technology	Developments required in 3D modelling, modelling human intelligence, and game engines for simulation and XR software development.
	Collaboration technology	It is essential to be able to connect multiple users to the industrial Metaverse at the same time and to see real-time changes to systems and machines.
	Synchronisation	Real-time synchronisation and the ability to stream accurate real-time data from sensors.
	Technology uncertainty and maturity	Uncertainty remains about the capabilities of metaverse technologies. It may be felt that technologies are currently not mature enough for deployment.
	Integration and interoperability	Integration of metaverse technologies with existing technologies and data sources is a large barrier to adoption.

		Interoperability with popular business applications (such as Microsoft Teams) will enable smoother adoption. Ensuring consistent metaverse performance across devices is important.
	Technology costs	The expense of hardware and XR devised hinder adoption. Rising development costs are also a concern.
	Inclusive accessibility	There are concerns about the accessibility of metaverse technologies, particularly for visually impaired users.
	Scalability	Ensuring that technologies and supporting infrastructure are scalable and extendable across manufacturing sites and firms.
	Security	Developments in data security, user authorisation, and user identity technologies are needed.
Organisation	Data management	Efficient data management, seamless integration of diverse data types, and understandable data transparency policies are needed. Data format, quality, accuracy, and storage are current barriers to adoption.
	Skills	Strategies for reskilling the workforce to take advantage of the industrial Metaverse, including developing learning capabilities and new training and education paths. Current technical capabilities and lack of software support are barriers to adoption.
	Knowledge management	Automation of knowledge management processes and internet of minds (connecting knowledge created by humans and knowledge created by machines).
	Key performance indicators (KPIs)	Development of new KPIs related to the industrial Metaverse.
	Design practices	Co-designing of sensing, communication, control, and computing technologies.
	Technology management	Internal assessments of how technologies are applied within operations, and awareness of new and developing technologies.
	Additional workload	One notion of the industrial Metaverse includes continuous running and 24/7/365 service provision. Additional work is

		needed to integrate digital goods and services into physical production planning.
	Content generation	The industrial Metaverse needs content to run - standardised content creation, consumption and distribution will support content generation.
Environment	Governance	Metaverse governance, including regulations around fair play and penalty mechanisms for breach of contract.
	Support from policy	Government provision of resources and policy support for manufacturers and retailers, efficient subsidy mechanisms, and enhanced regional innovation ability.
	Standards	Development of metaverse and sensor data standards, standardised cooperation, and standardised identification architecture will enable adoption. Current lack of data exchange, AI, and measurement standards are barriers to adoption.
	Access	Ubiquitous access to the industrial Metaverse is necessary for data to flow between systems and between firms in the industrial ecosystem. Limited access to hardware and devices currently hinders this. Psychological barriers may exist due to perceived risks of using metaverse technologies.
	Investment risk	Investment risk is currently high, but co-development of metaverse systems with multiple supply chain agents could share the costs and risks.
	Intellectual property	Intellectual property protection mechanisms are needed to facilitate data sharing across manufacturing ecosystems.
	Environmental sustainability	Land requirements for new infrastructure to support the industrial Metaverse, high energy consumption to power it, and the use of resources and materials to make metaverse devices.
	Trust and accountability	Trust is needed for the industrial Metaverse; however, concerns surround ownership, accountability, and liability.
	Acceptability and adoption	Social acceptability will enable the use of the industrial Metaverse in manufacturing. The current lack of users and

		lack of adoption of supporting technologies hinders deployment.