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Organizational impacts of the industrial metaverse

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Organizational impacts of the industrial metaverse

Abstract

Many industry analysts have argued that the metaverse's true transformative potential is likely to be realized in the industrial context. This paper provides a detailed analysis and description of the industrial metaverse ecosystem in terms of tools, data, and people and the interplay between them. We analyze multiple case studies of eight companies that have incorporated the industrial metaverse in manufacturing, logistics and other activities. The cases include companies in retail as well as non-retail sectors with different levels of implementation of industrial metaverse solutions. The article advances our understanding of how industrial metaverse can contribute to strategic objectives of companies related to cost, quality, delivery responsiveness to the customer, flexibility, innovation and sustainability.

Keywords: artificial intelligence; digital twin; industrial metaverse; Omniverse; sustainability

1. Introduction

Despite all the hype around the metaverse, the reality is that many consumer metaverse projects such as those initiated by Facebook's parent company Meta (Manjoo, 2022) and 3D virtual world browser-based platform Decentraland (Thompson, 2022) have struggled to figure out how to attract users to their platforms. Consumer metaverse platforms are likely to struggle for some time to come. In an article published in The Financial Times, the President and CEO of Nokia, Pekka Lundmark recently put the issue this way: "The real future of the metaverse is not for consumers" (Lundmark, 2022). Lundmark and many other analysts have argued that the metaverse's true transformative potential is more likely to be realized in the industrial context.

A number of industrial metaverse projects are already in operations and playing key roles in helping organizations meet their strategic objectives. Some early metaverse solution developers have found that business customers are a more attractive market segment than individual consumers for their offerings. For instance, consider the 3D virtual collaboration platform Omniverse, which is a metaverse created by the graphics processing unit (GPU) maker NVIDIA. It was reported that NVIDIA expected the initial market for the Omniverse to be the

content creation community such as creators of games and animation. However, Omniverse was found to be more useful in industrial applications. Companies can create digital twins of their physical buildings and factories in the Omniverse (Chen, 2022). By incorporating technologies such as AI, 5G, and autonomous robots, industrial digital twins in the Omniverse allow a company to represent the physical space in the virtual space with all the constraints and details of the physical system (Saracco, 2021).

The Omniverse is being used by companies such as Amazon, AT&T, BMW, Ericsson, Foxconn, GM, supermarket operator Kroger, Lowe's, Mattel, PepsiCo, manufacturing software maker Siemens, Sony, Universal Robots, and Valeo to model the reality by creating digital twins to improve operations and designs (Freund, 2022). Likewise, automobile company Renault's industrial metaverse has been running for some time (Omeñaca, 2022). By monitoring the production process in real time, Renault Group was reported to detect 300 alerts and avoid 300 production stoppages successfully during 2019-November 2022 (Flaherty, 2022).

To understand how the industrial metaverse can contribute to a firm's high-level strategic objectives, we draw on the system designs perspective. Prior research has noted that a variety of system designs can be used to satisfy the organization's requirements (Alfieri et al., 2013). Indeed, a key consideration in any design decisions in a manufacturing system is to make sure that these decisions support a firm's high-level strategic objectives (Cochran et al., 2001-2002). Among key traditional manufacturing objectives include cost, quality, delivery responsiveness to the customer, flexibility, innovation (Christiansen et al, 2003; Cochran et al., 2001-2002, Adam and Swamidass, 1989; Safizadeh et al., 2000; Sweeney, 1991; Miller and Roth, 1994) and sustainability (Galeazzo and Klassen, 2015). These are also key goals of retailing and retail supply systems (Anand and Grover, 2015). There is little direct research about

how the industrial metaverse can help firms in the retail, manufacturing and logistics sector archive their requirements and various objectives noted above.

The objectives of this study are: a) to document how the industrial metaverse is being used by manufacturing, retail, and logistics companies; and b) to provide insights into the contribution of the industrial metaverse to strategic objectives of companies in these sectors.

The article is organized as follows. We first discuss some background, concepts and facts related to the industrial metaverse. It is followed by the literature review section, which summarizes previous literatures on industrial systems related to the metaverse and manufacturing systems' key objectives to provide a clear rationale for the current research in the light of what has been done before. Then we discuss how the multiple case study method has been applied. Next, we discuss our findings regarding the nature of the industrial metaverse and contribution to firms' strategic objectives. In the discussion and implications section, we offer a commentary concerning the industrial metaverse's roles and discuss some future research directions. In the conclusion section, we summarize the main ideas of the paper and discuss the opportunities offered by the industrial metaverse.

2. The industrial metaverse: Some background, concepts and facts

A universally accepted definition for the industrial metaverse does not yet exist due to the fact that the metaverse is a rapidly evolving phenomenon. The industrial metaverse thus will take time to fully unfold and develop. President of Bell Labs Solutions Research at Nokia, Thierry Klein has offered a helpful definition of the concept as follows: “The industrial metaverse combines physical-digital fusion and human augmentation for industrial applications and contains digital representations of physical industrial environments, systems, assets and spaces that people can control, communicate, and interact with” (MIT Technology Review, 2022).

Since most of the media's attention is focused on consumer metaverse platforms, it is also important to understand where such platforms stand. A drawback of many consumer metaverse platforms is that the environment they envision and represent do not extend to the real world. They are not populated with and simulated using existing data such as design and material specifications. These platforms focus on information, entertainment and socialization. A major goal is to influence users to spend more time in the virtual world, which translates into more advertising revenue for the platform or game provider (Freund, 2022).

In contrast to this, the industrial metaverse involves mirroring real machines, factories, buildings, cities, grids, transportation systems, supply chain and logistics processes in the virtual world in order to simulate the physical system and find, analyze, and fix problems quickly. More importantly, problems can also be discovered before they arise or become critical (siemens.com, nd). By connecting the physical and digital world, the industrial metaverse can play a crucial role in designing and building products, and optimizing operations (King, 2022). Some estimates have suggested that the industrial metaverse's market opportunity will exceed \$200 billion by 2030 (King, 2022).

Renault Group views that there are four processes that underlie the company's industrial metaverse: collecting data, developing digital twins, integrating the digital twins with an extended ecosystem and making use of advanced technologies (Haett, 2022). These processes provides a helpful perspective for understanding how the industrial metaverse functions.

a) **Collecting data:** Real-world elements are blended within the virtual environment using contextualized data to make decisions that can enhance the efficiency of business processes (RCR wireless news, nd). The data from different physical settings such as manufacturing, supply chain, or logistics processes are populated into large scale data lakes in the cloud (King,

2022). To facilitate the data collection process, Renault Group has developed the Industrial Data Management Platform 4.0 (IDM4.0), which collects all the industrial data. The collected data are stored in Google Cloud platform and fed to the industrial Metaverse (Flaherty 2022). Renault Group has also teamed up with ATOS to market the solutions to other industrial players (Haett, 2022).

b) **Developing digital twins:** First proposed in 2002, Digital twins have become a key technology of the fourth industrial revolution or Industry 4.0 to facilitate automation and digitization across industries (MIT Technology Review, 2022). A digital twin is “a virtual representation of an object, a service process, a product or anything else that can be digitized” (Miskinis, 2018). A digital twin has three main parts: physical product, virtual product, and data that connect these two products (Wagner et al., 2019). A physical entity’s digital twin, which provides a virtual representation of and describes the product accurately both at micro as well as macro levels (Jones et al., 2020), can offer a number of benefits. It is fair to say that digital twins are the most important element of the industrial metaverse. For instance, Renault Group has developed digital twins that model its physical assets. The virtual world has replicas of each factory and the supply chain. A control tower controls them in real time (Haett, 2022).

c) **Integrating the digital twins with an extended ecosystem:** A digital twin’s value can be amplified by integrating it into an extended ecosystem. In addition to essential information such as supplier data, sales forecasts, quality information, exogenous information such as the weather and road traffic can also be incorporated (Haett, 2022). i

d) **Making use of advanced technologies:** In addition to digital twins, key technologies used in the industrial metaverse include industrial Internet of Things (IIoT), augmented reality (AR), mixed reality (MR), virtual reality (VR) (RCR wireless news, nd), cloud, real time, 3D, and big

data (Haett, 2022). Companies such as Renault Group have developed platforms, which manage all the technologies that are needed to run the digital twins and their ecosystems (Haett, 2022).

3. Literature review

The industrial metaverse and related industrial systems

There is some confusion in the literature about what is meant by “the metaverse” in the industrial context. Some have viewed the metaverse as a digital twin of a workspace that adds immersive experience to the cyber-physical systems (CPS) (Lee and Kundu, 2022). Digital twin and the metaverse are viewed as key technologies that can help achieve CPS goals in the context of smart manufacturing (Lee et al., 2014). Note that a cyber-physical system is defined as the integration of physical and digital systems (Gunes et al., 2014). Prior researchers have also noted the important role of a CPS in the manufacturing systems such as optimizing equipment operation, controlling and managing equipment remotely, predicting events such as machine downtimes, and performing maintenance remotely (Wang et al., 2015). The practical use of the term industrial metaverse is different from how it is used in the academic literature. The industrial metaverse a concept that is broader than digital twin as well as CPS.

Key objectives of manufacturing, retail and logistics sectors

Although this paper focuses on manufacturing, retail and logistics sectors, this section mainly discusses a manufacturing system due to the generalizable nature of the strategic objectives in other sectors. Put simply, a manufacturing system is a combination of actions and processes that are used in the production of goods. Manufacturing systems consist of different resources such as machines, and labor, which are employed to perform a variety of tasks to satisfy the system’s objectives (Eyers and Potter, 2017; Parnaby, 1979). In the context of smart manufacturing systems, which are most closely related to this paper, special emphasis is given to resources such as computing, service platform, data, and communication protocols (Zhang and Zhu, 2019).

A key point that needs to be emphasized is that a manufacturing system is a subset of the organization system (Alcalay and Buffa 1963). It is thus important for manufacturing system designs to satisfy a company's strategic objectives (Cochran et al., 2001-2002).

As prior researchers have indicated, there are a number of such objectives. Most studies have noted that manufacturing systems emphasize cost in their strategy (Miller and Roth, 1994). For instance, highly productive and cost-efficient production technologies and inventory level is often in the list of performance objectives and outcomes measures against which the manufacturing department is evaluated (Devaraj et al., 2004; Vickery et al., 1993).

A second objective is to ensure product quality. Researchers focusing on quality and customer satisfaction have recognized that two general types of quality exist: a) customization, which is related to the degree to which a good or service provides the key requirements that customers are looking for, b) reliability, which concerns how reliably customers' requirements are delivered (Fornell et al., 1996; Juran and Gryna, 1988). Furthermore, prior researchers have found that customers place relatively greater value on customization when a product's technological intensity is relatively low or high. For products that have intermediate technological intensity, equal importance is given to product reliability and customization (Johnson and Ettl, 2001). Some researchers have suggested that product durability, and conformance are also major quality dimensions that are closely related to reliability (Devaraj et al., 2004). Marketing scholars view the above features as marketing-oriented actions (De Meyer, 1990). This objective is often related to various forms of differentiation strategy. Note that forms that follow a differentiation strategy seek "to be unique in its industry along some dimensions that are widely valued by buyers" (Porter, 1985).

The third objective is to achieve delivery responsiveness (Cochran et al., 2001-2002). Some key performance indicators that are used to measure this objective include delivery time or speed, order fulfillment lead-time (Anand and Grover, 2015), manufacturing cycle time, and delivery dependability (Vickery et al., 1993; Devaraj et al., 2004).

The fourth objective is related to flexibility. Flexibility is defined as the manufacturing system's sensitivity to change (Chryssolouris, 1996). Prior researchers have focused on flexibility in terms of volume, product, and process (Vickery et al., 1993; Devaraj et al., 2004). Likewise, retail supply chains need to be adaptive to meet the demand of changing customer markets (Anand and Grover, 2015).

Innovation has also been included as an objective of manufacturing and logistics systems (Adam and Swamidass, 1989, Safizadeh et al., 2000; Sweeney, 1991; Miller and Roth, 1994). Moore and Tushman (1982) define innovation as "any product or process new to a business unit (firm)". In the manufacturing context, Schroeder et al. (1989, p.6) define innovation as "the implementation of new ideas or changes, big or small, that have the potential to contribute to organizational (business) objectives". Some consider innovation as a focus strategy, which focuses on a narrow set of competitive actions (Galeazzo and Klassen, 2015).

Note that a firm that follows a focus strategy "selects a segment or group of segments in the industry and tailors its strategy to serving them to the exclusion of others" (Porter, 1985). While focus also involves differentiation, whereas widely valued attributes used in a differentiation strategy, focus strategy uses segment-specific attributes (Sharp, 1991). This objective is closely related to other objectives discussed above. For instance, what Sum et al (2004) refer to as efficient innovators have the capability to quickly adapt and respond to

changes in the marketplace, and can do so at a low cost (Sum et al., 2004). Looking from this perspective, innovation is closely related to flexibility (Anand and Grover, 2015).

Finally, sustainability is also recognized as one of the objectives of manufacturing and logistics systems. Sustainable actions are those that are economically viable, environmentally sustainable and socially responsible (Jamali, 2006). Some researchers have, however, argued that a plant's strategic objectives for sustainability need to be balanced against other more traditional manufacturing objectives (Galeazzo and Klassen, 2015).

Firms differ in the relative emphasis placed on various objectives. However, a company may place high emphasis on more than one objective. For instance, manufacturers that are referred to as “speedy conformers” (Kathuria et al., 2010) emphasize both delivery and quality (Kathuria, 2000). Likewise, Zhao et al.’s (2006) “quality customizers” focus on produce high-quality products to meet changing demands. They place high importance on design flexibility and often produce many products in small volumes.

4. Methods

In this paper, we build theory from multiple cases (Eisenhardt and Graebner, 2007; Kshetri, 2016a). We selected only cases for which sufficient information could be obtained from secondary resources. Note that archival data is among a variety of recognized data sources for case studies (Ansari et al., 2016; Eisenhardt and Graebner, 2007).

Following Eisenhardt (1989), we selected eight cases. In order to select the cases, we combined two approaches: extreme method, and diverse method (Seawright and Gerring, 2008). More specifically, our process started with extreme case method. It evolved over time in order to implement different requirements and recommendations.

In the extreme case method, cases with extreme values on the independent (X= firm characteristics) or dependent variable (Y= the use of industrial metaverse) of interest are selected

(Seawright and Gerring, 2008). The cases we selected are extreme in the sense that they are among the earliest industrial metaverse adopters. In particular, prior researchers have suggested that best practices models are good candidates for case research (Eisenhardt, 1989).

If researchers have some idea about other factors that might affect Y (the outcome of interest), other case selection methods can be pursued (Seawright and Gerring, 2008). We utilize a diverse case method to select firms deploying industrial metaverse. A key goal is to achieve a maximum possible variance along relevant dimensions (Seawright and Gerring, 2008). The idea in this method is to select cases to represent full ranges of values characterizing X, Y, or some relationships between them (Seawright and Gerring, 2008).

Specifically, we considered the following two dimensions: (a) the sector in which the company belongs to: retail and non-retail, and (b) the adoption and implementation status of various industrial metaverse applications: firms with industrial metaverse applications already implemented, that is, in production and those that are in planning and development phase but not yet implemented (Table 1). In order to achieve diversity, we selected cases with different combinations of these two dimensions. We briefly illustrate the above with two examples: BMW (cell II] and PepsiCo (cell III].

Table 1 here

BMW Group has been deeply involved with the industrial metaverse. It has implemented what can be considered to be a full-fledged industrial metaverse application. BMW Group has teamed up with both Siemens and NVIDIA for its iFACTORY initiative (Schenker, 2022). The use of Siemens and NVIDIA solutions is expected to make BMW factories more efficient and sustainable (Schenker, 2022). Siemens and NVIDIA have collaborated to create what is widely seen as the most high-profile example of industrial metaverse. Both Nvidia and Siemens have

been building digital twins of physical product or process. Siemens' digital twins, for instance, allow multiple virtual representations of models, which can be used to simulate various aspects of physical behavior as well as predict, and optimize the product and production system across the product's lifecycle. A physical asset and its virtual representation can be bi-directionally connected using closed-loop digital twins (Slansky, nd). Siemens' partnership with NVIDIA Omniverse takes the level of functioning and performance of the industrial metaverse to the next level. BMW's factories' digital twins have been built on NVIDIA Omniverse. NVIDIA Omniverse simulates 31 BMW factories in the company's production network using NVIDIA artificial intelligence (AI). The simulation involves all components of the complete factory model such as the associates, robots, buildings and assembly parts to support diverse AI-enabled use cases such as virtual factory planning, autonomous robots and predictive maintenance (Caulfield, 2022).

BMW's industrial metaverse has provided the company with the capability to operate in a perfect simulation, which has drastically improved planning processes. BMW regularly reconfigures its factories to accommodate new vehicle launches (Caulfield, 2022). For example, BMW carried out simulation of a new factory in the metaverse for six months (Shaw, 2022) before deploying the factory's final layout. The simulations entailed building virtual cars on a one-to-one scale (Schenker, 2022). The digital twin made it possible to simulate features such as 300 cars running on a conveyor belt. It identified paths around the factory that were safest for employees to use during a shift (Bond, 2022). Following the simulation, the company was reported to change about 30% of the design from the original (Schenker, 2022). As of March 2022, working with technology consulting firm Kinetic Vision, which is a NVIDIA partner, PepsiCo was reported to be developing AI-powered digital twins of its distribution

centers in NVIDIA Omniverse (NVIDIA, 2022). The solution would also involve NVIDIA Metropolis, which consists of an application framework, set of developer tools, and partner ecosystem to bring visual data and AI together (NVIDIA, nd) and NVIDIA TAO, which facilitates the AI model training process with companies' own data and optimize for inference, without the requirement of AI expertise or large training datasets (Nvidia Tao Toolkit, 2022). PepsiCo hopes that Omniverse Enterprise and Metropolis-powered digital twins will improve the efficiency and environmental sustainability of its supply chain, which consists of over 600 distribution centers in 200 regional markets (Kerris, 2022).

4.1. Ensuring accuracy and quality of data

We made efforts to ensure the accuracy and quality of information. We assessed data's internal consistency. As suggested by prior researchers (e.g., Kshetri, 2016), we evaluated different data items for the same point in time. Additionally, the same data items have been analyzed for different points in time. For instance, in Table 2, key events and milestones related to BMW Group's industrial metaverse journey has been explained to illustrate internal consistency of data.

Table 2 here

The reputation and trustworthiness of the source as well as content of data are important. We mainly relied on information from reputable third parties instead of taking directly from the websites of organizations chosen in the analysis. We also corroborated data and information from multiple sources.

Timeliness and currency of the data are of equal importance. We followed the latest news items related to the cases chosen. In addition, we also visited the websites of the relevant companies for up-to-date data and information.

5. The nature of the industrial metaverse and contribution to firms' strategic objectives

The industrial metaverse ecosystem

Prior researchers have described a technological ecosystem in terms of tools, data, and people (Kandogan et al., 2014; Kiron and Shockley, 2011). In this section, we discuss these elements and the interplay between them in the context of an industrial metaverse ecosystem.

Data

An industrial metaverse is characterized by much more data flows compared to other contexts.

For instance, Renault's industrial metaverse entails a series of processes to allow the company to monitor data from its production lines (8,500 pieces of equipment), the supply chain, and 90% of the supply flows (Just Auto, 2022). Jose Vicente de los Mozos, EVP, Industry Group and Head of country for Spain and Portugal noted: "Every day, a billion [bits] of data are collected within the Renault Group's industrial sites. The Metaverse provides real-time supervision that increases the agility and adaptability of industrial operations as well as the quality of production and the Supply Chain. Renault Group is becoming a pioneer in the sector" (Flaherty, 2022).

Likewise, companies utilizing solutions provided by Siemens and NVIDIA can stream data from the factory floor industrial computers used for process automation known as Programmable Logic Controller (PLCs) and sensors into AI models. These models can help continuously optimize performance, predict problems, and reduce energy consumption. They also streamline the flow of parts and materials across the factory floor (DailyAlts, 2022; Schenker, 2022). In the same vein, Kroger expects that actionable insights will be gathered from the grocer's nearly 2,800 stores in the U.S. (STS News 2022).

The industrial metaverse is also making an extensive use of a special type of data - synthetic data. For instance, Siemens is reported to be accelerating the development of defect

detection models using NVIDIA Omniverse's 3D synthetic data generation tools. With the availability of better quality synthetic data, less real data is needed (Lebaredian, 2022).

Tools

The convergence of maturing technologies is arguably a key factor that has fueled the industrial metaverse's growth. Among the most important technologies contributing to this growth is 5G. 5G enables lower latency, higher transmission and more precise exchange of data (MIT Technology Review 2022).

Digital twin is one of the most important tools of the industrial metaverse. The value of a digital twin depends on how closely the virtual world can represent the real world (Schenker, 2022). A high degree of closeness with the real world has thus become a key focus of industrial metaverse initiatives. The Renault Group Metaverse is described as a "true replica of the physical world controlled in real time" (Just Auto, 2022).

Likewise, building digital twins that are true replicas of their real-world assets has been a key goal of Nvidia-Siemens partnership. Siemens has demonstrated its experience in building digital twins with physical accuracy or what is referred to as physics-based digital twins (Wang, 2022). That is the digital twins behave like their physical counterpart (Sutner, 2022). A physics-based model mathematically represents an object or its behavior. Such a model incorporates physical characteristics such as forces and energy, which can be used to carry out numerical simulation of its behavior (Kakadiaris, 1993). Thanks to Nvidia's deep experience in gaming, image synthesis and AI, the company has a demonstrated record of creating digital twins with high visual fidelity (Sutner, 2022). The NVIDIA Omniverse has adopted the U.S. computer animation studio Pixar's Universal Scene Description (USD) in order to create real-time photorealistic simulations of a wide range of systems such as an electronic component (e.g., an integrated circuit) to an entire factory (Sutner, 2022).

Digital twins allow architectures to work on different scenarios to lower energy consumption and carbon emission. For instance, it is possible to simulate in the virtual worlds in order to evaluate the energy consumption of different air conditioning distribution scenarios. The simulations can also be used to install and place solar panels to maximize light exposure. All these can help to redesign a building so that it cool down more efficiently during the summer to save the need for air conditioning (Chen, 2022).

AI is another key technology in the industrial metaverse. For instance, the solutions of Nvidia and Siemens create AI-infused virtual environments (Schenker, 2022). Companies are also making use of number of traditional AI applications such as computer vision. For instance, using NVIDIA's technology and computer vision and analytics, Kroger is expected to detect early signs of deteriorating freshness (Mitra, 2022).

Finally, edge computing is viewed as another key technology due to the requirement for extremely low latency involving decentralized local edge data centers that are close to users. Such data centers are needed for people to interact with one another and to use devices to access the metaverse (MIT Technology Review 2022).

People

The industrial metaverse is also promoting efficient and effective collaborations among teams. For instance, if something goes wrong on the factory floor, using the solutions developed by Siemens and NVIDIA, teams of users from around the world can meet virtually to collaborate and use the digital twin to quickly identify the problem and troubleshoot and solve it (Schenker, 2022). Omniverse's database and collaboration engine Omniverse Nucleus allows multiple users to connect together live using multiple applications (nvidia.com, 2022). Nucleus enables instant editing on a shared 3D scene on a real-time basis. There is no need to download entire scenes and reupload them and send to other users (venturebeat.com, 2022).

Finally, a key feature of the industrial metaverse is that some employees are being replaced by digital humans. BMW uses digital humans to simulate workflow in Omniverse. The digital humans are trained with data from real associates. They are used to test new workflows in simulation, which is useful to plan for efficiency and worker ergonomics (Caulfield, 2022).

Contribution of the industrial metaverse to firms' key strategic objectives

In Table 3 we summarize the industrial metaverse's roles in meeting firms' key strategic objectives.

Costs

As noted earlier, cost-efficient production technologies have been a major emphasis and priority for manufacturing systems (Miller and Roth, 1994; Vickery et al., 1993). The industrial metaverse serves as an important cost-saving mechanisms for companies. First, better data could help companies monitor costs. For instance, by monitoring data from the production lines, the entire supply chain, and 90% of the supply flows, Renault's industrial metaverse initiative is expected to save \$330 million by 2025 (Just Auto, 2022). Renault also predicted that warranty costs will reduce by 60% (Just Auto, 2022). Likewise, BMW uses its metaverse to carry out inspections (Schenker, 2022). Prior research has suggested that inspection plays a key role in reducing warranty costs to manufacturer and customer (Sahin, 1993).

Second, the industrial metaverse can help minimize issues such as downtime. For instance, BMW factories' digital twins on NVIDIA Omniverse utilize data-oriented applications such as predictive maintenance (Caulfield, 2022), which can result in cost saving by avoiding unnecessary equipment replacement and reducing machine downtime.

Third, the industrial metaverse can help cut unnecessary spending and thus contributes to cost saving. For instance, it can make some types of business travels unnecessary. For instance,

BMW's planning experts located in different parts of the world can test a new product design in Omniverse (Caulfield, 2022).

Finally, the industrial metaverse contributes to cost savings by making processes more efficient or optimizing resource usage. For instance, the Omniverse platform makes it possible to merge live data from all relevant databases in a joint simulation. This means that there is no necessary to re-import data. With this feature, Omniverse is expected to make BMW's production planning 30% more efficient. BMW can assess changes and adjustments to plans at an early stage and generate an overall view. Complex production systems can be designed and implemented more precisely and quickly (designnews.com, 2021).

Quality

The industrial metaverse can help firms achieve quality related goals in a number of ways.

Kroger has teamed up with NVIDIA to build an AI lab and demonstration center using Omniverse Enterprise to build digital twins, which will be used for simulations. The lab aims to expand the retailer's freshness initiatives, improve logistics and enhance shopping experience in stores. NVIDIA's GPU-accelerated platform for operations and logistics cuOpt will explore logistics optimizations (STS News 2022). As noted, a key aspect of quality is to reliably deliver customers' requirements (Fornell et al., 1996; Juran and Gryna, 1988). These initiatives are expected to help Kroger reliably deliver fresh products to customers. For instance, dynamic routing can be used for last-mile delivery to ensure that delivered products are fresh (Mitra, 2022).

Prior research has suggested that inspection plays a key role in improving a product's conformance quality, which is linked reliability (Sahin, 1993). The BMW metaverse makes it possible to inspect and optimize every component inside a factory (Schenker, 2022).

As discussed above, customization is an important quality-related aspect for products with low or high technological intensity (Fornell et al., 1996, Juran and Gryna, 1988; Johnson and Ettl, 2001). Product customization has been a key part of BMW's strategy, which provides a large number of choices to customers (Caulfield, 2022). For instance, BMW produces 2.5 million vehicles annually, 99% of which are custom made (Bond, 2022; Caulfield, 2022). BMW has more than 40 car models and over 100 options for some models. Overall, a new BMW car can be configured in 2,100 different ways. Each BMW factory can produce up to 10 different cars (Caulfield, 2022). As discussed above, the industrial metaverse has drastically reduced the planning time required to deliver customized cars.

Delivery

The industrial metaverse can play important roles in helping organizations achieve delivery-related objectives such as faster delivery time or speed, shorter order fulfillment lead-time, shorter manufacturing cycle time, and delivery dependability (Anand and Grover, 2015; Vickery et al., 1993; Cochran et al., 2001-2002; Devaraj et al., 2004). For instance, Renault's industrial metaverse initiative is expected to allow the company to reduce delivery times by 60% (Just Auto, 2022).

Likewise, as of early 2022, Amazon had over 200 robotics facilities that handled tens of millions of packages every day. About two-thirds of its packages are handled by robots (Weiss, 2022). There were over half a million mobile drive robots to support warehouse logistics. Amazon Robotics built AI-enabled full-scale digital twins of its warehouses using Omniverse Enterprise and robotics simulation application and synthetic data-generation tool Isaac Sim (Bloomberg.com 2022). The digital twins helped Amazon to optimize warehouse design, train more efficient robots, and enhance efficiency of the fulfillment process. The digital twins helped deploy "hundreds of thousands of mobile drive robots" and condense warehouse storage into

Pods. This arrangement enabled the company to stack more items in a warehouse than is possible to retrieve if humans did the work (Vigliarolo, 2022).

Flexibility

As mentioned, flexibility is related to sensitivity to change (Chryssolouris, 1996). It is important for organization to develop the ability to change production volume (volume flexibility), relative production quantities among products in the organization's product mix (product mix flexibility) and the production process (process flexibility) (Devaraj et al., 2004; Olhager, J., 1993; Vickery et al., 1993) to make adaptation to the changing environment (Anand and Grover, 2015).

The industrial metaverse tools have been widely used by companies to achieve these objectives. Amazon uses Omniverse and Isaac Sim to model its warehouses and simulate real-life conditions that Autonomous Mobile Robots (AMR) need to handle. That includes handling different sizes, shapes, orientation, taping of packages and other conditions (Davies, 2022).

NVIDIA announced a collaboration with Germany's railway operator, Deutsche Bahn's digital division Digitale Schiene Deutschland. Deutsche Bahn is looking ways to expand its network's capacity without building new tracks. The effort will involve building the country-scale photorealistic and physically accurate digital twin simulation of Deutsche Bahn's entire track system. Data need to be collected from many sources including tracks running through cities and countryside, station platform measurements and vehicle sensors. A digital twin of the entire network can be built into Omniverse by feeding real time data. The digital data runs alongside the actual railway network at the same time. It will use AI to monitor data from sensors and other sources for simulation, which can help to predict and prevent incidents (Dotson, 2022). The solution would allow Deutsche Bahn to assess the volume of passengers that

can be handled under different scenarios and hence develop what is referred to as volume flexibility (Devaraj et al., 2004).

NVIDIA Omniverse provides evidence that the industrial metaverse tends to perform better than the existing systems in term of flexibility, especially what is referred to as process flexibility (Vickery et al., 1993). As noted earlier, flexibility is related to the manufacturing system's sensitivity to change (Chryssolouris, 1996). BMW's global teams can collaborate in real-time to design and reconfigure the factories. They can use different software packages such as Revit, Catia, or point clouds to design and plan the factory in 3D. All the changes are visible on Omniverse (Caulfield, 2022).

Innovations

As noted, innovations involve the introduction and implementation of new product or process or ideas that can contribute to organizational objectives (Moore and Tushman 1982; Schroeder et al. 1989). Looking from these perspectives, the industrial metaverse can facilitate innovations in many different ways. For instance, product and process innovations have been developed using synthetic data especially for manufacturing applications such as a new assembly line that has little or no real-world data available. Among many uses, synthetic data can imitate operational or production data and can be used to train machine learning (ML) models or test mathematical models. Kroger is using Omniverse tools to generate synthetic data, which is expected to help get produce to consumers faster (Ray, 2022). Note that synthetic data is artificially produced information that is based on real data from existing inputs. Such data can be structured within a database or unstructured (Smith, 2022).

Organizations are implementing new processes using the industrial metaverse. Before making physical investments or applying changes to the physical distribution centers, PepsiCo uses digital twins in the Omniverse to simulate and test models and environments in real time

(Kerris, 2022). This process is used to optimize warehouse layouts and workflows to accelerate throughput (*TechInformed*, 2022). Tools such as NVIDIA Omniverse, NVIDIA® Metropolis and NVIDIA TAO have helped PepsiCo improve throughput, and reduce downtime (*NVIDIA*, 2022), and energy usage and waste.

The retail store Lowe's Innovation Labs team has used NVIDIA AI Enterprise software Omniverse to create digital twins. As of September 2022, digital twin was live in two test stores, one in Charlotte, and one in Seattle (*magicleap.com*, 2022). A visual package consisting of information from various sources such as product location and historical order information can be accessed on a range of devices such as desktop computers and Magic Leap 2 AR headsets (*Lowe's* 2022). These solutions have given employees X-ray vision to see things in a store. In order to read information on a small label on a cardboard-enclosed box that is high up in a top stock, an associate normally needs to climb a ladder. A digital twin and AR glasses make it possible to just look up. The glasses reveal the data of the item that is in that position. By comparing the AR holograms of the digital twins, the glasses can also be used to make sure that the shelves are stocked correctly. For instance, they can correct if the shelf has wrong products or if there are too few. The Nvidia Omniverse helped the company to pull data together that was not possible before (*Dotson*, 2022).

Store associates can also communicate and collaborate with centralized store planners via AR. For example, if a store associate notices an improvement that needs to be made in the retail store layout such as product placement, displays and point-of-sale (PoS) locations, they can use an AR “sticky note” to flag it on the digital twin (*Edwards*, 2022).

The industrial metaverse has also helped develop proactive customer-oriented processes. By using Omniverse and AI avatars created by Lowe’s Innovation-Labs, it is possible to simulate

the distance customers or associates need to walk to pick up items that are often purchased together. The data can be used to improve the placement for products across the store in order to improve the overall customer experience (Dominguez, 2022).

Sustainability

Sustainable actions are those that are economically viable, environmentally sustainable and socially responsible (Jamali, 2006). The most important contribution of the industrial metaverse is that it can help take actions that are environmentally sustainable. The industrial metaverse can be used to create different scenarios for an entity such as a city, and a factory in order to assess their impact on energy consumption. Especially digital twins in the metaverse can be employed to simulate real-world performance scenarios in a safe environment at a low total cost (Hughes, 2022). For instance, Renault’s industrial metaverse initiative is expected to reduce the carbon footprint of vehicle production by 50% (Just Auto, 2022).

Likewise, Microsoft has implemented industrial metaverse capabilities for Hellenic, which is among the largest Coca Cola bottlers. Hellenic has more than 55 facilities across Europe and serves 29 markets in the region. Just one Hellenic production line produces 90,000 bottles of Coca Cola products per hour. Microsoft created digital twins utilizing data from sensors, which made it possible for factory workers to become immersed in the twins. It was reported that, in a 12-week period, the factory cut energy consumption by over 9% (King, 2022).

As noted above, strategic objectives related to sustainability are often balanced against other traditional manufacturing objectives (Galeazzo and Klassen, 2015). For instance, PepsiCo’s use of digital twins in the Omniverse to simulate and test models and environments in real time and optimize warehouse layouts (TechInformed, 2022) is expected to contribute to many organizational goals including those related to sustainability (Kerris, 2022).

Table 3 here

6. Discussion and implications

Prior researchers have suggested that powerful computing networks with high computational capabilities, massive amounts of data from sensors, machines, devices, people and other sources and emerging technologies such as AI have brought the fourth industrial revolution and the underlying digital transformation, known as Industry 4.0 or the Smart Factory (Chien et al., 2020). This paper provides additional insight into the impact of Industry 4.0 on manufacturing and logistics processes by analyzing how the metaverse takes this transformation to the next level by incorporating more sophisticated tools into these processes. It is clear that the industrial metaverse has true transformative potential to strengthen the manufacturing, retail and logistics sectors. This paper also offers insight into the metaverse from a design perspective.

It is also worth noting that one confusing aspect of past research is the tendency to equate the metaverse in the industrial context with a digital twin. In this paper, we clarify that the metaverse is a broader concept that includes digital twin and many other emerging technologies.

The industrial metaverse projects discussed in this paper are viewed as only early examples and key technological elements are being developed in order to realize the potential of a full-scale metaverse (MIT Technology Review 2022). Nonetheless, the above discussion makes it clear that the industrial metaverse can help achieve various objectives related to manufacturing, retails and logistics. For instance, digital twins that closely represent the real world can help analyze different scenarios, which can help to reduce costs and lower energy consumption and carbon emission. By carrying out simulations in the virtual environment before implementing in the real world, a number of manufacturing objectives such as those related to optimization of store efficiency and processes can be achieved ((Mitra, 2022; Schenker, 2022). Likewise, as BMW's case suggests, some types of travels are no longer needed. The example of BMW also highlights how potential product flaws can be identified, defect rates can be reduced

and quality can be improved with a simulation of a factory using a digital twin and by comparing the design of a product in the digital twins to the physical version produced (Schenker, 2022).

The industrial metaverse plays a key role for manufacturers and retailers that are in agility and rapid alignment of key manufacturing functions to accommodate changing customer demands and preferences. For instance, BMW produces millions of cars consisting of many customized versions. BMW's focus has been to give customers choices.

Prior researchers have analyzed an ecosystem of tools, data, and people in applications, such as analytics programs (Kandogan et al., 2014; Kiron and Shockley, 2011). This research examined roles of these elements in the context of the industrial metaverse.

As noted above, human augmentation is a key component of the industrial metaverse (MIT Technology Review 2022). In general, better results could be achieved with AI augmentation or augmented intelligence, which according to Gartner is “a human-centered partnership model of people and AI working together to enhance cognitive performance” (gartner.com, 2019). As an example, BMW has intensified the use of AI in manufacturing. For instance, it uses Nvidia's AI platform Isaac to train robots for new tasks. Machine-learning models have proven to be an especially useful tool for learning by experimenting with situations or conditions that are unsafe and hazardous. For instance, experiments that involve the collision of two robots cannot be performed with real hardware. The simulation are a key component in BMW's AI initiatives. Machine-learning algorithms can be employed to simulate robots performing tasks that require complex maneuvers to find the most efficient process. BMW's future plans are to use the simulation to train robots to perform more complex jobs (Knight, 2021). In human-robot interaction methods, humans can provide a helping hand and can help robots formulate and carry out plans. For instance, when BMW's Mission Control receives an

alert, a human associate can look through a camera using a 5G connection and teleoperate the robot (Caulfield, 2022).

The industrial metaverse technologies also have the potential to enhance public welfare. The key technologies involving industrial metaverse can be developed at a much larger scale involving higher complexities. For instance, it is possible to create digital twins of systems such as airports, cargo terminals and cities (MIT Technology Review 2022). For instance, the Singapore government started worked with French software corporation Dassault Systèmes to develop the city state's digital twin known as Virtual Singapore. Virtual Singapore offers the city's 3D semantic model, in which the data's meaning can be related to the real world. It can display land attributes, different forms of transport, and components of buildings and infrastructures (Kshetri, 2023). Likewise, a city planner can roam the physical world's streets with extended reality (XR) glasses to identify intersections that are problematic. They can then be instantly redesigned in the virtual world. By looking at the intersection with an XR lens, it is possible to see the impact on the traffic of actions such as moving a bus stop or adding a traffic light. The planner can aggregate many proposals for individual changes and upload into the city's digital twin to see how many proposed projects collectively impact the transportation patterns of the entire city. After the construction is authorized, building crews can use the digital twin and XR, which would guide them the exact locations to place infrastructures and crossing aids such as stoplights and crosswalks. Pedestrians can also benefit since they can tap their own XR glasses to see the finished project by superimposing it over their fields of vision (Batra, 2022).

6.2. Future research implications

Before concluding, we suggest several fruitful future research avenues. Prior research in data analytics indicates that the right combination of tools, data and people is necessary but not a

sufficient condition to benefit from an analytics program. Researchers have highlighted the crucial roles of strong cultural commitments in the success of such program (Kiron and Shockley, 2011). The aspects of culture that exert influences in the success of the industrial metaverse could be different from those affecting analytics program. Further inquiry is thus needed to investigate the roles of different aspects of culture in industrial metaverse.

This paper explored how the industrial metaverse can help firms achieve a number of objectives. Different firms may not place the same level of emphasis on a given objective. A second area of future research might be to compare how firms with different characteristics may differ in terms of relative emphasis on the different objectives that can be achieved with the industrial metaverse.

In this paper, we described the industrial metaverse in terms of tools, data, and people (Kandogan et al., 2014; Kiron and Shockley, 2011). The various elements of technology ecosystem and the interplay between them are unique for each setting. Another intriguing avenue for future research is to examine how the industrial metaverse ecosystem differs from that is similar other settings such as enterprise metaverses and consumer metaverses.

Finally, like other technologies, the industrial metaverse deployment tends to diffuse from larger to smaller organizations. This is commonly known as the rank effect (Gotz 1999). Current industrial metaverse projects mainly involve larger companies. Due to cost and complexity, the industrial metaverse-tools such as digital twins are expensive to implement and manage. For this reason, the industrial metaverse is currently out of reach for many organizations. The industrial metaverse is soon expected to be accessible to smaller players. For instance, Siemens and Nvidia have promised that manufacturing companies of any size will be able use the industrial metaverse they have developed, which can used to analyze issues and

identify root causes of the problems they are facing. The industrial metaverse users can also use the industrial metaverse simulate and optimize solutions (Schenker, 2022). However, the metaverse in general and the industrial metaverse is an immature new technology. Prior researchers have noted that such technologies are more costly and requires greater investments to be competitive in the markets where they are introduced first. The diffusion time for such technologies is thus likely to be longer. This means that peripheral market such as those involving small and medium-sized enterprises (SMEs) (Grübler et al., 1999). Thus, in future research scholars should attempt to compare the industrial metaverse with other innovations in terms of the time required for the technology to diffuse SMEs (e.g., 50% of SMEs).

7. Concluding comments

The scale and nature of impacts of the metaverse vary across different settings such as industrial versus entertainment conditions. The above discussion makes it clear that the industrial metaverse has true transformative potential to strengthen manufacturing and logistics processes. For instance, testing in digital twins can help manufacturers and retailers correct problems early on before significant resources have been spent developing complex models that may be inadequate or such models are likely to result in significant cost overruns, project failure or risk factors related to serious health issues, such as work-related injuries. The industrial metaverse creates an opportunity to drive the agility and rapid innovation necessary to deal with rapidly changing technological landscape and customer demands. Emerging technologies and digitally enabled tools such as 5G, edge computing, computer vision and AI are playing key roles in enriching the industrial metaverse.

Data Availability Statement: Data derived from public domain resources

Table 1: Selection of cases



Sector  Implementation status 	Companies in the retail sector	Companies in non-retail sectors
Industrial metaverse solutions already implemented/ in production	[I] • Coca Cola bottler Hellenic • Lowe's • Amazon	[II] • BMW • Renault
Industrial metaverse solutions in planning and development phase/Not yet implemented.	[III] • Kroger • PepsiCo	[IV] • Deutsche Bahn's digital division Digitale Schiene Deutschland

Table 2: BMW Group’s industrial metaverse journey

Time	Event/milestone	Remarks
April 2021	BMW Group announced that it was working with NVIDIA to use the Omniverse platform to generate a new approach to planning complex manufacturing systems (bmwgroup.com, 2021).	In a first pilot project, NVIDIA fitted special AI control modules and high-performance technologies to logistics robots and BMW’s self-developed autonomous transport robots (STR) (bmwgroup.com 2021).
Q3 2021	During NVIDIA’s Q3 2021 earnings call, it noted that BMW was evaluating the Omniverse platform (seekingalpha.com 2021).	NVIDIA reported that more than 700 companies were evaluating the platform.
November 2021	BMW was reported to be using Omniverse at three new factories that totaled an area over 10 million m ² (nvidia.com 2021). At Nvidia’s GTC Conference, BMW presented its Omniverse in production. A virtual tour of the Regensburg factory’s fully functioning, real-time digital twin was provided (Columbus, 2021).	It simulated at scale production and finite scheduling taking into account the constraints down to work order instructions and robotics.
Mid-November 2021	Siemens announced that it was working with Nvidia to use the Omniverse digital twin (Flaherty, 2022).	The first project involved connecting the open digital business platform Siemens Xcelerator with NVIDIA Omniverse.
August 2022	Siemens, Nvidia and BMW announced a plan to collaborate to develop the first pilot metaverse solution for BMW’s electric vehicle manufacturing site in Debrecen, Hungary (siemens.com, 2022).	Keynote address by Siemens President and CEO Roland Busch is available at: (https://www.youtube.com/watch?v=xAAHgH4isFw)

Table 3: The industrial metaverse’s roles in meeting firms’ key strategic objectives

Objective	Explanation	A sample of some mechanisms	Examples
Cost	Reducing operational cost or waste	Digital twins to simulate and test models and environments in real time can help take measure to cut costs	PepsiCo: digital twins to simulate and test to optimize warehouse layouts and workflows to accelerate throughput, reduce downtime Kroger Digital twin and store simulation to optimize store efficiency and processes Amazon: optimize warehouse design, train more efficient robots, and enhance efficiency of the fulfillment process BMW: predictive maintenance using Omniverse (Caulfield, 2022)
Quality	Ensuring the conformity of products and enhancing customer satisfaction	Using metaverse technologies in monitoring quality and taking action to fix and correct any issues.	Kroger: AI lab to expand freshness initiatives: use of NVIDIA’s technology, computer vision and analytics, to detect early signs of deteriorating freshness and dynamic routing to ensure that delivered products are fresh.
Delivery	Ensuring On-time customer delivery	Collecting real-time data to monitor warehouses, delivery routes and other relevant factors continuously and plan logistics better.	Kroger: Use of dynamic routing for last-mile delivery Renault: expected to to reduce delivery times by 60% (Just Auto, 2022).
Flexibility	Developing adaptability/ ability to adjust activities to react to changes	Synthetic data allows more flexibility in training sophisticated AI applications	Amazon: Omniverse and Isaac Sim to model warehouses and simulate real-life conditions that AMR need to handle (Davies, 2022). Deutsche Bahn: digital twin of the entire network to be built into Omniverse by feeding real time data to assess volume flexibility.
Innovation	Introducing new product/ process or implementing new ideas or changes	Using synthetic data for manufacturing applications that have little or no real-world data available/in training ML models or testing mathematical models.	Amazon Robotics: digital twins in Omniverse Enterprise and robotics simulation application and synthetic data-generation tool Isaac Sim Kroger’s use of synthetic data: to help get produce to consumers faster Lowe's: AR headsets giving employees X-ray vision to see things in a store. PepsiCo: use of digital twins in the Omniverse to simulate and test models and environments in real time before making physical investments or applying changes to the physical distribution centers (new processes).
Sustainability	Actions that are economically viable, environmentally sustainable and socially responsible.	Digital twins: architectures can work on different scenarios to lower energy consumption and carbon emission	PepsiCo: Omniverse Enterprise and Metropolis-powered digital twins to improve environmental sustainability of supply chains. Hellenic: cut energy consumption by over 9% Renault: reduce the carbon footprint of vehicle production by 50%.

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