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Metaverse supply chain and operations management

Alexandre Dolgui² and Dmitry Ivanov^{1*}

¹ Berlin School of Economics and Law
Supply Chain and Operations Management, 10825 Berlin, Germany
Phone: +49 30 308771155; E-Mail: divanov@hwr-berlin.de

² IMT Atlantique, LS2N - CNRS, La Chantrerie, 4 rue Alfred Kastler, 44307 Nantes, France
E-Mail: alexandre.dolgui@imt-atlantique.fr

* Corresponding author

Abstract

The metaverse and Web 3.0 create a new, digital world with specific properties and behaviors replicating behaviors and processes of physical entities, and influencing them. This study aims at advancing our understanding on how the metaverse will impact supply chain and operations management (SCOM). Using elements of structured literature search and drawing upon cyber-physical system, digital twin, cloud and digital supply chain, and Industry 4.0/Industry 5.0 concepts, we propose a framework for metaverse SCOM encompassing multiple socio-technological dimensions. We pose that further metaverse developments could result in a co-existence of physical SCOM, metaverse SCOM, and SCOM for coordination of physical and metaverse worlds. We offer a structured future research agenda pointing to new research questions and topics stemming from metaverse-driven visibility, computational power for data analytics, digital collaboration, and connectivity. New research areas can appear specifically dedicated to the metaverse and novel SCOM processes and decision-making areas (e.g., joint demand forecasting for metaverse and physical products, digital inventory allocation in the metaverse, integrated production planning for metaverse and physical worlds, and pricing and contracting for digital products) as well as new performance measures (e.g., virtual customer experience level, availability of digital products, and digital resilience and sustainability).

Keywords: manufacturing; supply chain management; metaverse; digital twin; blockchain; internet-of-things; Web 3.0; digital supply chain.

1. Introduction

The metaverse creates a new world where every physical entity (e.g., people, products, and enterprises) has a digital twin. The entities in the metaverse are not just digital replicas of some physical entities; they possess own properties and behaviors influencing behaviors and processes of physical entities. The metaverse is expected to completely change our lives in very near future, much faster as we can think now (Kathiala, 2022).

What is the metaverse? The term ‘metaverse’ was coined in 1992 in Neal Stephenson’s literary work, Snow Crash (Stephenson, 1992), visualizing it as a black spherical planet accessible to

users through terminals with integrated virtual reality capabilities and where users could appear as avatars (The Economist, 2020). According to Maersk (2022), “The metaverse is the next evolution of the Internet. It’s a fusing of the digital and physical worlds powered by technologies, including virtual and augmented reality, blockchain, artificial intelligence, and the Internet of things that connects smart devices”. Lovich (2022) defines the metaverse as “a combination of the virtual reality and mixed reality worlds accessed through a browser or headset, which allows people to have real time interactions and experiences across distance.”

Metaverse develops fast. Digital technology leaders like Nvidia with Omniverse and Facebook with Meta profoundly invest in metaverse solutions (Huynh-The et al., 2023). SupplyOn supplier collaboration platform (Holzwarth et al., 2022) and the Catena-X data ecosystem have been developed in automotive industry allowing for creation of digital product passports and improving sustainability and resilience of supply chains from the ecosystem perspective (Catena, 2022). Siemens and BMW developed smart manufacturing platforms using cloud technology (Siemens 2022, Open Manufacturing 2022). Manufacturing companies like Puma, Nike, Gucci, and Adidas started using the idea of metaverse in marketing and e-commerce to interact with customers allowing them to view or even buy digital versions of their products (Barrera and Shah, 2023). However, the role of the metaverse in supply chain and operations management (SCOM) remains underexplored.

Mourtzis et al. (2022) claim that the metaverse represents a new era in Internet connectivity, characterized by interactivity, simulation, decentralized environment, and persistent reality facilitated by the next evolution of Internet (also known as Web3.0) to combine digital and physical worlds. Lee and Kundu (2022) point to conceptual similarities of the metaverse to cyber-physical systems, the application of which to manufacturing has been discussed by Panetto et al. (2019). A survey by Accenture (2022a) found out that 64% of supply chain management executives believe that the metaverse will make impact in their organizations.

Analysis of the existing literature shows that the metaverse impacts on the SCOM go beyond technological dimension only. The metaverse is not only a technology but a complex socio-technological phenomenon. In this setting, a scientific approach is needed to reflect on chances, barriers, and challenges that the development of the metaverse will impose on SCOM.

This study aims at advancing our understanding on how the metaverse will influence SCOM. In particular we are interested in exploring the following research questions (RQ):

RQ1: How the metaverse will impact SCOM in the physical world?

RQ2: What are potential SCOM processes and decision-making areas in the metaverse?

RQ3: What are the mutual impacts from co-existence of physical and metaverse SCOM?

We contribute to literature by proposing a framework describing metaverse SCOM from multiple socio-technological-economical perspectives, i.e., people, organization, technology, management, scope, task, and model. We pose that the further metaverse developments could result in three major decision-making domains in SCOM, i.e., physical supply chain and operations, metaverse supply chain and operations, and coordination of physical and metaverse supply chains and operations. These domains are mutually interconnected.

To provide some guidelines and structure for further research on metaverse SCOM and inter-relations between physical and metaverse SCOM, we discuss a future research agenda. We show that future research can explore new opportunities for SCOM stemming from the metaverse, i.e., visibility, computational power for data analytics, digital collaboration, and connectivity. At the same time, we show that new SCOM activities can appear specifically dedicated to the metaverse and leading to novel SCOM processes and decision-making areas (e.g., joint demand forecasting for metaverse and physical products, digital inventory allocation in the metaverse, integrated production planning for metaverse and physical worlds, and pricing and contracting for digital products) as well as new performance measures (e.g., virtual customer experience level, availability of digital products, and digital resilience and sustainability).

The remainder of this paper is organized as follows. In Section 2, the results of a SCOPUS search for the metaverse literature related to SCOM are presented. Drawing upon keyword analysis, we propose the metaverse SCOM framework in Section 3. In Section 4, future research questions and new topics focused on metaverse are discussed. We conclude in Section 5 by summarizing major insights of this study and pointing to some future extensions.

2. Analysis of main topics in research on the metaverse and SCOM

To understand the state-of-the art in research on the metaverse and SCOM, we first run a SCOPUS search organised as follows:

```
TITLE-ABS-KEY ( metaverse ) AND ( LIMIT-TO ( DOCTYPE , "ar" ) ) AND ( LIMIT-TO ( SUBJAREA , "ENGI" ) OR LIMIT-TO ( SUBJAREA , "BUSI" ) OR LIMIT-TO ( SUBJAREA , "DECI" ) )
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We searched for “metaverse” in the titles, abstracts, and keywords of the journal articles in the business and management, decision sciences, and engineering areas. The search yielded 217 papers and 119 keywords with a minimum threshold of using a particular keyword in at least 3 articles. The result of the VOS Viewer co-occurrence analysis is presented in Fig. 1.

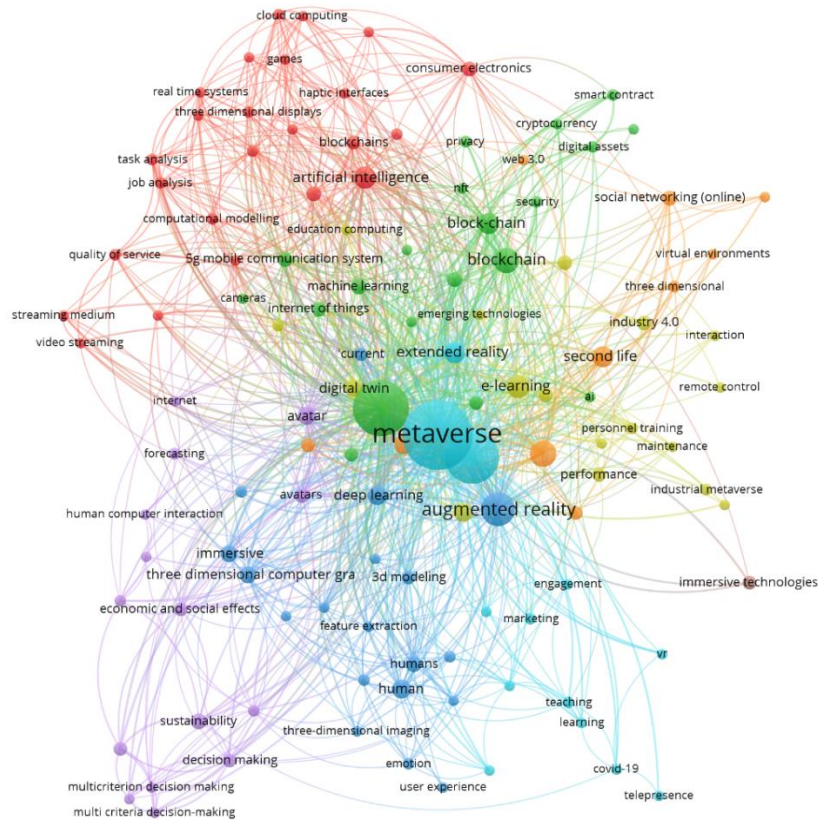


Fig. 1. Metaverse and SCOM research map

We carefully analysed the keywords identified by SCOPUS and structured them based on three frameworks. First, we used a framework from organisation theory, namely Leavitt’s diamond model, which is based on four elements: structure, task, people and technology. In addition, we consider the 3D framework of Industry 4.0 (Ivanov et al., 2021a), which classifies technology, management, and organisation elements, and the digital twin framework proposed by Freese and Ludwig (2022), which suggests scope, actor, asset, flow reference object, performance measurement, and supply chain process as major SCOM digital twin elements. Integrating these frameworks, we propose the following seven elements to be included in the metaverse SCOM framework: technology, people, management, organisation, scope, task, and modelling (Table 1).

Table 1. Metaverse SCOM elements

Technology	Organi- sation	People	Management	Scope	Task	Model- ing
Virtual Reality Augmented Reality Blockchain Artificial Intelli- gence Mixed Reality 3D Computer Graphics	Industrial Metaverse Real- Time Sys- tems Smart City	Virtual Worlds E-learning Extended Reality Second Life Avatar	Decision- making Visibility Sustainability Performance Multi Criteria Decision- making	Web 3.0 Digital Assets Digital Devices Multi- media Con- tents	Market- ing User ex- perience Forecast- ing Smart contract	Big Data Deep Learning Machine Learning Neural Networks Mathe- matical

5G Industry 4.0 Cloud Computing Internet of Things Interactive Computer Graphics Network Security Interactive Computer Systems Cryptocurrency Remote Control 3D Printers Cyber Physical System	Virtual Environments Decentralization	Social Networking X Reality Computer Aided Instruction Human Computer Interaction Streaming Medium	Interaction		Manufacturing	Programming Graphs Discrete Events Systems Discrete Events Simulation 3D Modeling Digital Twin
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It can be observed in Table 1 that the existing research on the metaverse and SCOM covers a broad socio-technological-economical spectrum. On the one hand, our analysis allows to identify key digital technologies enabling the metaverse. On the other hand, the key role of people and human-machine interface becomes evident through the keywords represented in Table 1. The metaverse enables new organizational forms and management capabilities (e.g., visibility and interaction). A large variety of artificial intelligence-based modeling methods supports decision-making tasks in forecasting, manufacturing, and contracting in different system scopes.

3. Metaverse SCOM framework

Based on the keyword analysis, we can now propose a metaverse SCOM framework (Fig. 2).

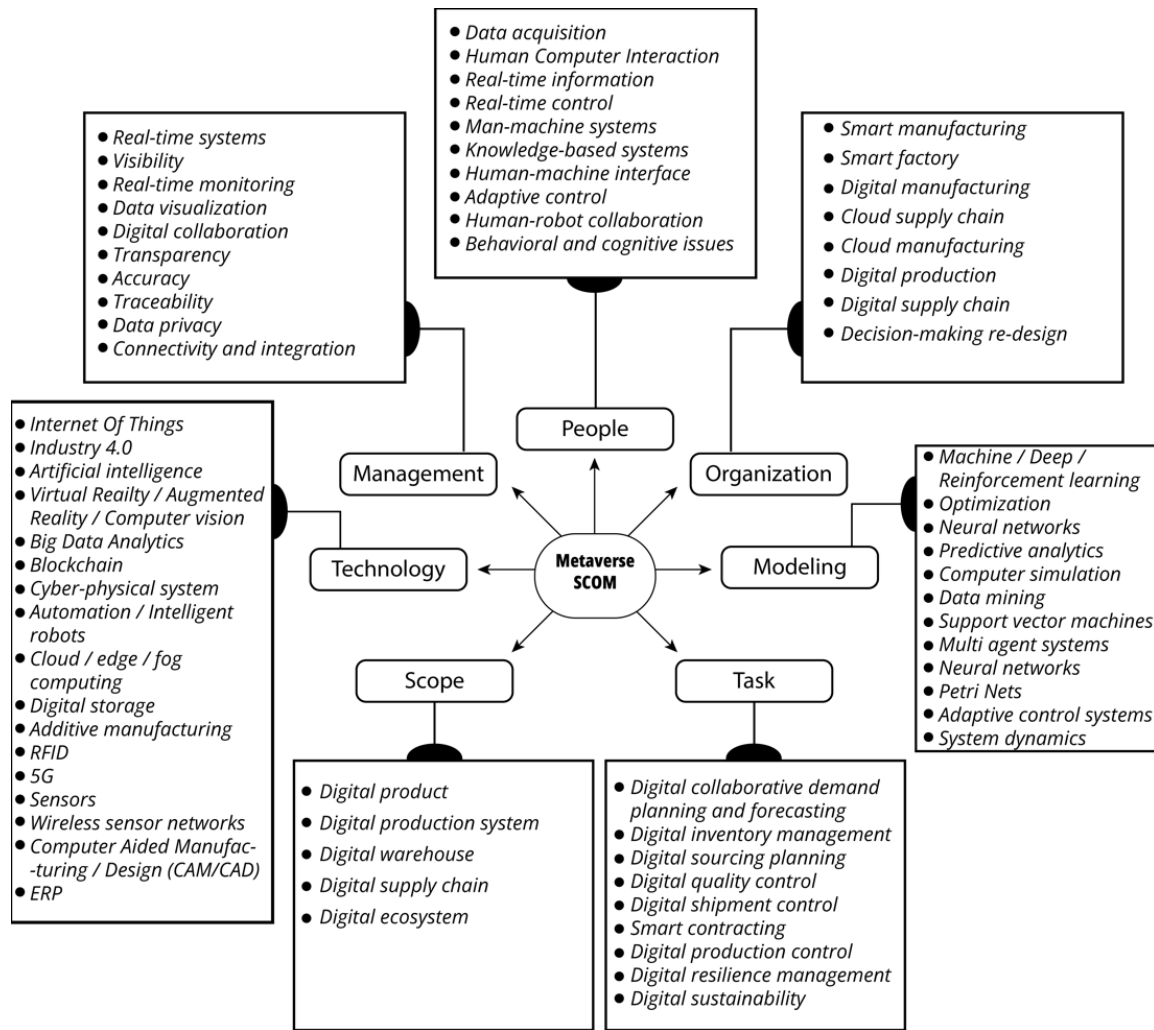


Fig. 2. The metaverse SCOM framework

In Fig. 2, we combine keywords identified by the SCOPUS search with our integrative analysis of the relevant frameworks such as digital twins (Negri et al., 2017; Badakhshan et al., 2022; Berti and Finco, 2022; Burgos and Ivanov, 2021; Frazzon et al., 2021; Huang et al., 2022), cloud and digital supply chain (Ivanov et al., 2022; MacCarthy and Ivanov, 2022; Zhang et al., 2022), collaborative networks (Camarinha-Matos and Afsarmanesh, 2005), reconfigurable supply chain (Dolgui et al., 2020), cloud manufacturing (Moghaddam and Nof, 2018), open manufacturing (Kusiak, 2020), Physical Internet (Pan et al., 2017), and Industry 4.0/Industry 5.0 (Yin and Stecke, 2018; Tang and Veelenturf, 2019; Zennaro et al., 2019; Winkelhaus and Grosse, 2020; Choi et al., 2022; Ivanov, 2022a).

Further, in Fig. 3 we illustrate the extension of traditional SCOM understanding as a “a cross-department and cross-enterprise integration and coordination of material, information, and financial flows to transform and use the supply chain resources in the most rational way along the entire value chain, from raw material suppliers to customers” (Ivanov et al., 2021b, p. 9) toward a triple-SCOM view whereas physical, metaverse, and physical-metaverse SCOMs co-exist.

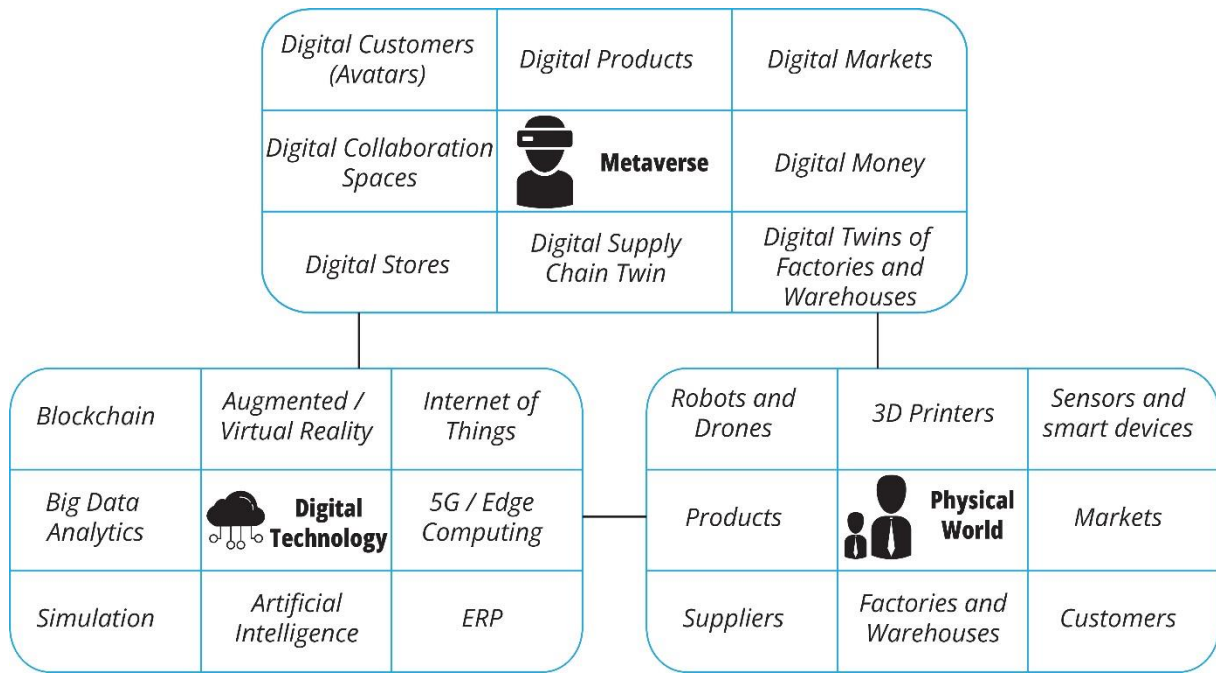


Fig. 3. SCOM in the metaverse era

Fig. 3 depicts that physical and metaverse worlds are connected through digital technology such as augmented/virtual reality, Blockchain, Artificial Intelligence, Internet-of-Things, 5G/Edge computing, ERP, Big data analytics, and simulation (Brintrup et al., 2020; Cai et al., 2021; Chabanet et al., 2022; Cui et al., 2022; Dolgui and Ivanov, 2022; Dubey et al., 2021; Elmachtoub and Grigas, 2022). Smart devices and sensors from physical products along with 3D printers represent another part of data sources for the metaverse. In the metaverse, digital customers (i.e., avatars) act in the digital markets where digital products are offered and sold using digital money (probably, a mix of physical and digital products can be considered, too). Managers use digital collaboration spaces for sourcing, production, and logistics coordination. Digital stores, factories, warehouses represent the supply chain in the metaverse, which can be digital replicas of physical stores, factories, and warehouses, or represent new, additional entities, which do not exist in the physical supply chain.

4. Open research questions

In this section, we outline open research questions related to the metaverse SCOM.

4.1 Area 1: Scope and task

The scope of the metaverse SCOM will cover digital products, digital factories and warehouses, digital supply chain, and digital ecosystems. The metaverse supply chain is not just a digital replica of a physical supply chain. **The digital and physical supply chains evolving autonomously but co-jointly.** When we assume that a digital twin is a digital replica of a physical supply chain, then the metaverse is more than a digital twin. On the one hand, the metaverse enhances decision-making support and analytics applications for physical SCOM. On the other hand, the digital and physical supply chains mutually influence each other (Liu et al., 2020; Lv et al., 2022).

For example, an increased popularity of a product in the metaverse can lead to an increased demand for this product in the physical supply chain. A timely recognition of these trends

through data analytics can help supply chain managers to prepare for the peak load. The metaverse data analysis can also be used for new product introductions in the market and decisions on initial order quantity – for example, a product can be first introduced in the metaverse and the sales/inventory data from the digital supply chain can be used to setup the physical supply chain processes. In another example, a product shortage in the physical supply chain can be substituted by an increased supply of this product in the metaverse so that customers (or their avatars) who cannot buy the physical product could obtain it in the digital form. This is a novel context for supply chain resilience management.

Assuming that people will have more and more activities in the metaverse, we can expect new SCOM activities specifically dedicated to the metaverse and leading to appearance of novel SCOM processes and decision-making areas. For example, joint demand forecasting for metaverse and physical products belongs to a new research area. Since digital products will also require some storage place in the metaverse, digital inventory allocation in the metaverse can arise as a novel optimization context. Pricing and contracting for digital products as well as new performance measures (e.g., virtual customer experience level and availability of digital products, and digital resilience and sustainability) can motivate new research. Through digital analytics, testing and forecasting customer and suppliers behaviors can be used for demand, inventory and capacity planning.

Inventory management research can also be innovated through the metaverse. For example, a part of customers might like to have both physical and digital products, another part – only physical, and another one – only digital products. E.g., a luxury car, which can be too expensive in real life can be purchased in the metaverse. Competition between digital and physical products can lead to new interesting problem settings in pricing and inventory management. In some cases, digital products can even be wanted more as physical ones – a new setting for revenue management. Sourcing and production planning in the metaverse SCOM can be adjusted by digital collaboration places with an improved delivery visibility and coordination. In addition, physical products might be increasingly supplemented by some digital services, and digital products can have some physical add-ons. In this setting, sourcing and production planning can encounter novel and counter-intuitive decision-making problems.

4.2 Area 2: Management

As indicated in Fig. 2, three SCOMs could exist when the metaverse becomes an important part of everyday life – SCOM for physical world, SCOM for digital world, and SCOM for coordinating physical and digital worlds. The metaverse can be used for decision-making support in physical SCOM through enhanced management capabilities such as visibility, computational power for data analytics, digital collaboration, and connectivity (Dolgui and Ivanov, 2022).

Through supply chain mapping, it becomes possible to obtain more accurate, real-time data on lead-times, delays, deliveries, shortages, physical locations of containers and trucks, and costs (MacCarthy et al., 2022). Forecasted, known-unknown becomes knowable. For example, in a metaverse “collaboration room”, supply chain managers could “review expected sales forecasts, projected production plans and possible supplier limitations that could affect manufacturing volume. They could also see, on an immersive supply chain network map, exactly where inventory is, virtually walk through key ports to identify possible shipping delays because of

congestion, and model possible alternatives to keep products moving to the right stores and shelves.” (Accenture, 2022b).

Resilience management can be enhanced by disruption recognition, impact prediction, recovery actions (Ralston and Blackhurst, 2020; Ivanov, 2021; Ivanov and Dolgui, 2021; Ivanov, 2022b). Using digital twin-based simulation environments, managers can analyse different scenarios in the virtual world using the digital supply chain before implementing decisions in the physical supply chain. Recognizing bottlenecks and enforcing supply chains for peak loads (e.g., demand increase) and supply disruptions will be easier and stress-testing of supply chains can be performed with a higher knowledge awareness (Aldrighetti et al., 2021; Aldrighetti et al., 2023; Ivanov and Dolgui, 2022a).

Sustainability management can be improved through transparency about carbon emissions, visibility about the entire product life cycle of products and associated environmental footprints. The digital supply chain can help in tracing the upstream suppliers to ensure that suppliers do not use child work and produce products according to sustainability standards and laws.

4.3 Area 3: Technology

Huynh-The et al. (2023) point to six major technological elements for the metaverse, i.e., a digital twin (cyber-physical interface), neural interface (brain-computer interface), machine vision (virtual/augmented reality), networking (e.g., multi-access edge computing), blockchain (data collection, storage, sharing, and management), and natural language processing (e.g., text-to-speech processing). Bhandal et al. (2022) point to Internet-of-Things, Blockchain, Artificial Intelligence and Data analytics, augmented and virtual reality, and Industry 4.0 as digital twin enablers. In addition, through 3D printing, production can be triggered by customers. Customers can also design products and they will be produced on demand (Boute et al., 2022; Peron et al., 2022). This will have implications on supply chain complexity and environmental footprint along with increased customer satisfaction. Digital platforms and supplier collaboration portals are used to ensure collaboration and communication in Industry 5.0 (Reim et al., 2022; Holzwarth et al., 2022; Sawik, 2022). End-to-end visibility, which is so important for both proactive and reactive decision making, is supported across the supply chain by ERP systems, Blockchain, and T&T systems (Roeck et al., 2020; Choi et al., 2022; Li et al., 2022; Maccarthy and Ivanov, 2022).

Digital twins can be enabled by technologies of different scopes (Boyes and Watson, 2022; Nguyen et al., 2022). CAD/CAM systems are applied at the product level while MES and ERP systems enable building of digital twins of processes and organisations. At the supply chain level, special software such as anyLogistix in combination with external data sources (e.g., data from logistics service providers, weather data, financial market data) are used to build supply chain digital twins (Ivanov and Dolgui, 2021; Burgos and Ivanov, 2021). Future research areas highlight both a technical understanding of system integration and interoperability and management conceptualisation of needs and limits for data-driven decision-making support. Technologies allow for the integration of models with external data sources and ensure interactions with other digital twins.

4.4. Area 4: People

The metaverse will change the work and role of people in SCOM. Automatic responses with minimal human intervention, new standards for working places and remote work, collaboration of people (virtual meeting platforms), and human-robot collaboration are just some examples (Rozanek et al., 2022; Sheu and Choi, 2022; Saghafian et al., 2022; Sun et al., 2022). The metaverse is being developed and used by people, and at the same time it changes the human behaviours and SCOM decision-making.

Decisions in SCOM depend on the expertise of the manager, knowledge and skills they exhibit, and their access to real-time data and information (Sgarbossa et al., 2020). The metaverse can help managers providing decision-making support by acquiring real-time data and simulating potential outcomes of certain decisions (e.g., alternative recovery policies after a disruption or changes in an environmental footprint due to a supply chain redesign). Digital twins can also consider the competence of making decisions (e.g., placing orders in an inventory control system). Most centrally, the metaverse offers real-time, data-driven decision-making support.

Further research is needed to examine the impacts of a continuous access to real-time data on managerial decision-making. In addition, behavioural aspects of data-driven decision-making and cognitive biases in human–artificial intelligence interactions belong to the novel topics when digital twins can be explored in SCOM research (Fahimnia et al., 2019; Fu et al., 2022; Sun et al., 2022). At the manufacturing system level, human–robot collaboration is one of the central digital twin–related future research topics (Sheu and Choi, 2022). Mourtzis et al. (2022) stress the human-centric perspective of the metaverse echoing an integration of human-centricity, resilience, and sustainability in Industry 5.0 framework (Ivanov, 2022a).

4.5 Area 5 Organisation

Technology determines organisation. The metaverse will not only mirror physical SCOM organisations but also create and develop new business and operational models. Through digital twins, novel organisational constructs such as digital manufacturing, cloud supply chain, and collaborative platforms arise (Sharma et al., 2022; Ivanov et al., 2022). Examination of the metaverse–driven transformations in the organisation of SCOM can be conducted in future research areas where impactful and substantial contributions can be made. In addition, digital twins can lead to new organisational structures and a redistribution of decision-making competencies across departments. Metaverse solutions can be applied to factory design and planning through simulation of their digital twins. In the created virtual simulation environments, processes and flows can be represented, analyzed, and improved. New organizational forms (e.g., cloud supply chains, intertwined supply networks, ecosystems) and new categories in SCOM such as creator economy, discovery, and digital experience can appear (Ivanov and Dolgui, 2020).

In the context of viability, digital technology allows for the implementation of the viable supply chain model (Ruel et al., 2021; Ivanov, 2022c; Ivanov and Keskin, 2023). Visibility, reconfigurable manufacturing systems, and additive manufacturing, along with analytics and digital collaboration tools, are vital for viable manufacturing and supply chains. In light of the increasing resource shortages in physical supply chains due to [component \(e.g. semiconductors\)](#) shortage, workforce variability, energy blackouts, and inflation (Ivanov and Dolgui, 2022b; Hägele

et al., 2023), the importance of viable supply chains and the metaverse will continue to grow in the future.

Following Ivanov (2022c), “the Viable Supply Chain Model is based on adaptable structural network designs for situational supply-demand allocations and, most importantly, the establishment and control of adaptive mechanisms for transitions between the structural designs (Ivanov, 2021e). Moreover, supply chain viability and the ecosystem view have been synthesized in the lens of the human-centred ecosystem perspective by Ivanov and Dolgui (2022a).” In addition, the reconfigurable supply chain framework can be considered a part of future Industry 5.0 developments (Dolgui et al., 2020; Ivanov, 2022a). Dolgui et al. (2020) note that “supplementing the reconfigurable manufacturing concept (Zennaro et al., 2019; Battaia et al., 2020), the reconfigurable supply chain adds three specific features: active behaviour of network elements, networking effects across multiple structures and their dynamics (i.e., organizational, information, financial, technological, energy), and network complexity (i.e., multi-echelon supply chains). The reconfigurable supply chains are characterized by structural and process variety, which is beneficial for supply chain resilience.”

4.6. Area 6 Modelling

Analytics capabilities offered through the metaverse can hardly be imagined now to full extent. Modelling in the metaverse will be based on shifting historical data-based forecasting for supply chain and operations planning methods toward real time, data-driven decisions (Fig. 4).

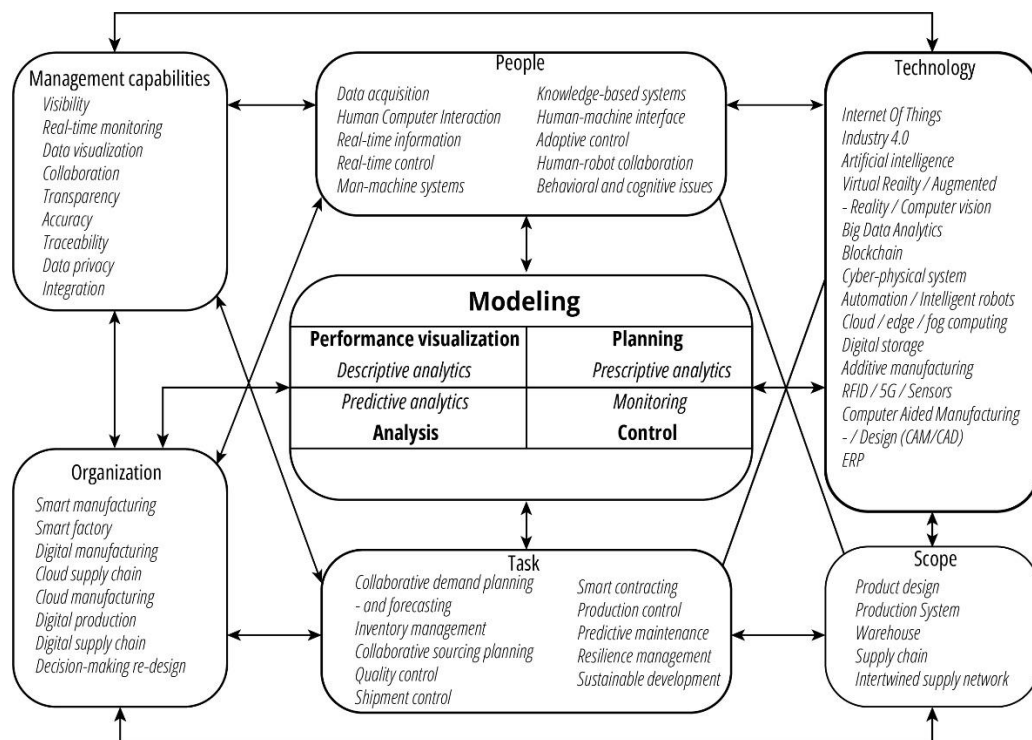


Fig. 4. Modelling in the SCOM metaverse framework

Optimisation, discrete-event simulation, neural networks, machine and reinforcement learning, agent-based modelling and system dynamics allow for the implementation of the full variety of descriptive, predictive and prescriptive algorithms in SCOM (Cavalcante et al., 2019; Rai et al., 2021; Fu et al., 2022; Kusiak, 2022; Rolf et al., 2022). While real-time data-driven models

constitute a narrow view of digital twins (i.e., a digital twin as a stand-alone software package), in a broader sense, digital twins can be considered as a combination of different information systems and models. Seamless digital and physical integration can become the centric element of the SCOM metaverse. For example, imagine a product that knows its location, inventory status, price, and costs. Using edge computing, an algorithm would trigger automatic replenishment, routing, pricing, and demand prediction decisions enhancing margins, product availability, on-time delivery, and overall profitability. New computational capacities for supply chain and operations analytics and the use of synthetic data along with industrial Internet-of-Things can be used to predict customers and supplier behaviors in terms of demand recognition and delivery accuracy. Future research can shed more light on the transition from offline to real-time data-driven modelling, revealing its value and barriers through improved end-to-end visibility in the supply chain.

5. Conclusion

The metaverse and Web 3.0 represent new and strong trigger for further evolution of SCOM. They not only create a new, digital world with specific properties and behaviors replicating behaviors and processes of physical entities, but also influence physical SCOM. Despite some fragmented literature with the focus on the metaverse and SCOM, there is a lack of understanding of how the metaverse will impact SCOM in the physical world, what are potential SCOM processes and decision-making areas in the metaverse, and what are the mutual impacts from co-existence of physical and metaverse SCOM.

Driven by these questions, our study aimed at advancing our understanding on how the metaverse will impact SCOM drawing upon cyber-physical system, digital twin, cloud and digital supply chain, and Industry 4.0/Industry 5.0 concepts. We proposed a framework for metaverse SCOM encompassing seven socio-technological dimensions, i.e., organization, management, people, technology, scope, task, and modelling.

Our analysis shows that in future we can expect a co-existence of physical SCOM, metaverse SCOM, and SCOM for coordination of physical and metaverse worlds. We offered a structured future research agenda pointing to new research questions and topics stemming from metaverse-driven visibility, computational power for data analytics, digital collaboration, and connectivity. New research areas can appear specifically dedicated to the metaverse and novel SCOM processes and decision-making areas (e.g., joint demand forecasting for metaverse and physical products, digital inventory allocation in the metaverse, integrated production planning for metaverse and physical worlds, and pricing and contracting for digital products) as well as new performance measures (e.g., virtual customer experience level, availability of digital products, and digital resilience and sustainability).

References

- Accenture (2022a). <https://www.accenture.com/us-en/insights/technology/technology-trends-2022>, accessed on January 12, 2023.
- Accenture (2022b). <https://www.accenture.com/us-en/blogs/business-functions-blog/metaverse-supply-chain-networks>, accessed on January 12, 2023.

- Aldrighetti R., Battini D., Ivanov D., Zennaro I. (2021). Costs of resilience and disruptions in supply chain network design models: a review and future research directions. *International Journal of Production Economics*, 235, 108103.
- Aldrighetti R., Battini D., Ivanov D. (2023). Efficient resilience portfolio design in the supply chain with consideration of preparedness and recovery investments. Omega, forthcoming.
- Badakhshan E., Ball, P. (2022). Applying digital twins for inventory and cash management in supply chains under physical and financial disruptions. *International Journal of Production Research*, forthcoming
- Barrera, KG, Shah, D. (2023). Marketing in the Metaverse: Conceptual understanding, framework, and research agenda. *Journal of Business Research*, 155 A, 113420.
- Battaia, O., L Benyoucef, X Delorme, A Dolgui, S Thevenin (2020). Sustainable and energy efficient reconfigurable manufacturing systems. *Reconfigurable Manufacturing Systems: From Design to Implementation*, Springer, pp. 179-191
- Berti N., Finco S. (2022). Digital Twin and Human Factors in Manufacturing and Logistics Systems: State of the Art and Future Research Directions. *IFAC-PapersOnLine* 55(10), 1893-1898.
- Bhandal, R., Meriton, R., Kavanagh, R.E. and Brown, A. (2022), "The application of digital twin technology in operations and supply chain management: a bibliometric review", *Supply Chain Management*, Vol. 27 No. 2, pp. 182-206
- Boute RN, Disney SM, Gijsbrechts J, Van Mieghem JA (2022) Dual sourcing and smoothing under nonstationary demand time series: Reshoring with speedfactories. *Management Science* 68(2):1039–1057.
- Boyes, H., Watson, T. (2022). Digital twins: An analysis framework and open issues. *Computers in Industry*. 143, 103763
- Brintrup, A., Pak, J., Ratiney, D., Pearce, T., Wichmann, P., Woodall, P., and McFarlane, D. (2020). Supply chain data analytics for predicting supplier disruptions: a case study in complex asset manufacturing. *International Journal of Production Research*, 58(11), 3330-3341.
- Burgos, D., Ivanov D. (2021). Food Retail Supply Chain Resilience and the COVID-19 Pandemic: A Digital Twin-Based Impact Analysis and Improvement Directions. *Transportation Research – Part E: Logistics and Transportation Review*, 152, 102412.
- Cai, Y., T.M. Choi, J. Zhang. (2021) Platform supported supply chain operations in the blockchain era: supply contracting and moral hazards. *Decision Sciences*, 52(4), 866-892.
- Camarinha-Matos, L.M. and Afsarmanesh, H. (2005) Collaborative networks: a new scientific discipline. *Journal of Intelligent Manufacturing*, 16, 439–452.
- Catena (2022). <https://catena-x.net/de/>, accessed on December 14, 2022.
- Cavalcante, I.M., Frazzon E.M., Forcellinia, F.A., Ivanov, D. (2019). A supervised machine learning approach to data-driven simulation of resilient supplier selection in digital manufacturing. *International Journal of Information Management*, 49, 86-97.
- Chabanet, S., Bril El-Haouzi, H., Morin, M., Gaudreault, J., Thomas, P. (2022). Toward digital twins for sawmill production planning and control: benefits, opportunities, and challenges. *International Journal of Production Research*, forthcoming.
- Choi, T.M., S. Kumar, X. Yue, H.L. Chan. (2022). Disruptive technologies and operations management in the Industry 4.0 era and beyond. *Production and Operations Management*, 31(1), 9-31.
- Choi, TM., Dolgui, A., Ivanov, D., Pesch, E. (2022). OR and analytics for digital, resilient, and sustainable manufacturing 4.0. *Annals of Operations Research*, 310(1), 1-6.
- Cui, R., Li, M., & Zhang, S. 2022. AI and Procurement. *Manufacturing & Service Operations Management*, 24(2), 691-706.
- Dolgui, A., Ivanov, D., Sokolov, B. (2020) Reconfigurable supply chain: The X-Network. *International Journal of Production Research*, 58(13), 4138-4163.
- Dolgui, A. Proth, J.-M. (2010) *Supply chain engineering: Useful methods and techniques*, London: Springer.

- Dolgui A., Ivanov D., (2022). 5G in Digital Supply Chain and Operations Management: Fostering Flexibility, End-to-End Connectivity and Real-Time Visibility through Internet-of-Everything. *International Journal of Production Research*, 60(2), 442-451
- Dubey, R., Gunasekaran, A., Childe, S. J., Wamba, S. F., Roubaud, D., & Foropon, C. (2021). Empirical Investigation of Data Analytics Capability and Organizational Flexibility as Complements to Supply Chain Resilience. *International Journal of Production Research*, 59(1), 110–128.
- Elmachtoub, A. N., & Grigas, P. (2022). Smart “Predict, then Optimize.” *Management Science*, 68(1), 9–26.
- Fahimnia, B., Pournader, M., Siemsen, E., Bendoly, E., and Wang, C. (2019). Behavioral operations and supply chain management—a review and literature mapping. *Decision Sciences*, 50(6), 1127-1183.
- Frazzon, E.M., Freitag, M., Ivanov, D. (2021). Intelligent Methods and Systems for Decision-Making Support: Toward Digital Supply Chain Twins. *International Journal of Information Management*, 57, 102281.
- Freese, F., Ludwig, A. (2021). How the Dimensions of Supply Chain are Reflected by Digital Twins: A State-of-the-Art Survey. In: Ahlemann, F., Schütte, R., Stieglitz, S. (eds) *Innovation Through Information Systems. WI 2021. Lecture Notes in Information Systems and Organisation*, Springer, Cham.
- Fu, R., Aseri, M., Singh, P. V., Srinivasan, K. (2022). “Un”fair machine learning algorithms. *Management Science*, 68(6), 4173-4195.
- Hadavi, C. (2022). The Metaverse Of Supply Chain Planning: Creating Virtual Supply Chains. <https://www.forbes.com/sites/forbestechcouncil/2022/07/12/the-metaverse-of-supply-chain-planning-creating-virtual-supply-chains/>, accessed on January 6, 2023.
- Hägele S., Grosse, E., Ivanov, D. (2023). Supply chain resilience: a tertiary study. *International Journal of Integrated Supply Management*, 16(1), 52-81.
- Holzwarth A., Staib C., Ivanov D. (2022). Building Viable Digital Business Ecosystems with Collaborative Supply Chain Platform SupplyOn. In: Dolgui A., Ivanov D., Sokolov B. (Eds.). *Supply Network Dynamics and Control*. Springer, Cham, pp. 187-210.
- Huang, S., Wang, G., Yan, Y. (2022). Building blocks for digital twin of reconfigurable machine tools from design perspective. *International Journal of Production Research*, 60(3), pp. 942-956.
- Huynh-The, T., Pham, Q.V, Pham, XQ, Nguyen, TT, Han, Z, Kim, D.S. (2023). Artificial intelligence for the metaverse: A survey. *Engineering Applications of Artificial Intelligence*, 117(A), 105581
- Ivanov D., Dolgui A. (2021). A digital supply chain twin for managing the disruptions risks and resilience in the era of Industry 4.0. *Production Planning and Control*, 32(9), 775-788.
- Ivanov D., Tang C.S., Dolgui A., Battini D., Das A. (2021a). Researchers’ Perspectives on Industry 4.0: Multi-Disciplinary Analysis and Opportunities for Operations Management. *International Journal of Production Research*, 59(7), 2055-2078.
- Ivanov D., Tsipoulanidis, A., Schönberger, J. (2021b) *Global Supply Chain and Operations Management: A decision-oriented introduction into the creation of value*, Springer Nature, Cham, 3rd Ed
- Ivanov, D. (2021). Digital supply chain management and technology to enhance resilience by building and using end-to-end visibility during the COVID-19 pandemic. *IEEE Transactions on Engineering Management*, DOI 10.1109/TEM.2021.3095193
- Ivanov, D. (2022a). The Industry 5.0 framework: viability-based integration of the resilience, sustainability, and human-centricity perspectives. *International Journal of Production Research*, DOI: 10.1080/00207543.2022.2118892
- Ivanov D. (2022b). Blackout and Supply Chains: Performance, Resilience and Viability Impact Analysis. *Annals of Operations Research*, DOI : 10.1007/s10479-022-04754-9.
- Ivanov D. (2022c). Viable Supply Chain Model: Integrating agility, resilience and sustainability perspectives – lessons from and thinking beyond the COVID-19 pandemic. *Annals of Operations Research*, 319, 1411-1431.

- Ivanov D., Dolgui A. (2020). Viability of Intertwined Supply Networks: Extending the Supply Chain Resilience Angles towards Survivability. A Position Paper Motivated by COVID-19 Outbreak. *International Journal of Production Research*, 58(10), 2904-2915.
- Ivanov D., Dolgui A., Sokolov B. (2022). Cloud Supply Chain: Integrating Industry 4.0 and Digital Platforms in the “Supply Chain-as-a-Service”. *Transportation Research – Part E: Logistics and Transportation Review*, 160, 102676.
- Ivanov D., Dolgui A. (2022a). Stress testing supply chains and creating viable ecosystems. *Operations Management Research*, 15, 475-486.
- Ivanov, D., Dolgui, A. (2022b). The shortage economy and its implications for supply chain and operations management. *International Journal of Production Research*, 60(24), 7141-7154.
- Ivanov D., Keskin B (2023). Post-pandemic adaptation and development of supply chain viability theory. *Omega*, 116, 102806.
- Kathiala, R. (2022). Look out supply chain—Here comes the Metaverse. https://www.scmr.com/article/look_out_supply_chain_here_comes_the_metaverse, accessed on January 7, 2023
- Kusiak, A. (2022). Predictive models in digital manufacturing: research, applications, and future outlook. *International Journal of Production Research*, forthcoming.
- Kusiak, A. (2020). Open manufacturing: A design-for-resilience approach. *International Journal of Production Research*, 58 (15), 4647-4658.
- Li G., Xue J., Li N., Ivanov D. (2022). Blockchain-supported business model design, supply chain resilience, and firm performance. *Transportation Research – Part E: Logistics and Transportation Review*, 163, 102773.
- Lee, J., Kundu, P. (2022). Integrated cyber-physical systems and industrial metaverse for remote manufacturing. *Manufacturing Letters*, 34, 12-15.
- Liu, C., P. Jiang, W. Jiang (2020). Web-based digital twin modeling and remote control of cyber-physical production systems. *Robot Comput. Integr. Manuf.*, 64, 101956.
- Lovich D. (2022). What Is The Metaverse And Why Should You Care? <https://www.forbes.com/sites/deborahlovich/2022/05/11/what-is-the-metaverse-and-why-should-you-care/?sh=1784d21b2704>, accessed on January 5, 2023.
- Lv, Z., L. Qiao, A. Mardani and H. Lv (2022) Digital Twins on the Resilience of Supply Chain Under COVID-19 Pandemic. *IEEE Transactions on Engineering Management*, doi: 10.1109/TEM.2022.3195903.
- MacCarthy B., Ivanov D. (2022). The Digital Supply Chain—emergence, concepts, definitions, and technologies. In: MacCarthy B., Ivanov D. (Eds.). *The Digital Supply Chain*. Elsevier, Amsterdam, pp. 3-14.
- MacCarthy, B., Ahmed, W., Demirel, G. (2022). Mapping the supply chain: Why, what and how? *International Journal of Production Economics*, 108688.
- Maersk (2022) <https://www.maersk.com/insights/digitalisation/how-the-metaverse-will-transform-supply-chain-management>. (accessed on January 14, 2023).
- Moghaddam, M., and S. Y. Nof. 2018. “Collaborative Service-Component Integration in Cloud Manufacturing.” *International Journal of Production Research* 56 (1–2): 677–691.
- Mourtzis, D., Panopoulos, N., Angelopoulos, J., Wang, B., Wang, L. (2022). Human centric platforms for personalized value creation in metaverse. *Journal of Manufacturing Systems*, 65, 653-659.
- Negri, E., L. Fumagalli, M. Macchi (2017). A review of the roles of digital twin in CPS-based production systems. *Procedia Manuf.*, 11 (2017), pp. 939-948.
- Nguyen, T., Duong, QH., Nguyen, TV., Zhu, Y., Zhou, L. (2022). Knowledge mapping of digital twin and physical internet in Supply Chain Management: A systematic literature review. *International Journal of Production Economics*, 244, 108381.
- Open Manufacturing (2022). <https://open-manufacturing.org/> (accessed on January 4, 2022).
- Pan S, Ballot E, Huang GQ, Montreuil B (2017) Physical internet and interconnected logistics services: research and applications. *International Journal of Production Research* 55(9):2603–2609.

- Panetto H., Iung B., Ivanov D., Weichhart G., Wang X. (2019). Challenges for the cyber-physical manufacturing enterprises of the future. *Annual Reviews in Control*, 47, 200-213.
- Peron, M.; Basten, R.; Knofius, N.; Lolli, F.; Sgarbossa, F. (2022). Additive or Conventional Manufacturing for Spare Parts: Effect of Failure Rate Uncertainty on the Sourcing Option Decision. *IFAC PapersOnLine*, 55(10), 1141-1146.
- Rai, R., Tiwari, MK, Ivanov D., & A. Dolgui (2021). Machine learning in manufacturing and Industry 4.0 applications. *International Journal of Production Research*, 59(16), 4773-4778.
- Ralston, P., Blackhurst, J. (2020). Industry 4.0 and resilience in the supply chain: a driver of capability enhancement or capability loss? *International Journal of Production Research*, 58(16), 5006-5019.
- Reim, W., Andersson, E., Eckerwall, K. (2022). Enabling collaboration on digital platforms: a study of digital twins. *International Journal of Production Research*, forthcoming.
- Roeck, D., H. Sternberg & E. Hofmann (2020) Distributed ledger technology in supply chains: a transaction cost perspective. *International Journal of Production Research*, 58:7, 2124-2141.
- Rolf, B., Jackson, I., Müller, M., Lang, S., Reggelin, T., Ivanov, D. (2022). A review on reinforcement learning algorithms and applications in supply chain management. *International Journal of Production Research*, DOI 10.1080/00207543.2022.2140221.1
- Rožanec, J.M., J. Lu, J. Rupnik, M. Škrjanc, D. Mladenčić, B. Fortuna, X. Zheng & D. Kiritsis (2022) Actionable cognitive twins for decision making in manufacturing, *International Journal of Production Research*, 60:2, 452-478
- Ruel, S., El Baz J., Ivanov, D., Das, A. (2021). Supply Chain Viability: Conceptualization, Measurement, and Nomological Validation. *Annals of Operations Research*, <https://doi.org/10.1007/s10479-021-03974-9>
- Saghafian, S., Tomlin, B., & Biller, S. 2022. The internet of things and information fusion: who talks to who?. *Manufacturing & Service Operations Management*, 24(1), 333-351
- Sawik T. (2022). A linear model for optimal cybersecurity investment in Industry 4.0 supply chains. *International Journal of Production Research*, 60(4), 1368-1385.
- Sgarbossa, F., EH Grosse, WP Neumann, D Battini, CH Glock (2020). Human factors in production and logistics systems of the future. *Annual Reviews in Control* 49, 295-305
- Sharma, A., Kosasih, E., Zhang, J., Brintrup, B., Calinescu, A. (2022). Digital Twins: State of the art theory and practice, challenges, and open research questions. *Journal of Industrial Information Integration*, 30, 100383.
- Sheu, JB., Choi, T.-M. (2022). Can We Work More Safely and Healthily with Robot Partners? A Human-Friendly Robot-Human Coordinated Order Fulfillment Scheme. *Production and Operations Management* (DOI: 10.1111/poms.13899).
- Siemens (2022). MindSphere. <https://siemens.mindsphere.io/en>, (accessed on January 4, 2022).
- Stephenson N. (1992). *Snow Crash*. Bantam Books, New York (1992)
- Sun, J., Zhang, D. J., Hu, H., and Mieghem, J. A. V. (2022). Predicting human discretion to adjust algorithmic prescription: A large-scale field experiment in warehouse operations. *Management Science*, 68(2), 846-865.
- Tang C.S., Veelenturf L.P. (2019). The strategic role of logistics in the Industry 4.0 era. *Transportation Research Part E: Logistics and Transportation Review*, 129, 1-11.
- The Economist. (2020). A novelist's vision of the virtual world has inspired an industry. <https://www.economist.com/technology-quarterly/2020/10/01/a-novelists-vision-of-the-virtual-world-has-inspired-an-industry>; accessed on January 4, 2023.
- Winkelhaus, S., EH Grosse (2020). Logistics 4.0: a systematic review towards a new logistics system. *International Journal of Production Research* 58 (1), 18-43
- Yin Y, Stecke K.E., Li D. (2018) The evolution of production systems from Industry 2.0 through Industry 4.0. *International Journal of Production Research*, 56(1-2), 848-861.
- Zennaro, I., S Finco, D Battini, A Persona (2019). Big size highly customised product manufacturing systems: a literature review and future research agenda. *International Journal of Production Research* 57 (15-16), 5362-5385

Zhang G., MacCarthy B., Ivanov D. (2022). The cloud, platforms, and digital twins—Enablers of the digital supply chain. In: MacCarthy B., Ivanov D. (Eds.). *The Digital Supply Chain*. Elsevier, Amsterdam, pp. 77-91.