

The application of digital twin technology in operations and supply chain management: a bibliometric review

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Abstract

Purpose – The application of digital twins to optimise operations and supply chain management functions is a burgeoning practice. Scholars have attempted to keep pace with this development initiating a fast-evolving research agenda. The purpose of this paper is to take stock of the emerging research stream identifying trends and capture the value potential of digital twins to the field of operations and supply chain management.

Design/methodology/approach – In this work we employ a bibliometric literature review supported by bibliographic coupling and keyword co-occurrence network analysis to examine current trends in the research field regarding the value-added potential of digital twin in operations and supply chain management.

Findings – The main findings of this work are the identification of four value clusters and one enabler cluster. Value clusters are comprised of articles that describe how the application of digital twin can enhance supply chain activities at the level of business processes as well as the level of supply chain capabilities. Value clusters of production flow management and product development operate at the business processes level and are maturing communities. The supply chain resilience and risk management value cluster operates at the capability level, it is just emerging, and is positioned at the periphery of the main network.

Originality/value – This is the first study that attempts to conceptualise digital twin as a dynamic capability and employs bibliometric and network analysis on the research stream of digital twin in operations and supply chain management to capture evolutionary trends, literature communities and value-creation dynamics in a digital-twin-enabled supply chain.

Keywords Digital twin, Cyber-physical systems, Operations management, Supply chain management, Bibliometric analysis, Bibliographic network analysis, Keywords co-occurrence network analysis

Paper type Literature review

1. Introduction

1.1 Background

The strategic importance of supply chains has been growing in prominence in recent years, with many scholars remarking that increasingly, market competition takes place no longer between individual companies but supply chains (Farahani *et al.*, 2014). Indeed, the rapid evolution of supply chain management (SCM) as a sub-discipline within operations management (OM) provides strong evidence for this (Christopher, 1998). As such, there is widespread recognition of the supply chain as an increasingly important lever of value creation for firms in an

ever more dynamic and unpredictable marketplace. The transformation of the operations and supply chain management (OSCM) field into a competitive necessity can be attributed in large parts to successive technological disruptions that have taken place over the years. Digital twin (DT) technology is the most recent instalment of Industry 4.0 technologies that promises to further exacerbate the ongoing trend.

The notion of a DT is, however, not new; it was first introduced back in the 1960s, a practice established and developed by NASA for the Apollo 13 space program. NASA produced physical replicate versions of systems at ground level, which were exact mirror-images of the systems in space.

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Consequently, this DT technology enabled NASA to simulate and measure situations in the Apollo 13 spacecraft while in space (Miskinis, 2019). Thus, with its roots firmly fixed in aeronautics, the DT paradigm is arguably an early example of science and manufacturing fusing together (Barricelli et al., 2019).

Although the first vision of a DT dates back more than a decade (Grieves 2002), it has only recently obtained increased research interest within multiple domains. The main reason for this lies in the fact that central technological enablers, such as the Internet of Things (IoT), have only recently reached the maturity to be deployed profitably in economic environments. Within the different interested communities, the term has evolved leading to at least two different viewpoints of a DT (Negri et al., 2017). The first defines the DT merely as the simulation of the physical asset itself and is mostly used by engineering scholars. However, beyond the scope of simulation, the second perspective refers to a DT as a model which constitutes the basis for simulations, analyses and the like. The latter perspective is currently the most adopted view on DTs and thus the focused viewpoint of this work (Dietz and Pernul, 2020). In the context of OSCM we thus define a DT as “a virtual replica of the real process operation, which is connected to the real world by sensor data and advanced big data analytical tools” (Verboven et al., 2020, p. 79).

A variety of tools from different areas of technological development are currently being explored for such task. Internet of Things technologies facilitate transfer of data from and to different sensors, computers and machines. Cloud Computing offers ways to store, share and work with the data more effectively (Kavanagh et al., 2015). Data Mining and Artificial Intelligence allow to process the data in a smart and efficient way, more and more like the human brain does (Verboven et al., 2020). Other notable innovations associated with DT include Augmented Reality (AR), Robotics (R), Sensor Technology (ST), Omni Channel (OC) and 3D Printing (3DP), to name a few (Büyükoçkan and Göçer, 2018).

These methods and innovations presented above are typically developed in the domain of information and communication technology (ICT) and use software tools for digital data handling, inherent to the strategic initiative Industry 4.0. Therefore, the application of these tools in the supply chain can also be referred to as the digitalization of the supply chain (Verboven et al., 2020). The term digital supply chain (DSC) has been coined to reflect the transformative influence of digital technologies such as DT in the operations of supply chain business processes. In fact, the DT has been argued to be a proactive digital approach introducing the next step in SC digitalization (Dietz and Pernul, 2020). A digital supply chain is defined as a smart, value-driven, efficient process to generate new forms of revenue and business value for organisations and to leverage new approaches with novel technological and analytical methods (Sanders and Swink, 2019; Misrudin and Foong, 2019).

DSC is not about whether goods and services are digital or physical, rather, it is about the way in which OSCM processes are managed employing a wide variety of innovative technologies (Büyükoçkan and Göçer, 2018). A key value of a DSC is the ability to extract intelligence and optimal decisions from large amounts of real-time data quickly by applying machine learning algorithms to those data streams (Moufaddal et al., 2019). Consequently, under the auspices of IT-enabled supply chain management, the

emerging literature concerning the DSC examines how digital technologies such as DT create value in supply chains, and in turn how DSC can add value to firms. Early indications reveal the huge potential of DT to enhance numerous performance metrics at varying levels of OSCM abstractions.

1.2 Value creation in SCM and DT

According to Borys and Jemison (1989), value creation is the process whereby the capabilities of partners in a supply chain are combined such that the competitive advantage of one or more of the partners is improved. However, the notion of value has emerged to be much wider than just economic implications (Pal and Sandberg, 2017). Indeed, with the emergence of the new service and knowledge-based economy, Letaifa (2014) has noticed a shift away from a post-industrial economic understanding of value (cost, efficiency, customer expectations) towards a more knowledge-based, social, subjective, intangible and complex perspective. According to a comprehensive review by Schenkel et al. (2015), value manifestations of four types of value, namely, economic, environmental, information and customer value, can be identified in the literature.

In the literature, value creation has typically been characterized as either exogenous spanning organisations or endogenous focussing on internal efforts to improve supply chain performance (Jayaram et al., 2010). At the empirical level, research has tended to focus on the intra- and extra-organisational generative mechanisms of value (Meriton et al., 2020) and in establishing a link between those and value manifestations. It is also worth noting, however, that the supply chain makes up a quasi-organisation where interdependencies, time and shifting boundaries impose on firms the imperative of efficient management of relationships of supply chain actors to successfully achieve value objectives of the focal firm.

In this context, one of the key research strands in the supply chain value creation literature focusses on the dynamics of relational capital (Cousins et al., 2006) variously operationalised as relationship management (Kähkönen and Lintukangas, 2018), cooperation (Sousa et al., 2012), collaboration (Fu and Piplani, 2004) or co-creation (Letaifa, 2014). Employing a sample of Finnish companies, Kähkönen and Lintukangas (2018) show that supplier relationship management (SRM) capabilities can be a supply management factor that significantly influences its ability to create value. Sousa et al. (2012) show that greater levels of cooperation with customers have a significant impact on the intensity of lean production adoption, which is considered an important value creation lever. Employing a series of numerical experiments, Fu and Piplani (2004) show that the supply-side collaboration can improve the supply chain performance in terms of better stabilizing effect and service level.

Research shows the important enabling role of IT, or rather IT capabilities, in enabling and maintaining relational capital in supply chains. IT capability is defined as technological capability used to acquire, process and transmit information to support organisational decision-making (Grover and Malhotra, 1999) and to facilitate communication, coordination and collaboration between multiple parties along the supply chain. Capability here emphasises the fact that technology is not inherently valuable, rather, value is incumbent on how it can be

exploited to transform SC operations and relationships (Wu *et al.*, 2006). In the research conducted by Fawcett *et al.* (2011), the authors draw on the resource-based view paradigm to describe how IT capabilities could be leveraged to create a higher order collaboration capability. The dynamic collaboration capability is shown to have a positive influence on operational performance and customer satisfaction. An important take-away from this study, besides the obvious, concerns the ontological status of value in supply chains. It can be observed that value manifests at different levels of abstraction, in other words, value could be argued to have emergent properties embedded in processes, capabilities and performance outcomes.

More recent examples of IT-enabled value creation in supply chains can be found in the literature concerning the intersection of big data analytics (BDA) and supply chain management. An interesting study to this effect by Chen *et al.* (2015) conceptualises the use of BDA as a dynamic capability. The notion of dynamic capabilities describes how firms integrate, build and reconfigure internal and external competences to address rapidly and unpredictably changing environments (Teece *et al.*, 1997). The authors reason that BDA can be considered as a dynamic capability due to its organisational information processing capability that reduces uncertainty by stimulating insights and knowledge creation and increases organisational capability for strategic decision. Against this backdrop and employing a survey approach, the authors show that the use of BDA in supply chains can indeed lead to value creation measured as asset productivity and business growth.

Here we wish to argue that DTs can be viewed through the same lens as an IT capability given the above definition of the latter. Furthermore, according to Qi and Tao (2018), value creation based on data and analytics is very similar to that based on the DT. As we have already explained, data and analytics are indeed an enabling part of the DT. As such and drawing on Chen *et al.*'s (2015) argument in favour of BDA as a dynamic capability, we can similarly come to the same conclusion with respect to a DT. Chen and colleague also reinforce our position with respect to IT-enabled value creation noting that the value contribution of BDA is incumbent on its embeddedness into and assimilation with supply chain processes. This therefore opens up the potential of BDA-enabled value creation across the landscape of SC business processes.

A comprehensive review of BDA-inspired value creation in the supply chain Meriton *et al.* (2020) has revealed a multilevel framework of value creation across the supply chain. They show that value is a nested concept and can manifest at different levels, such as the business processes level, the supply chain level, and the firm level. Drawing on Croxton *et al.*'s (2001) conceptualisation of supply chain management in terms of a series of interrelated business processes, the authors show that big data analytics could be leveraged to enhance business processes such as demand management, order fulfilment, product management, production management, supply management and customer services management. In turn, enhanced processes could lead to capabilities such as agility, flexibility and collaboration at the supply chain level with a knock-on effect on firm performance. In this work, we seek to draw on the notion of supply chain as business processes to examine the dynamics of value at the digital twin and supply

chain interface. It is our contention that the influence of DT in supply chains could follow a similar trajectory; however, these dynamics are yet to be captured in a structured and systematic way in the academic literature. We specifically survey the state-of-the-art concerning the value creation potential of DT in OSCM. We recognise that this is a fairly nascent sub-field of the DSC literature where most of the potential of DT for value creation may still be unclaimed; however, it is growing in importance and stature warranting a synthesis of the emerging knowledge domains. The study discusses the value-added potential of DT in OSCM to guide researchers and industry experts in organising, conceptualising and conducting their research on DT of the future.

1.3 Previous literature reviews

The fast-developing research stream on the application of digital twin in operations and supply chain context has prompted a growing number of literature reviews. However, most of these reviews are narrative (see Table 1). A systematic literature review is preferred to the traditional approach, as it is replicable, scientific, evidence-based and transparent (Tranfield *et al.*, 2003). Earlier reviews on the application of digital twin technologies in operations and supply chain management (DT-OSCM) have focused on enabling technologies ($f=22$), manufacturing ($f=18$), supply chain management ($f=4$), product design ($f=3$), additive manufacturing ($f=3$), sustainable business model ($f=1$) and logistics ($f=1$). To address this research gap, we present a systematic and bibliometric literature review of the application of DT-OSCM based on bibliographic coupling analysis. A total of 1,856 research articles, published from 2011 to 2021, were collected, and 234 articles met our inclusion criteria for the review. The main objectives of the review are to (i) identify the major trends in DT-OSCM research, (ii) identify the major research fronts in DT-OSCM, (iii) identify value potential of DT and (vi) set a research agenda.

The remainder of this paper is organised as follows. In Section 2, we discuss our research methodology along with some initial statistics regarding recent trends in the output of DT-OSCM research. In Section 3, we present our initial bibliometric analysis resulting in additional author and affiliation statistics. Section 4 presents a detailed network analysis including a bibliographic coupling of citing articles and a co-occurrence network analysis of influential keywords which leads to the identification of key communities of primary research streams areas and subsequent discussions in Section 5. We conclude this paper in Section 6 with implications for practice, theory and future research.

2. Methodology

Literature reviews aim to summarize and synthesize earlier studies to illuminate what has been done regarding a particular research problem (Boell and Cecez-Kecmanovic, 2014) and identify potential avenues for further research highlighting the boundaries of existing knowledge (Tranfield *et al.*, 2003). Systematic literature reviews aim to summarize research studies related to a specific research question in a way that is fair, rigorous and auditable. Systematic reviews are different from traditional narrative reviews in many ways. Narrative reviews tend to be mainly descriptive, lacks a systematic search of the

Table 1 Reviews on DT-OSCM

Author	No. of review papers	Type of review		Main focus					Sustainable business model	Logistics
		Traditional	SLR	Manufacturing	Product design	Additive manufacturing	Enabling technologies	Supply chain management		
Marmolejo-Saucedo and Hartmann (2020)	280	–	✓					✓		
Butt (2020)	–	✓				✓				
Rymarczyk (2020)	–	✓					✓			
Li et al. (2020)	–	✓							✓	
Roy et al. (2020)				✓						
Liu et al. (2021)	240	–	✓	✓			✓			
He and Bai (2020)		✓		✓						
Bányai et al. (2019)	370	–	✓	✓						✓
Tomiyama et al. (2019)	–	✓		✓	✓		✓			
Lim et al. (2020)	145	–	✓		✓		✓			
Jones et al. (2020)	92	–	✓				✓			
Dolgui et al. (2020)	1383	–	✓					✓		
Barricelli et al. (2019)	75	–	✓				✓			
Cimino et al. (2019)	–	✓		✓			✓			
Cheng et al. (2018)	–	✓		✓			✓			
Zhang et al. (2019)	122	–	✓	✓			✓			
Tao et al. (2019a)	–	✓		✓			✓			
Lu et al. (2020)	–	✓		✓			✓			
Tao et al. (2019b)	50	–	✓	✓			✓	✓		
Kritzinger et al. (2018)	–	✓		✓			✓	✓		
Negri et al. (2017)	–	✓		✓			✓			
Qi and Tao (2018)	–	✓		✓			✓			
Zhang et al. (2020)	–	✓					✓			
de Paula Ferreira et al. (2020)	184	–	✓				✓			
Errandonea et al. (2020)	167	–	✓	✓			✓			
Zhu et al. (2020)	–	✓					✓			
Ciano et al. (2020)	496	–	✓	✓			✓			
Kumar et al. (2020)	844	–	✓	✓			✓			
Chen et al. (2020)	–	✓		✓	✓		✓			

Notes: NLR: Narrative literature review; SLR: systematic literature review

literature and thereby often focus on a subset of studies in an area chosen based on availability or author selection (Uman, 2011). Thus, while informative, narrative reviews can often include an element of selection bias (Srivastava, et al., 2018). They can also be confusing at times, particularly if similar studies have diverging results and conclusions (Evangelista and Durst, 2015).

Systematic reviews, as the name suggests, typically involve a detailed and comprehensive plan and search strategy derived a priori, with the goal of reducing bias by identifying, appraising and synthesizing all relevant studies on a particular topic (Uman, 2011). Rowley and Slack (2004) provide guidance for a structured methodology involving scanning resources, designing the mind map to structure the literature review, writing the study and building the bibliography. Following in their footsteps, we adopt a five-step methodology for data collection and comprehensive evaluation of the field aiming to identify the most influential studies, determine the topical areas of research and provide insights for current research interests and directions for future research in the field.

2.1 Defining the search terms

Keywords used for data collection include “Digital Twin”, “Virtual Twin”, “Digital Shadow” and “Evaluation Twin”. To arrive at these keywords, we scour practice-based articles published on the internet as well as academic literature on digital twin to capture the nomenclature employed by authors in discussions on digital twin. While digital and virtual twin are used interchangeably, digital shadow is a closely related concept. A digital shadow is a replica of all processes instantiated within a physical system such as a production system (Ehrhardt and Hoffmann, 2020). While a digital twin can be used for simulations, a digital shadow is exclusively descriptive. The use of a digital shadow promises to offer potential in the application of predictive analytics. Not only is a digital shadow a vital component of a digital twin, but it is also increasingly being discussed as a more cost-effective representation of physical systems without the need for complex simulations. The term evaluation twin has been used to emphasise a digital twin designed to solely perform evaluative tasks (Zhang et al., 2020). The list of keywords generated was validated with the help of an expert digital twin practitioner engineer.

2.2 Initial search results

Using the “title, abstract, keywords” search in the Scopus database, publication with the keywords discussed above were downloaded and stored. Scopus is now considered the largest searchable citation and abstract source of searching literature which is continually expanded and updated (Rew et al., 2009). Comparisons are often drawn between Scopus and Web of Science (WOS) in discussions regarding the most suited database for a particular study. One of the main differences

between Scopus and WOS databases is the breadth of coverage. In a comparative study, Vieira and Gomes (2009) found that Scopus provides 20% more coverage than WOS. Their results reveal that 2/3 of these records can be found in both databases but 1/3 of the records are only in one database (Aghaei Chadegani et al., 2013). Furthermore, in a recent systematic review on blockchains application in supply chains, Pournader et al. (2020) decided to retain Scopus as the main search database following comparative searches which yielded Scopus search results that completely covered the WOS search outcomes while introducing more academic resources. The initial search in Scopus was conducted on 12 January 2021 and it returned a total of 1,856 resources, see Table 2 for details. By further limiting the search to articles and reviews written in English the sample was reduced to 652. In the next step, two of the authors independently reviewed all the titles and abstracts to ensure that the papers meet with our inclusion criteria. The final lists of included articles were verified by another author and any discrepancies were resolved during an online meeting involving all the authors. The main inclusion criteria were designed to capture the modalities of value-creation by digital twins in operations and supply chain management. Thus, during the screening process colleagues were guided by the following criteria:

- conceptual, empirical and modelling studies on implementation of digital twin at various supply chain levels, including supply chain business processes, emergent supply chain capabilities and other related operations, and
- studies that could be downloaded as full text.

Application of this inclusion criteria produced a final sample of 234 papers which served as the primary data source for the literature analysis. The final agreed sample was stored in RIS format to include all the essential paper information such as paper title, authors’ names, and affiliations, abstracts, keywords and references (Fahimnia et al., 2015a).

2.3 Initial data analysis

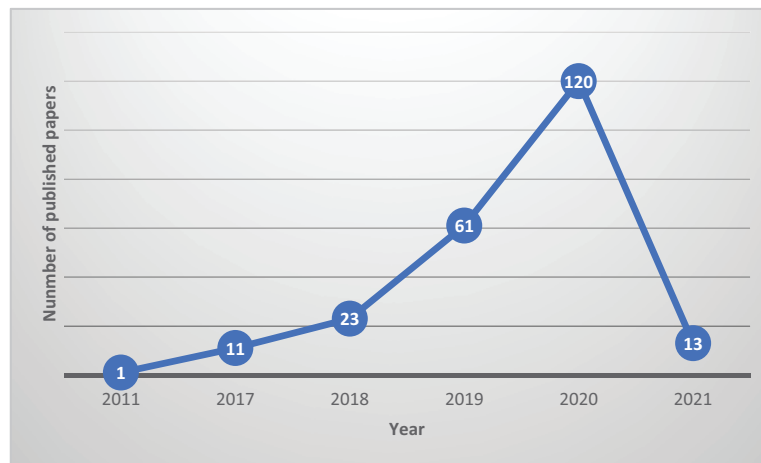
Figure 1 illustrates the trend in publishing from 2011 to 2021 suggesting DT-OSCM to be a fairly nascent field of study, barely 10 years old. A constant growth in the number of publications can be observed with a particularly significant increment between 2019 and 2020. The initial statistics also show that 99 journals have contributed to the publication of those 234 papers. Those journals appear to represent the engineering and manufacturing fields more substantially. Table 3 shows the contribution of journals in which at least four of the DT-OSCM papers have featured.

3. Data analysis

There are two parts to data analysis, and these include “bibliometric analysis” and “network analysis”. A bibliometric analysis provides summaries of data, which provide a broad

Table 2 Article search and screening strategy

Step 1	Search for “digital twin*” OR “virtual twin” OR “evaluation twin” OR “digital shadow” in title, keyword or abstract in Scopus database	1,856
Step 2	Retain journal articles and reviews in English language	652
Step 3	Full screening of abstracts and titles for relevance (see inclusion criteria for details)	234

Figure 1 Publishing trend in the area of DT-OSCM**Table 3** Top journals contributing to the area of DT-OSCM

Journal	Hi	TC	Publication year					Total
			2017	2018	2019	2020	2021	
<i>Journal of Manufacturing Systems</i>	7	265	1	2	1	14	1	19
<i>International Journal of Computer Integrated Manufacturing</i>	8	144			9	8		17
<i>International Journal of Production Research</i>	9	419			7	9		16
<i>Applied Sciences (Switzerland)</i>	4	41			4	5	1	10
<i>International Journal of Advanced Manufacturing Technology</i>	6	721		3		5	1	9
<i>IEEE Access</i>	4	571	1	1	3	3		8
<i>Advances in Computers</i>	1	2				6		6
<i>Journal of Cleaner Production</i>	4	151		1	1	3	1	6
<i>Robotics and Computer-Integrated Manufacturing</i>	4	201			1	3	1	5
<i>CIRP Annals</i>	4	169		2	2			4
<i>Computers in Industry</i>	3	92		1	2	1		4
<i>Journal of Ambient Intelligence and Humanized Computing</i>	4	191			4			4
<i>Journal of Intelligent Manufacturing</i>	3	92			1	2	1	4
<i>Lecture Notes in Networks and Systems</i>	1	2			1	3		4
<i>Sustainability (Switzerland)</i>	3	15				3	1	4
Total			2	10	36	65	7	120

Notes: TC: total citation within the sample; Hi: Hindex within the sample

perspective on the activities and impact of research, especially in terms of most cited researchers, articles, keywords, countries and universities (Ferreira *et al.*, 2020). We employ BibExcel for the bibliometric analysis due to its capability to handle large data sets and its compatibility with different computer applications including Excel, Pajek and Gephi (Persson *et al.*, 2009). BibExcel is also used to prepare the input data for a detailed network analysis (Fahimnia *et al.*, 2015b). The network analysis part uses an open-source visualisation tool called Gephi to perform topical content-based classification of the existing DT-OSCM research. Gephi is preferred over other existing network analysis software such as Pajek (Batagelj and Mrvar, 2011) and VOSviewer (van Eck and Waltman, 2013) due to its capability to work efficiently with large data sets, and its flexibility to develop a wide range of innovative analysis and investigation options.

3.1 Bibliometric analysis

The initial author and affiliation statistics obtained from our initial bibliometric analysis are presented and discussed in this section. Identifying the key researchers and universities in different geographical regions can help scholars and students who are interested in conducting research of digital twin in OSCM with researchers from other universities. BibExcel, an open-source bibliometric toolbox, was employed to perform the initial bibliometric and statistical analyses and to prepare the raw data for additional network analysis. BibExcel is a tool for analysing bibliographic data, or any data of a textual nature formatted in a similar manner (Persson *et al.*, 2009). A default input file contains data fields that can be reformatted into other formats to retrieve bibliometric information. The data output can be exported to Excel or any program that takes tabbed data records. Fahimnia *et al.* (2015a) observe that this high degree of

flexibility makes BibExcel a powerful tool, however, relatively difficult to work with especially in performing the initial setup. RIS format, Scopus output, was used as input for BibExcel.

3.1.1 Author influence

We extracted the author field from the BibExcel doc file and recorded the frequency of appearance of all authors associated with the sample of 234 articles. Most of the contributing authors appeared in only a single paper. Only 18% of 699 contributing authors have contributed to more than one paper, leaving 576 authors appearing in only one paper. In Table 4, the key contributing authors based on the number of published articles are listed. We also performed an analysis to capture key collaborating authors. Table 5 shows collaborating authors outcomes with the majority of authors listed in both tables. This is somewhat encouraging suggesting active collaboration between researchers in the early stages in the development of the field. Active collaboration between researchers can have a significant impact on productivity and is critical to the development and establishment of a new knowledge domain.

3.1.2 Affiliation statistics

The address field containing the affiliations information for the authors were extracted from the RIS file in BibExcel. For each affiliation, the city where the institution is located was obtained. The coordinates of these cities were obtained from gpsvisualizer.com to plot the geographical locations of institutions contributing to the literature as shown in Figure 2. Each red circle represents one institution. Greater density of

Table 4 Key contributing authors

Author	No. published articles	Author	No. published articles
Tao, F.	13	Zhang, M.	6
Zhang, Y.	9	Chen, X.	5
Wang, Y.	8	Leng, J.	5
Qi, Q.	7	Liu, Q.	5
Zhang, H.	7	Liu, Z.	5
Ivanov, D.	6	Noh, S.D.	5
Liu, J.	6	Park, K.T.	5
Lu, Y.	6	Xu, X.	5
Nee, A.Y.C.	6		

Table 5 Key contributing paired authors

Author 1	Author 2	No. of joint publications	Author 1	Author 2	No. of joint publications
Tao, F.	Nee, A.Y.C.	6	Leng, J.	Zhang, D.	3
Park, K.T.	Noh, S.D.	5	Lu, Y.	Xu, X.	3
Tao, F.	Qi, Q.	4	Zhang, H.	Chen, X.	3
Tao, F.	Zhang, M.	4	Zhang, M.	Nee, A.Y.C.	3
Leng, J.	Chen, X.	4	Yan, D.	Zhang, D.	3
Leng, J.	Liu, Q.	4	Qi, Q.	Nee, A.Y.C.	3
Liu, Q.	Chen, X.	4	Zheng, P.	Chen, C.-H.	3
Tao, F.	Liu, A.	4	Ivanov, D.	Dolgui, A.	3
Yan, D.	Chen, X.	3	Liu, Q.	Zhang, D.	3
Yan, D.	Liu, Q.	3	Zhuang, C.	Liu, J.	3
Qi, Q.	Tao, F.	3	Liu, A.	Nee, A.Y.C.	3
Leng, J.	Yan, D.	3			

contributing institutions can be found in Europe, Germany in particular, in spite of China boasting the largest number of contributing institutions as a single country. The figure also summarises the top contributing countries.

The top contributing institutions, their geographical locations and the quantity of published papers are shown in Table 6. The geographical dispersion of these institutions demonstrates that digital twin in OSCM research has attracted institutions from around the globe. Surprisingly, none of the top institutions in Table 5 are located in North America (USA more precisely). The effort to establish a research agenda around digital twin application in OSCM in the US appears still fragmented compared to Europe and parts of Asia. While there is clearly an appetite, evidenced by the large cohort of participating institutions, leading research centres are yet to take root in the US. This is, however, an assumption and additional research would be needed to determine the veracity of this initial supposition.

We performed an additional analysis to capture international collaborations between authors from different institutions. International research collaborations can help elevate an institution's international ranking and reputation and can also boasts its ability to attract research funding. The results displayed in Table 7 show China leading the way, collaborating with 7 other countries on a total of 38 papers followed by the US also collaborating with 7 other nations but on fewer publications. It can also be observed from Table 7 the significant contributions of developing countries such as China, Russia, India, Hong Kong and Singapore being active internationally.

3.2 Network analysis and literature clustering

A network analysis and graphical investigation followed for the selected sample. "Gephi", an open-source software package for graph and network analysis (Bastian *et al.*, 2009), was employed for this purpose. Gephi uses a 3D render engine to develop illustrations of large networks in real-time and assist in speeding up the exploration process (Gephi, 2013; Cherven, 2013). The flexible and multi-task architecture facilitates innovative approaches to work with complex data sets and produce insightful visual aids (Fahimnia *et al.*, 2015a). Gephi provides easy and broad access to network data and assist in specializing, filtering, navigating, manipulating and clustering

Figure 2 Geographical locations of all contributing institutions**Table 6** Top contributing institutions

Institutions	Country	No. of papers
Xi'an Jiaotong University	China	13
Jinan University	China	10
Berlin School of Economics and Law	Germany	7
Indian Institute of Technology Kharagpur	India	7
The University of Hong Kong	Hong Kong	7
Guangdong University of Technology	China	6
People's Education Society University	India	6
University of Bremen	Germany	6
National University of Singapore	Singapore	5
Beihang University	China	4
IMT Atlantique	France	4
Jinan University (Zhuhai Campus)	China	4
St. Petersburg Polytechnic University	Russia	4
The University of Auckland	New Zealand	4
Khalifa University of Science and Technology	Abu Dhabi	4

Table 7 International collaboration statistics

Country 1	Country 2	No. of papers	Country 1	Country 2	No. of papers
China	Hong Kong	9	France	Russia	2
China	Singapore	7	Singapore	Sweden	2
China	United States	6	France	United States	2
Australia	China	6	Australia	United States	2
France	Germany	6	Sweden	United States	2
China	United Kingdom	4	Hong Kong	Singapore	2
China	Sweden	4	United Kingdom	United States	2
Australia	Singapore	4	Australia	Sweden	2
India	United States	3	Germany	United States	2
Germany	Spain	2	China	France	2
Germany	Russia	2	Sweden	United Kingdom	2
Finland	Sweden	2	Australia	France	2

of data (Bastian *et al.*, 2009). A graph data set is needed to be generated to enable Gephi to map and visualize literature networks (Fahimnia *et al.*, 2015b) in which published papers are shown as nodes and relationships, such as citations or couplings, are represented by the arcs/edges between the nodes (Grandjean, 2015). The bibliographic data obtained from Scopus (in RIS format) was reformatted into a graph data set. BibExcel was used to transform the raw data into useable data for Gephi. Gephi accepts various graph data formats including “.NET” that BibExcel can generate.

3.2.1 Citation analysis

Different approaches have been employed to examine the significance of a publication. A citation analysis is most commonly employed for this purpose which aims to establish the popularity of a publication by establishing the frequency a publication is cited by other publications (Ding and Cronin, 2011). Compared to other approaches such as expert surveys, a citation analysis has an advantage in how it achieves an inter-subjectively testable result as its findings are independent of the subjective viewpoints and opinions of the interviewed experts (Kraus *et al.*, 2012). A further advantage of this approach is that it presents a “real time” state of current research (Tahai and Meyer, 1999). Table 8 shows the top 10 papers based on their number of local and global citations. The local citations reflect the total number of citations an article has received within the sample of 234 articles whereas the global citations provide the overall number of citations in the Scopus database that are related to other research fields.

3.2.2 Eigenvector centrality

“Prestige” is another indicator of importance besides citation counts (Ding *et al.*, 2009). Prestige can be measured as the number of times a paper is cited by other highly cited papers (Fahimnia *et al.*, 2015b). A highly cited paper may not necessarily entail prestige, although in some cases there might be a strong positive correlation between the two (Fahimnia *et al.*, 2015a). Eigenvector centrality has been argued as a more preferred metric to identify the influential papers in a bibliographic network considering the entire network pattern (Bonacich, 2007; Borgatti, 2005). Eigenvector centrality premises that a node’s importance in a network may increase by having connections to the other nodes that are themselves important and it is calculated by giving each node a relative score proportional to the sum of the scores of its neighbours

Table 8 Top 10 papers based on citations

Author	Local citation	Global citation
Qi and Tao (2018)	2	269
Lu and Xu (2019)	2	76
Lu and Xu (2018)	2	56
Ivanov and Dolgui (2020a)	2	45
Qi and Tao (2019)	2	17
Ivanov and Dolgui (2019)	2	8
Tao <i>et al.</i> (2018)	1	533
Schleich <i>et al.</i> (2017)	1	297
Tao and Zhang (2017)	1	252
Negri <i>et al.</i> (2017)	1	251

(Bonacich, 2007). Eigenvector centrality x can be defined in two equivalent ways via a matrix equation and a sum as:

$$Ax = \lambda x \text{ and } \lambda x_c = \sum_{v=1}^V a_{cv} x_v \text{ respectively,}$$

where λ is the largest eigenvalue of A (Bonacich, 1987). According to Rajagopal *et al.* (2017) the eigenvector centrality can be large either because a node has many neighbours or because it has important neighbours (or both). This suggests that eigenvector centrality can be treated as a measure of both popularity and importance of a paper in a bibliographic network. Table 9 shows the top 10 papers based on an eigenvector centrality measure. For this study’s 125-node network, eigenvector centrality values vary between 0.0011 and 1. It can be observed that a higher number of global citations cannot guarantee the “prestige” of a paper in a bibliographic network. In fact, the different rankings produced very different results for our sample.

3.2.3 Bibliographic coupling

Bibliographic coupling was chosen as the network structure to be analysed over others such as co-authoring and co-citation. Two documents are said to be co-cited when they both appear in the reference list of a third document (Egghe and Rousseau, 2002). Small (1973) argues that the frequently co-cited papers represent the key concepts, methods or experiments in a field. Osareh (1996a, 1996b) and Cawkell and Newton (1976) also observe that co-cited papers are significant and related in subject to each other. As such, it has been argued that the clusters of cited documents that make up a co-citation network comprise the intellectual base of the field (Persson, 2010). Bibliographic coupling is premised on the concept that two documents are related if they share the same sets of citations (Small, 1973). In other words, a coupling unit between two documents is an item of reference used by these two documents (Jarneving, 2007).

Therefore, in bibliographic coupling mapping, clusters of citing papers largely founded on the same intellectual base are produced. Such clusters make up the current research trends (Jarneving, 2005) that comprise the field of enquiry often representing topical or emerging areas of research (Bornmann *et al.*, 2012). Owing to its reliance on cited documents, bibliographic coupling is criticised for being fixed and retrospective, while co-citation analysis is viewed as dynamic and forward looking (Surwase *et al.*, 2011) for its dependence on citing documents. Nevertheless, while facilitating the construction of the intellectual base of the field, co-citation analysis cannot be used to establish current research trends or research authors (Ibekwe-SanJuan, 2009). This led us to capture the dynamics of the fast-evolving DT-OSCM research through the lens of bibliographic coupling which is able to cluster very recent papers (Boyack and Klavans, 2010).

The initial bibliographic coupling mapping with Gephi revealed that 159 articles out of a total of 234 have co-cited another paper either internal or external to the sample. A raw network of nodes and edges was generated by the software with a random positioning of the nodes when the “.NET” file was first opened in Gephi. It is difficult to interpret this layout due to a lack of a discernible pattern. The Force Atlas layout

Table 9 Top 10 papers based on eigenvector centrality

Author	Eigenvector centrality	Local citation	Global citation
Ciano <i>et al.</i> (2020)	1	0	0
Tao <i>et al.</i> (2019a)	0.9432	1	71
Barricelli <i>et al.</i> (2019)	0.9416	1	24
Lim <i>et al.</i> (2020)	0.9261	1	1
Jones <i>et al.</i> (2020)	0.9201	1	16
Yi <i>et al.</i> (2020)	0.9125	1	4
Ding <i>et al.</i> (2019)	0.9094	1	78
Bao <i>et al.</i> (2019)	0.9017	1	33
Tao <i>et al.</i> (2019b)	0.8897	1	151
Errandonea <i>et al.</i> (2020)	0.8881	0	0

(Jacomy, 2009) was then applied to the raw network. The Force Atlas algorithm works in such a way that linked nodes attract and non-linked nodes repulse each other. It also permits the manual adjustment of the repulsion strength, gravity, speed, node size and other characteristics (Bastian *et al.*, 2009). With this algorithm the most connected nodes gravitate towards the centre of the network and the lesser connected nodes away from it.

The Force Atlas layout of the proposed 159-node bibliographic coupling map is shown in Figure 3. Co-citing papers (shown by nodes) are well-connected; least connected nodes are positioned more remotely from the centre. To develop meaningful clusters that correspond to a specific theme in the bibliographic network, we first had to filter the network and limit the *degree* feature of the network to a minimum of 2 to eliminate weakly connected nodes (i.e. papers that were weakly connected to the network due to low co-citing frequency). Excluding weakly connected nodes resulted in a network with 135 nodes and 1,634 edges as shown in Figure 4.

3.2.4 Literature clustering

In a bibliographic network each node relates to a given article and the links represent the presence of one or more citations

Figure 3 The initial 159-node bibliographic network

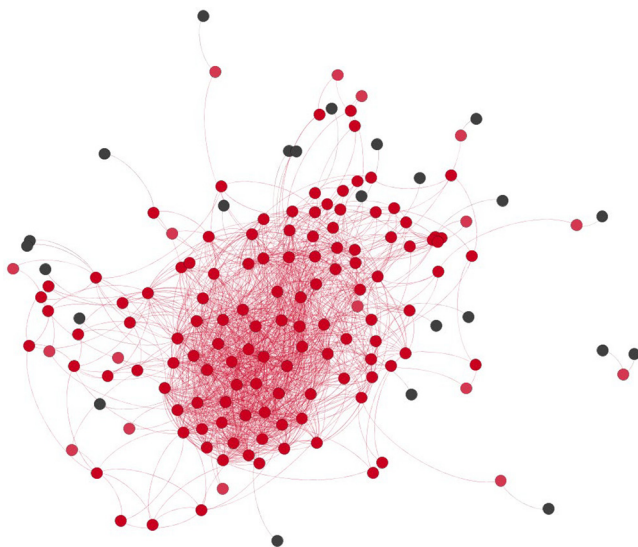
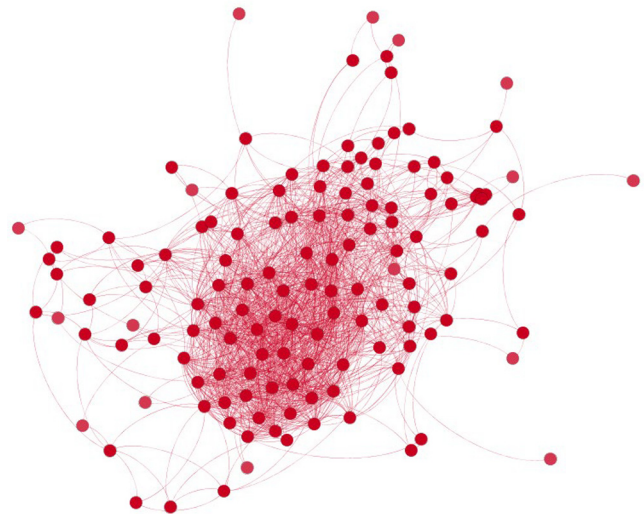


Figure 4 The 135-node bibliographic network after removing remote nodes



between two publications. The network is represented by the adjacency matrix A of elements a_{ij} . The elements a_{ij} are set equal to 1 when publication i cites publication j while elements on the principal diagonal (a_{ii}) are set equal to 0, since a publication cannot cite itself (Caschili *et al.*, 2014). Data clustering (also termed modularity) has been used in the past as a classification tool for grouping of a set of given publications (Radicchi *et al.*, 2004). In bibliographic networks, data clustering is employed to examine the local interconnections among nodes. This analysis can be used to understand if publications, directly connected to a given publication, cite with each other and if they tend to form local highly interconnected clusters of publications (Caschili *et al.*, 2014). A high propensity to clustering might point out tight groups of publications belonging to the same research area or have similar research focus (Caschili *et al.*, 2014). These help to gain an insight with regards to the current status of a research front such as DT-OSCM.

Gephi uses the Louvain algorithm as the default clustering tool; this is an iterative optimization model that aims to determine the optimal number of partitions that maximize the modularity index (Blondel *et al.*, 2008). Modularity, which

measures the density of links inside communities versus the links between communities, is gaining attention in the research community (Mishra *et al.*, 2017). The modularity index of a partition is a scalar value between -1 and $+1$ that measures the density of links inside communities versus the links between communities (Fahimnia *et al.*, 2015b). For a weighted network (i.e. networks with weighted links, such as the number of co-citing articles), the modularity index Q can be calculated as:

$$Q = \frac{1}{2m} \sum_{ij} \left[A_{ij} - \frac{K_i K_j}{2m} \right] \delta(C_i, C_j),$$

where A_{ij} represents the weight of the edge between nodes i and j , k_i is the sum of the weights of the edges attached to node i ($k_i = \sum_j A_{ij}$), C_i is the community to which node i is assigned, $\delta(u, v)$ equals 1 if $u = v$; and equals 0, otherwise, and finally $m = \frac{1}{2} \sum_{ij} A_{ij}$ (Blondel *et al.*, 2008).

Eight clusters were created by the application of this algorithm to the 135-node bibliographic network in Gephi. The size of each cluster varied from 1 for cluster 6 to 44 for clusters 1 and 3, respectively. Clusters 5, 6 and 7 containing only 5, 1 and 4 articles, respectively, were dropped from further analysis, as they did not appear to be significant to be considered as major literature clusters. This resulted in a 125-node network comprising of 5 clusters. Employing the partitioning function, a colour template was applied to the 125-node network to distinguish between the clusters. Figure 4 illustrates the positioning of and interaction among the five clusters. An edge between two nodes indicates they have at least one bibliographic coupling count, meaning that the two articles represented by the nodes have one or more articles they cite in common (Hosoya *et al.*, 2017). The modularity index for this network is equal to 0.366 which indicates strong relationship between the nodes within each cluster and yet a relatively strong relationship between the nodes of different clusters.

3.2.5 Keywords co-occurrence analysis and research concepts identification

To determine the area of research focus for each cluster, we performed a keyword co-occurrence analysis. Keywords have the potential to effectively describe the contents of a paper (Rajagopal *et al.*, 2017). Co-occurrence analysis is built on the assumption that a group of keywords could indicate the underlying themes and that the co-occurrences of keywords could reveal the association with the underlying themes (Hu and Zhang, 2015). If two

keywords occur simultaneously in an article, then they have a semantic relationship. The higher the co-occurrence frequency of two keywords, the greater is the correlation (Liu *et al.*, 2012). Studies have used co-occurrence analysis to determine the knowledge structure in various research fields (Ravikumar *et al.*, 2015; Stegmann and Grohmann, 2003).

In the first instance we extracted the keywords from all the 234 papers in our sample producing a list of 501 keywords. Table 10 shows the top 20 keywords by frequency of occurrence while Table 11 shows the top 20 keywords by eigenvector centrality. It comes as no surprise that the term “digital twin” (frequency = 111, eigenvector centrality = 1) sits at the top of both tables. This also means that from the search terms employed, digital twin is by the far the most prominent term used in academic research. Most of the top keywords from both lists are either related to manufacturing or technology; this may infer as to the focus of most research in our sample. Indeed, the top co-occurring pair of keywords is digital twin and manufacturing ($f = 55$) as can be observed in Table 12; this is followed by digital twin and industry 4.0 ($f = 37$).

We employed the eigenvector centrality measure to identify the 10 most influential papers (Fahimnia *et al.*, 2015b; Hosoya *et al.*, 2017) in each of the 5 literature clusters to identify the research themes. This is, with the exception of cluster 2 comprising only of 6 articles (see Table 13), inclusion of centrality which was based on the strong interconnection between the articles; they all appear to be related to the same topic. VOS viewer (Van Eck and Waltman, 2013) was used to extract the keywords and perform the network mapping of keywords co-occurrence for each cluster. VOS viewer is a very useful tool for collecting bibliographical material, providing visualizations of the bibliographic connections of documents, journals, authors, as well as keywords by using a wide range of techniques including bibliographic coupling (Kessler, 1963) and co-occurrence analysis (Cancino *et al.*, 2019).

In VOS, network analysis is achieved by employing a unified framework that brings together the well-known technique of multidimensional scaling (van Eck and Waltman, 2010) for mapping and a variant of modularity-based clustering (Newman and Girvan, 2004). This ensures that small clusters can always be identified by choosing a sufficiently large value for the resolution parameter (Waltman *et al.*, 2010), making VOS viewer a powerful tool for analysing the keywords co-occurrence network of each literature cluster. Each cluster was

Table 10 Top 20 keywords by frequency of occurrence

Key words	Occurrence frequency	Keywords	Occurrence frequency
Digital twin	111	Industrial research	24
Manufacturing	69	Simulation	24
Industry 4.0	58	Product design	24
Life cycle	49	Big data	23
Embedded systems	46	Virtual reality	22
Cyber Physical System	39	Production system	22
Smart manufacturing	35	Digital twins	21
Internet of things	34	Blockchain	21
Decision making	32	Intelligent Manufacturing	20
Flow control	31	Digital storage	20

Table 11 Top 20 keywords by eigenvector centrality

Keyword	Eigenvector centrality	Keyword	Eigenvector centrality
Digital twin	1	virtual reality	0.512817
Manufacture	0.864539	Production system	0.479714
Life cycle	0.707403	Big data	0.474789
Industry 4.0	0.706363	Simulation	0.471727
Smart manufacturing	0.687019	Digital storage	0.430077
Cyber-physical system	0.670974	Floors	0.418721
Embedded systems	0.653097	Enabling technologies	0.3709
Flow control	0.603058	Data Analytics	0.336579
Industrial research	0.599459	Interoperability	0.318288
Internet of things	0.563073	Computer architecture	0.313076

Table 12 Top 20 paired keywords

Keyword 1	Keyword 2	Co-occurrence frequency
Digital twin	Manufacturing	55
Digital twin	Industry 4.0	37
Digital twin	Life cycle	32
Digital Twin	Embedded systems	32
Cyber-physical system	Digital twin	31
Digital twin	Smart manufacturing	26
Manufacturing	Smart manufacturing	22
Cyber-physical system	Embedded systems	22
Decision making	Digital twin	19
Digital twin	Flow control	18
Embedded systems	Manufacturing	18
Digital twin	Industrial research	18
Digital Twin	Internet of Things	18
Cyber-physical system	Manufacturing	17
Flow control	Smart manufacturing	17
Flow control	Manufacture	16
Digital twin	Product design	15
digital twin	Simulation	14
Digital storage	Digital twin	14
Digital twin	Production system	14

Table 13 Top papers of each cluster based on eigenvector centrality

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
Butt (2020)	Ivanov (2020)	Sun <i>et al.</i> (2020).	Cimino <i>et al.</i> (2019)	Barricelli <i>et al.</i> (2019)
Knapp <i>et al.</i> (2017)	Ivanov & Das (2020)	Huang <i>et al.</i> (2020)	Fang <i>et al.</i> (2019)	Kusiak (2020)
Cai <i>et al.</i> (2020)	Ivanov and Dolgui (2020a)	Lim <i>et al.</i> (2020)	Hasan <i>et al.</i> (2020)	Schleich <i>et al.</i> (2017)
Ciano <i>et al.</i> (2020)	Ivanov and Dolgui (2020b)	Liu <i>et al.</i> (2021)	Leng <i>et al.</i> (2019)	Shahidi <i>et al.</i> (2020)
Gaikwad <i>et al.</i> (2020)	Ivanov <i>et al.</i> (2019)	Nikolakis <i>et al.</i> (2019)	Leng <i>et al.</i> (2019)	Söderberg <i>et al.</i> (2017)
Longo <i>et al.</i> (2019)	Narula <i>et al.</i> (2020)	Park <i>et al.</i> (2020)	Lin <i>et al.</i> (2021)	Tan <i>et al.</i> (2019)
Wang and Wang (2019)		Yi <i>et al.</i> (2020)	Rocca <i>et al.</i> (2020)	Tao <i>et al.</i> (2019a)
Cahyati and Achdianto (2019)		Zhang <i>et al.</i> (2020)	Tomiyama <i>et al.</i> (2019)	Tao <i>et al.</i> (2019b)
Nagar <i>et al.</i> (2019)		Zheng <i>et al.</i> (2018)	Sierla <i>et al.</i> (2018)	Wang & Luo (2021)
Wang <i>et al.</i> (2020)		Zhuang <i>et al.</i> (2020)	Zhang <i>et al.</i> (2020)	Zhang <i>et al.</i> (2019)

labelled subjectively based on the popular keywords within the cluster.

The significance of a keyword can be assessed by its frequency count or total link strength (TLS) in VOS. In a

keyword co-occurrence network the TLS attribute indicates the total strength of the co-occurrence links of a given keyword with other keywords (van Eck and Waltman, 2020). Thus, the more important and influential keywords tend to have higher

TLS. VOS retrieved the keywords of all the papers in each cluster; the top 15 keywords for each literature cluster based on TLS are shown in Table 14. Figures 6–10 represent the keywords co-occurrence networks of Clusters 1, 2, 3, 4 and 5, respectively. The sizes of the nodes are proportional to their weights measured in TLS; the higher the TLS of a keyword the larger the node. Lines between keywords represent links; the keywords central to the network with thicker edges denote the major research area of that cluster.

4. Discussion: analysis of research clusters

Analysis of the research clusters reveals broadly four value clusters and one enabler cluster. The value clusters include articles that help to illustrate how DT can be used to enhance supply chain activities at the level of supply chain processes as well as at the level of supply chain capabilities. The business processes value clusters comprise alternative manufacturing, smart manufacturing, product development and life-cycle management. In line with Croxton *et al.*'s (2001) categorisation of supply chain business processes, it can be argued that alternative manufacturing and smart manufacturing are aligned with the manufacturing flow management process. According to Croxton *et al.* (2001), the manufacturing flow process is tasked with making the products and instilling the manufacturing flexibility needed to serve the target markets. The process comprises all activities necessary for managing the product flow through the manufacturing facilities and for obtaining, realising and managing flexibility.

In a similar vein, arguably, product development and life-cycle management could be attributed to the product development and commercialisation process. Croxton and colleagues recognise the criticality of product development to the ongoing success of the firm. They thus view supply chain management as including integrating customers and suppliers into the product development process with the aim of reducing time to market. The discussions below begin to shine a light as to the potential of digital twin to optimise those supply chain business processes.

Supply chain capability value cluster is made up of supply chain resilience and risk management. As such, the value proposition of digital twin is directed at a more abstract level as compared to the business processes discussed above. The enabler cluster is made of articles that broadly discuss technologies that can play a supportive role in the application of DT.

4.1 Alternative manufacturing

Cluster 1 is among the largest cluster comprising 44 nodes and centrally located as can be observed in Figure 5. We have labelled this cluster as alternative manufacturing based on the most prominent keywords being additive manufacturing and remanufacturing. On close inspection of the co-occurrence network in Figure 6, we can also discerned the strong links between these terms and digital twin.

The field of additive manufacturing has seen an explosive growth in recent years, due to renewed interest in manufacturing in the United States, and other parts of the world (Bose and Bandyopadhyay, 2019). Additive manufacturing is a suite of emerging technologies that

fabricates three-dimensional objects directly from digital models through an additive process, typically by depositing and “curing in place” successive layers of polymers, ceramics or metals. Unlike traditional manufacturing processes involving subtraction (e.g. cutting and shearing) and forming (e.g. stamping, bending and molding), additive manufacturing joins materials together to build products (Ford, 2014). These technologies have been widely researched and implemented to produce homogeneous and heterogeneous products with complex geometries (Butt, 2020). Properties and serviceability of additively manufactured components are affected by their geometry, microstructure and defects. These important attributes are now optimized by trial and error because the essential process variables cannot currently be selected from scientific principles (Knapp *et al.*, 2017).

In this research stream authors explore how the digital twin technology could be leveraged to help reduce the flaws in the additive manufacturing process. For example, Gaikwad *et al.* (2020) combine predictions from a physical model with in-situ sensor signatures in a machine learning framework to show improved detection of flaws in the manufacturing of thin-wall titanium alloy part. Another way to eradicate flaws in the additive manufacturing process is through proactive maintenance. The research by Cahyadi and Achdianto (2020) describes the prototyping of an additive manufacturing process with cyber-physical system enabling the creation of a virtual twin. In turn this allowed a virtual maintenance program to be made for the system.

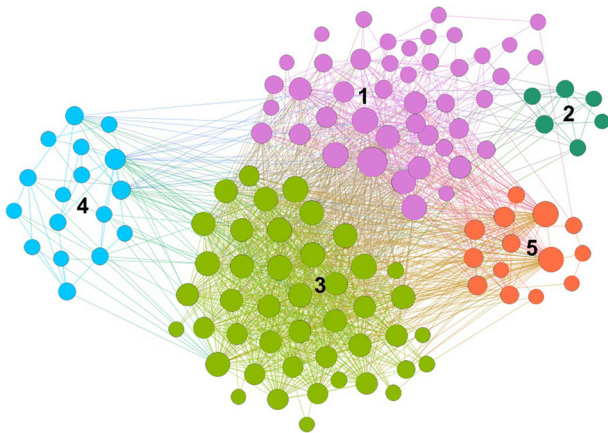
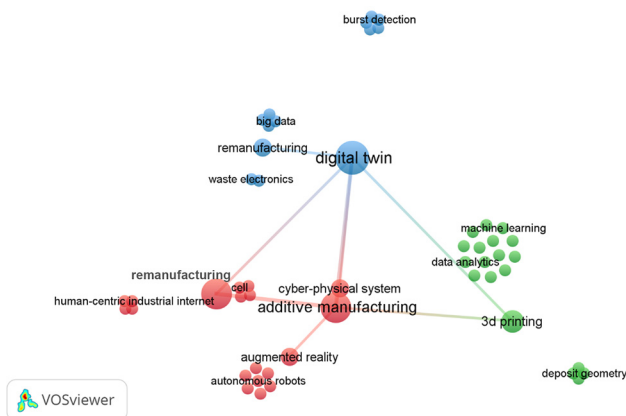
A further issue associated with additive manufacturing besides defects is the slow manufacturing pace given that the filling of solid contours takes place with mere single deposition lines of material. In this context, Cai *et al.* (2020) demonstrate how a digital twin methodology could be developed to allow concurrent deposition of materials without collision among them. Similarly, Nagar *et al.* (2019) show how a digital twin system for additive manufacturing could be used to optimise the process through reduced downtime and larger productivity. As such, it could be argued that digital twin could be used to add value to varying processes resulting in improved speed, quality, efficiency and productivity; these are key ingredients in achieving an effective and efficient manufacturing flow process for additive manufacturing.

Remanufacturing is the subject of the other sub-cluster. As an industrial process, remanufacturing concerns the restoration of products to useful life. It is often considered as an environmentally preferable choice of end-of-life option in comparison to material recycling or manufacturing new products (Sundin and Lee, 2012). However, the major problems in implementing a remanufacturing strategy result from the extreme uncertainty and variability of the remanufacturing environment (Ijomah *et al.*, 1999). Wang *et al.* (2020) also observe the lack of product multi-life-cycle remanufacturing process tracking management as particularly problematic. In this sub-cluster authors (Wang and Wang, 2019; Wang *et al.*, 2020) approach solutions to the ongoing problems from a product lifecycle management perspective, discussing different permutations as to how this is achievable by employing disruptive technologies such as cyber-physical systems and digital twins.

Table 14 Top 15 keywords based on total link strength measure in each cluster

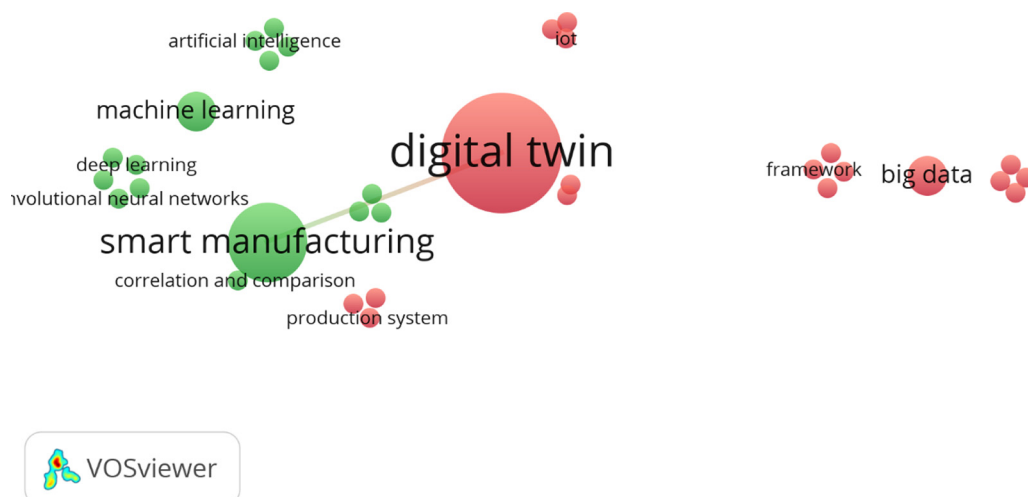
Keywords	Cluster 1: Alternative manufacturing			Cluster 2: SC resilience and risk management			Cluster 3: Product innovation management			Cluster 4: Enabling technologies			Cluster 5: Smart manufacturing		
	F	TLS	Keywords	F	TLS	Keywords	F	TLS	Keywords	F	TLS	Keywords	F	TLS	Keywords
Digital twin	6	37	Digital twin	5	40	Digital twin	9	37	Digital twin	6	29	Digital twin	7	27	
Additive manufacturing	5	37	Resilience	4	32	Cyber-physical production system	3	12	Blockchain	4	21	Smart manufacturing	4	17	
Industry 4.0	5	25	Supply chain	4	32	Smart product	2	14	Industry 4.0	4	20	Cyber-physical system	3	11	
3d printing	3	24	Ripple effect	3	26	Complex product	2	10	Smart contracts	3	13	Machine learning	2	11	
Augmented reality	2	13	Coronavirus	2	19	Data management	2	8	Cyber-physical system	2	12	Manufacturing	2	10	
Remanufacturing	2	9	Covid-19	2	19	Industry 4.0	2	8	Industrial internet of things	2	8	Big data	2	9	
Cyber-physical system	2	7	Epidemic outbreak	2	19	Product lifecycle management	2	8	Manufacturing	1	6	Internet of things	2	9	
Data analytics	1	16	Pandemic plan	2	19	Data management	2	8	Simulation	1	6	Smart factory	2	8	
Directed energy deposition	1	16	Risk management	2	19	Connected product	1	5	Big data	1	5	Convolutional neural networks	1	6	
Graph theory	1	16	Sars-cov-2	2	19	Product data package	1	5	Circular economy	1	5	Deep learning	1	6	
Laser powder bed fusion	1	16	Simulation	2	19	Product family design	1	5	Cloud simulation	1	5	Generative adversarial networks	1	6	
Machine learning	1	16	Industry 4.0	3	17	Product optimization	1	5	Ethereum	1	5	Intelligent manufacturing	1	6	
Meltpool	1	16	Blockchain	2	16	Product-service systems	1	5	Cps-digital-twin	1	5	Artificial intelligence	1	5	
Overhang	1	16	Supply chain resilience	1	8	Product configuration	1	5	Virtual reality	1	5	Data lifecycle	1	5	
Photodetector	1	16	Risk analysis	1	8	Data driven design	1	5	Efficient parallel simulation	1	5	Design theory	1	5	

Notes: F: occurrence frequency; TLS: total link strength

Figure 5 Literature clusters**Figure 6** Alternative manufacturing

4.2 Smart manufacturing

Cluster 5 is the second smallest cluster comprising 14 articles. While the concept of smart manufacturing transcends all the clusters, it takes on a more prominent role in this cluster; [Figure 7](#)

Figure 7 Smart manufacturing

displays a strong link between smart manufacturing and digital twin. Smart or intelligent manufacturing is an emerging form of production integrating manufacturing assets of today and tomorrow with sensors, computing platforms, communication technology, control, simulation, data intensive modelling and predictive engineering ([Kusiak, 2018](#)). The essence of smart manufacturing is the connection of all systems, in the factory setting to create a federated digital twin and this would include logistics, supply chain, building services and other systems ([O'Sullivan et al., 2020](#)). In this cluster authors investigate different permutations, as to how the application of digital twin and cyber-physical systems could make manufacturing truly smart or intelligent.

Research by [Shahidi et al. \(2020\)](#), [Tan et al. \(2019\)](#) and [Zhang et al. \(2019\)](#) focus on smart factories. Shahidi and colleagues discuss the enablers of smart factories particularly focusing on a big data architecture for digital twin application. They come up with the concept of decentralized Digital Shadows (dDS) which is essentially a digital architecture which promises optimal space allocation for big data and fast response to modelling. Tan and colleagues are also concerned with data integration in a smart factory digital twin approach proposing a digital twin construction framework and scheme for inputting data derived from the IoT into a simulation model. Zhang and colleagues are primarily interested in how to realize the interconnection and interoperability of shop-floor elements between the physical space and the virtual space. As such, the main focus of this paper concerns the implementation approach of digital twin-driven cyber physical production system, towards smart shop floor particularly for the production phase. To achieve this, the authors propose and validate a digital architecture solution.

Works by [Söderberg et al. \(2017\)](#) and [Schleich et al. \(2017\)](#) examine the issue of quality assurance in the context of smart manufacturing. Söderberg and colleagues' paper specifies and highlights functionality and data models in a digital twin environment necessary for real-time geometry assurance for production systems. Schleich and colleagues recognise the need for more realistic virtual models of manufactured products to bridge, what they assessed as a gap between design

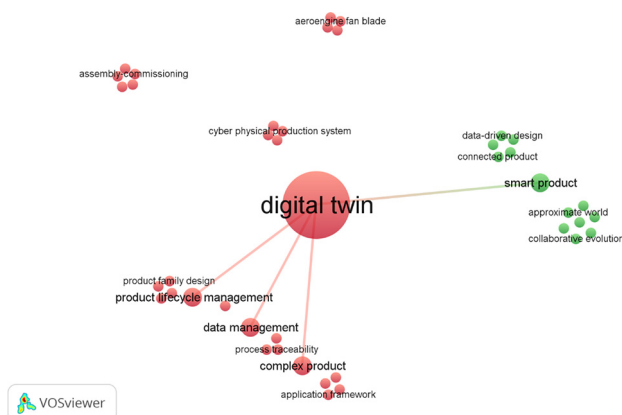
and manufacturing. As such, they propose a comprehensive reference model based on the concept of Skin Model Shapes, which serves as a digital twin of the physical product in design and manufacturing. Such a framework could also be used to address quality issues in production and design. Measuring performance is an important element of the manufacturing flow process. Croxton *et al.* (2001) argue that at the core of performance management includes the analysis of product quality and an examination of the root causes of quality problems. In this light, it can be argued that a digital twin solution could add significant value to the manufacturing flow process.

4.3 Product development and lifecycle management

Cluster 3 is the joint largest community also comprising 44 articles. As can be observed in Table 14, most of the top 15 keywords are related to processes involving product such as complex product, product life cycle management and product optimisation; thus, product development and lifecycle management was deemed a suitable name to represent this cluster. Figure 8 illustrates the key linkages in this cluster resonating the statistics in Table 14. In particular, complex product, data management, smart product and product lifecycle management have the strongest link with digital twin. Careful inspection of the articles does reveal the presence of three sub-clusters comprising complex product, smart product and product lifecycle management (PLM), with data management playing an integral part in these processes.

A complex product is one that has many constituent parts, each part is manufactured to high precision backed up by a level of research and development, for example, a computer server, sports car and refrigerator. These are normally innovative products with less predictable demand (Wong *et al.*, 2002). Zhuang *et al.* (2020) observe that the assembly process for these complex products involves high complexity, strong dynamics, many uncertainties and frequent rework and repair, especially in the model development stage. According to Sun *et al.* (2020), the traditional assembly process of complex products is based on manual experience, which results in low assembly efficiency and poor-quality consistency. The studies in this subgroup variously recognise the potential of cyber-physical system to address the assembly

Figure 8 Product development and lifecycle management



problems of complex products. Consequently, each of the three papers proposes a digital twin-driven assembly-commissioning approach for complex products. Case studies involving the assembly of a satellite (Yi *et al.*, 2020) and an electro-hydraulic servo valve (Sun *et al.*, 2020) show the effectiveness of the respective approaches.

Gutiérrez *et al.* (2013, p. 206) define a smart product as “an autonomous object which is designed for self-organised embedding into different environments in the course of its life-cycle and which allows for a natural product-to-human interaction. Smart products are able to proactively approach the user by using sensing, input, and output capabilities of the environment thus being self-situational, and context-aware.” The two papers in the subcluster focus on smart product development and innovation, two areas adjudged as requiring attention. In Lin *et al.* (2021), evolutionary digital twin (EDT) is proposed as a new mode for intelligent industrial product development. A case study shows that EDT instils more flexibility and adaptability in the development process of intelligent industrial product. Beyond intelligent products, flexibility and adaptability are increasingly needed in more general product development particularly given the uncertain nature of demand and the move away from mass customisation toward personalisation. On one hand, by instilling such attributes in the product development process, the value-added potential of DT is revealed.

Zheng *et al.* (2018), on the other hand, applies the digital twin concept to the service innovation of smart product which they refer to as smart product-service systems. The service innovation is enabled by a platform-based approach and generated in a data-driven manner. A case study involving a personalised wearable is used to validate the digital twin framework for service innovation.

Optimisation of the process of PLM is an increasingly important objective for manufacturing enterprises to improve their sustainable competitive advantage (Zhang *et al.*, 2017). PLM is often defined as a set of functions and procedures which allows the management and exploitation of the data at the same time defining the products and the processes implemented for their developments (Zina, 2006). Huang *et al.* (2020) note that in PLM, there are many participating actors constructing a complicated network with enormous product lifecycle data; this makes the implementation of a PLM solution difficult. The papers in this subcluster discuss the various ways digital twin could offer a workable solution to the data management issues faced by PLM. Huang and colleagues discuss a data management method for digital twin, of PLM based on blockchain technology. It is argued that blockchain technology enhances data sharing efficiency among participating actors. The effectiveness of the proposed data management method is evaluated using a case study, which shows that the proposed framework can solve the data management problem.

4.4 Supply chain resilience and risk management

Cluster 2, which we have named supply chain resilience and risk management, is the smallest comprising only 6 articles. From Figure 5, it can be observed that this community is somewhat removed from the core of the network. Nevertheless, the articles form a tightly woven literature cluster, focussing on examining the role of cyber-physical systems and digital twin in

the development of supply chain resilience. Figure 9 indeed reveals the strongest links in this cluster are between supply chain, resilience, digital twin and ripple effect. These studies are inspired by the ongoing Covid-19 pandemic, conceptualised as the single most pervasive source of supply chain disruption risk in most of the studies. As such, the studies in this cluster mostly focus on discussing the digital strategies built around cyber-physical systems and digital twins to mitigate supply chain disruptions and recover in case of severe disruptions (Ivanov and Dolgui, 2019).

Predicting the impact of epidemic outbreaks on global supply chains is the subject of Ivano's (2020) study. Supply chains are complex systems; unlike manufacturing or a piece of machinery where the avatar is a virtual representation of the physical object, the conceptualisation of a supply chain digital twin requires the modelling of the supply chain design supported by real time operational parameters (Ivanov and Dolgui, 2020a, 2020b), employing both prescriptive and predictive analytics. In this study the value-added potential of a digital twin is thus conceptualised at the level of supply chain capability. Previous research has positioned supply chain resilience as a dynamic capability, to prepare for unavoidable risk events and to respond to and recover from unexpected disruptions. Ivanov and Dolgui (2020a, 2020b) show how the application of a DT could enable such a dynamic capability, by matching supply chain designs to different sets of disruption patterns, while key performance measures are monitored. Decision makers can draw on the outcomes of these predictive simulations and prescriptive optimization, to transform the supply chain design to absorb the negative effects from a range of different risk sources (Teece, 2007) in real time. Ivano's study for instance, reveal that the timing of the closing and opening of the facilities at different echelons, might be a significant factor that determines the epidemic outbreak impact on the SC performance, rather than an upstream disruption duration or the speed of epidemic propagation.

Three studies in this cluster recognise the ripple effect (Ivanov and Dolgui, 2019; Ivanov et al., 2019; Ivanov and

Dolgui, 2020a, 2020b) as a significant threat to supply chain resilience resulting from disruptions. The ripple effect occurs when a disruption, rather than remaining localized or being contained to one part of the supply chain, cascades downstream and impacts the performance of the supply chain (Ivanov and Dolgui, 2019). Ripple effect control is thus seen as a critical risk management task to achieve supply chain resilience. In these studies, a supply chain digital twin for risk management is conceptualised, and the ripple effect of an epidemic outbreak in global supply chains is modelled to evaluate optimal supply chain risk measures and potential recovery paths. Based on the results of simulations, redundancy, flexibility and leanness are assessed as key supply chain capabilities effective to control the ripple effect caused by a global pandemic. Similarly, these studies are examples of value creation at the level of supply chain capability level orchestrated by the application of a DT.

4.5 Enabling technologies

Cluster 4 is dedicated to enabling technologies particularly focussing on blockchain as can be observed in Figure 10. Disruptive technologies are foundational to the digital twin concept; they are the very bedrock enabling the physical-virtual manifestations. Some of the core disruptive technologies captured across the five clusters include cyber physical systems, Industry 4.0, Internet of Things, robotics, artificial intelligence, virtual reality, simulations, 3D printing, machine learning, big data analytics, predictive analytics, smart contract and of course blockchain. Figure 10 shows a strong link between digital twin, blockchain and smart contracts. Blockchain and smart contract are related concepts. Blockchain is defined as a distributed data base or digital ledger, which records transactions of value using a cryptographic signature that is inherently resistant to modification (Mylrea and Gourisetti, 2017). Applying blockchain-based smart contracts presents an opportunity to increase the speed, scale and security of transactions.

The articles in this cluster investigate how blockchain technologies could be dispensed to enhance the existing digital twin frameworks. Hasan et al. (2020) point out some limitations of current approaches, systems and technologies of digital twin

Figure 9 SC resilience and risk management

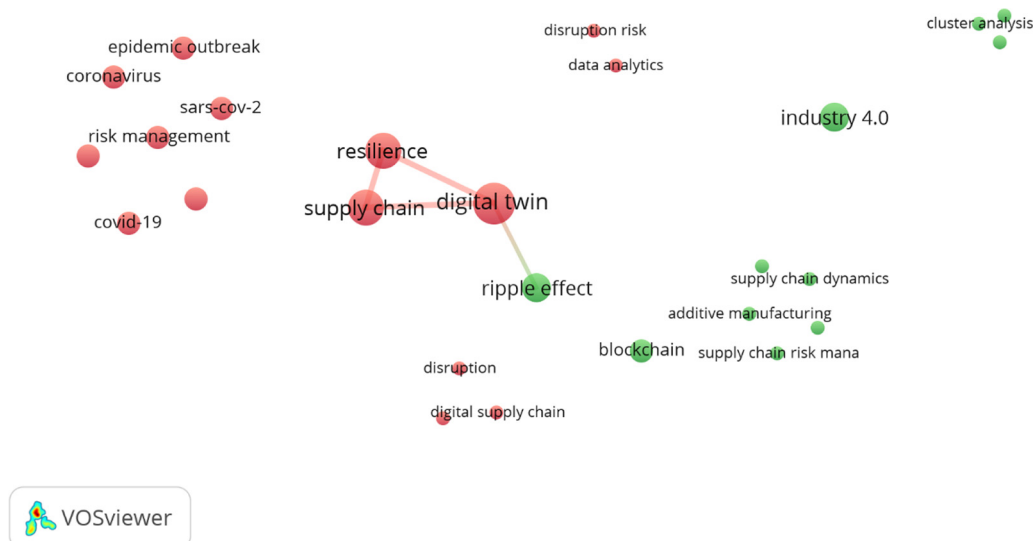
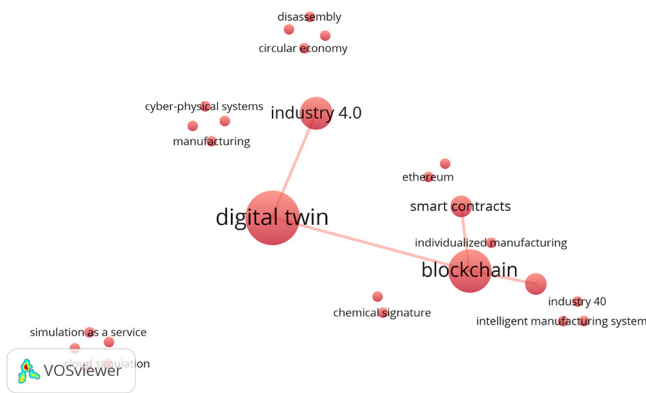


Figure 10 Enabling technologies

related to centralization and falling short of providing trusted data provenance, audit and traceability. A blockchain approach to digital twin promises to resolve some of those limitations; possessing the advantage of distributed consensus and tampering-resistant, blockchain makes decentralized and collaboration in manufacturing possible (Leng *et al.*, 2019). Hasan and colleagues propose a blockchain-based creation process of digital twins to ensure secure and trusted traceability, accessibility and immutability of transactions, logs and data provenance. Their approach uses smart contracts to govern and track transactions initiated by participants involved in the creation of digital twins.

To address the challenge of ensuring trust among makers in the social manufacturing paradigm, Leng *et al.* (2019) propose a blockchain-driven decentralized self-organizing model they named Makerchain, through which a decentralized network of makers can cooperate in a manufacturing ecosystem. The implementation of the Makerchain is validated via a case study of 3D printer manufacturing based on an open-source project named RepRap. The work by Leng *et al.* (2019) addresses the problem of inflexibility of centralized control associated with Industrial Internet of Things (IIoT) with respect to the manufacturing of individualized products. They argue that the current system is unable to cope with the disturbance and changes required of individualized manufacturing. As such, they propose a novel iterative bi-level hybrid intelligence model they called ManuChain to get rid of unbalance/inconsistency between holistic planning and local execution in individualized manufacturing systems. ManuChain is based on incorporation of blockchain into a digital twin for individualized manufacturing on a decentralized network. A blockchain data model and smart contracts are built to autonomously execute plans being given to the manufacturing unit based on real-time tracking of IIoT events. Zhang *et al.* (2020) also employ a blockchain approach to address the problem of inflexibility of IIoT in the intelligent manufacturing paradigm. To address the problem, the authors combine IIoT with the permissioned blockchain and propose a novel Manufacturing Blockchain of Things (MBCoT) architecture for the configuration of a secure, traceable and decentralized Intelligent Manufacturing System (IMS).

5. Conclusion

Digital twins promise to revolutionise the practice of operations and supply chain management and is the most recent in a long

list of technologies that have helped give strategic purchase to the field. The practice-based literature reports on the marvels of this technology accounting for its value-added potential in glorious details. Given the pre-eminence of big data analytics (BDA) in the functioning of a DT, in this work we have relied on the literature on BDA-enabled capabilities to advance arguments to support the use of DT in OSCM, as a dynamic capability and by doing so recognising its ability to create value is incumbent on its embeddedness in supply chain processes. We have then examined the literature to capture how far the conversation on the value potential of DT in OSCM has reached in the academic world.

Our findings reveal that while this conversation is still in its infancy, value clusters are beginning to appear in the literature. Researchers have examined the value-added potential of DT at the level of supply chain business processes (Croxtan *et al.*, 2001), with an accentuated focus on manufacturing flow management and product development and commercialisation. We believe that these are maturing literature streams. Furthermore, there is an emerging cluster which focusses attention on value at a more abstract capability level. This emerging cluster discusses supply chain resilience as a dynamic capability and the pivotal role DT can play in its enablement. These findings provide an initial point of entry for discussions with respect to practice, theory development and future research.

5.1 Implication for practice

Our analysis of the literature reveals the huge potential of DT to add value to the manufacturing flow process and the product development process. With respect to the manufacturing flow management process, the findings reveal that DT adds value mostly through process optimization (Cimino *et al.*, 2019; Sun *et al.*, 2020; Leng *et al.*, 2019) and predictive maintenance (Cahyati and Achdianto, 2019; Cimino *et al.*, 2019). Manufacturing in its various forms has frequently been accused of being wasteful often to the detriment of the environment. The findings in this review suggest avenues where DT could be employed as an operational capability to streamline processes, remove manufacturing flaws, enhance quality and efficiency and improve the overall productivity. Although evidence linking these value improvements to value manifestations such as waste reduction, cost reduction, and overall firm performance is not provided, these appear to be the natural conclusion.

There has been much talk by industrial nations such as the US and the UK, regarding the reshoring of manufacturing activities. In the context of the UK, Brexit has provided the momentum for the made in Britain movement. Much of the manufacturing activities were offshored from the UK in the 1980s (Bailey and De Propriis, 2014) under the leadership of Margaret Thatcher citing the growing lack of competitiveness of the UK as the key economic argument. Digital twin potentially helps to redress this situation and could be seen as the *raison d'être* to fuel the reshoring or made in Britain ambitions. The UK has indeed recognised the benefits of DT to manufacturing and supports numerous initiatives (e.g. Slingshot Simulations). As such our findings serve to reinforce the need for a national debate on the benefits of DT as a distinct manufacturing capability, as well as the development of inclusive industrial policy framework that sets out mechanisms to support and encourage UK industries, especially SMEs, to adopt such digital technologies.

Our findings also provide some points of reflections as to how DT could add value to the product development process particularly with respect to innovation. An interesting emphasis concerns product development from the perspective of whole lifecycle management which also tends to carry an environmental sustainability connotation. This is a sector which is gaining popularity especially amongst millennials believed to be more environmentally conscious than previous generations. Our findings reveal two different facets of DT as a dynamic capability, it can be leveraged into a dynamic collaborative capability for the large number of actors involved in the product development process, as well as dynamic capability for information processing for product life-cycle data handling. Manufacturing firms can thus employ DT to help reconfigure existing capabilities and achieve competitive advantage. However, this comes with a caveat concerning data management and the issue of trust is also at play. While trust can be nurtured data management issues such as data quality, privacy and security are a different beast altogether. Employing a DT in the context of product development potentially involves the collection of large amounts of personal data. While legislation exists (such as the General Data Protection Regulation) aimed at safeguarding personal data, there is a lack of a legal framework as to the use of product data collected from embedded technologies for commercialisation purposes. This is a grey area that needs addressing from a both an ethical and legal perspective. Companies wishing to develop a DT solution to build dynamic capabilities around the product development process would do well to consider such issues very carefully to avoid potential costly legal consequences in the future.

The dynamic capability potential of DT is also visible when firms can leverage it to reconfigure supply chain design in anticipation of expected disturbances. The findings reveal how firms can employ DT to develop resilience in their supply chains. Resilience is an important supply chain dynamic capability that can help firms survive unexpected events and is particularly salient in times of a global health crisis such as Covid-19. Whether a supply chain is resilient or not can often determine whether a firm survives or not. Therefore, our findings provide a lens to understand how firms could instil survivability in their operations by employing DT solutions to create dynamic capabilities. We also wish to sound a cautious note here to companies thinking about developing a DT solution for supply chain resilience. While such a system utilises real-time data from operational processes, a large amount of data is third party data, and this may be data held by private entities or public bodies both local and foreign. This leads to questioning the issues of data acquisition and data quality. These are issues beyond the control of firms but nevertheless must be factored in from the onset of an investment project to develop a DT for supply chain resilience. A potential solution could be to outsource data acquisition to third party data companies; however, the veracity of such data remains a sticking point. Furthermore, firms would need to ensure an effective internal data management system to support such an initiative and with this comes the prerequisite IT infrastructure.

5.2 Implication for theory development

We have pursued the analysis of extant DT-OSCM literature on the conceptual assumption that DT could be treated as an enabler of dynamic capability in supply chains. As pointed out, the literature is still in its infancy and DT is yet to be theoretically

conceptualised as a value-creation vehicle for OSCM in any meaningful way. Our findings do, however, show that when embedded in existing processes, DT has the ability to improve and at times transform them into higher level capabilities. Furthermore, dynamic capabilities have been described as a bundle of unique resources and capabilities (Wang and Ahmed, 2007). DT is a constellation of different technologies, and these are increasingly ubiquitous. Therefore, it can be argued that the value potential of DT also rests in the unique way companies bundle these technologies to create a distinctive DT architecture. As such, we believe that our analysis of the literature is foundational to initiating a conversation about the conceptual framing of DT in OSCM. There might also be a need to examine the value creating mechanisms at a more granular level where the microfoundations of capabilities reside. This will necessarily require conceptualisations at lower level of abstraction to capture the mechanisms of interaction between DT and supply chain processes. As such, in the tradition of IT-enabled supply chain management, we believe that DT will find a home under the auspices of the resource-based view.

5.3 Implications for future research

The findings and conclusions of this review have some important implications for future research. Supply chain resilience and risk management are viewed as an emerging research stream although resilience and risk have a long tradition in quantitative and modelling approaches. Supply chain practitioners are particularly well placed to benefit from insights from carefully crafted research on the benefit of a supply chain digital twin to inform robust and adaptable supply chain design. Digital twin is fast transcending the manufacturing landscape, this presents many opportunities for empirical work particularly in the shape of case studies that could produce actual knowledge about the specificities, challenges, and benefit of a digital twin approach to supply chain resilience and risk management.

It is disappointing to note the limited contribution of supply chain and operations management scholars to the field so far. However, on the positive side, this presents a great opportunity for scholars to make significant contributions towards the development of the field. For example, there is a pressing need to address the first and last mile issues in supply chain, we see supply chain digital twin as offering useful insights as to how to optimise decision making regarding these functions. Overall, we believe future work could examine the mechanics of value creation where DT intersects with supply chain business processes such as demand management, order fulfilment, supply management and customer services management.

We further see the need for the development of a scale enabling the measurement of the “digital twin capability” construct. This will enable the conceptualisation of digital twin as a capability or dynamic capability in empirical work by drawing on the resource-based view. Research work employing survey instruments could test the relationship between digital twin capability and value manifestations such as firm performance and customer satisfaction. Furthermore, this will also allow antecedents or enablers of digital twin capability to be closely examined. These developments would help move the field along and attract a more diverse pool of scholars.

As we have already highlighted, theoretical work in this area also remains outstanding, we urge scholars to take on the

challenge; this can be in the form of conceptual work or case studies as directed above. Digital twin presents the supply chain with endless possibilities to achieve optimal functioning; we have highlighted a few areas where we think supply chain research would benefit the most. However, a digital twin approach has the potential to revolutionize operations and supply chain management research; we hope the findings in this work can provide the momentum to make this happen.

5.4 Limitations

In spite of our best efforts to ensure robustness and inclusivity, our research is limited by the exclusive focus on peer reviewed material. This could be addressed by future research that employs non-academic publications as well as a broader swathe of academic articles. In addition to the areas of research identified above, future empirical research could take a more contextual approach with the aim of understanding the mechanics of DT-OSCM across different economic sectors. Another limitation concerns the use of only one database to extract the articles for this review. Although Scopus is by far the most comprehensive and updated repository for scholarly works, there is a chance that our review may have missed studies published in other outlets.

References

Aghaei Chadegani, A., Salehi, H., Yunus, M., Farhadi, H., Fooladi, M., Farhadi, M. and Ale Ebrahim, N. (2013), "A comparison between two main academic literature collections: Web of Science and Scopus databases", *Asian Social Science*, Vol. 9 No. 5, pp. 18-26.

Bailey, D. and DE Propriis, L. (2014), "Manufacturing reshoring and its limits: the UK automotive case", *Cambridge Journal of Regions, Economy and Society*, Vol. 7 No. 3, pp. 379-395.

Bandyopadhyay, A. and Bose, S. (Eds) (2019), *Additive Manufacturing*, CRC press.

Bao, J., Guo, D., Li, J. and Zhang, J. (2019), "The modelling and operations for the digital twin in the context of manufacturing", *Enterprise Information Systems*, Vol. 13 No. 4, pp. 534-556.

Bányai, Á., Illés, B., Glistau, E., Coello Machado, N.I., Tamás, P., Manzoor, F. and Bányai, T. (2019), "Smart cyber-physical manufacturing: extended and real-time optimization of logistics resources in matrix production", *Applied Sciences (Sciences)*, Vol. 9 No. 7, pp. 1287, pp.1-33.

Barricelli, B.R., Casiraghi, E. and Fogli, D. (2019), "A survey on digital twin: definitions, characteristics, applications, and design implications", *IEEE Access*, Vol. 7, pp. 167653-167671.

Bastian, M., Heymann, S. and Jacomy, M. (2009), "Gephi: an open source software for exploring and manipulating networks", *Proceedings of the International AAAI Conference on Web and Social Media*, Vol. 3 No. 1, pp. 361-362.

Batagelj, V. and Mrvar, A. (2011), *PAJEK: Program for Analysis and Visualization of Large Networks – Reference Manual*, University of Ljubljana, Slovenia, p. 1.

Blondel, V.D., Guillaume, J.L., Lambiotte, R. and Lefebvre, E. (2008), "Fast unfolding of communities in large networks", *Journal of Statistical Mechanics: Theory and Experiment*, Vol. 2008 No. 10, pp. P100081-P1000812.

Boell, S.K. and Cecez-Kecmanovic, D. (2014), "A hermeneutic approach for conducting literature reviews and literature searches", *Communications of the Association for Information Systems*, Vol. 34 No. 12, pp. 1-32.

Bonacich, P. (1987), "Power and centrality: a family of measures", *American Journal of Sociology*, Vol. 92 No. 5, pp. 1170-1182.

Bonacich, P. (2007), "Some unique properties of eigenvector centrality", *Social Networks*, Vol. 29 No. 4, pp. 555-564.

Borgatti, S.P. (2005), "Centrality and network flow", *Social Networks*, Vol. 27 No. 1, pp. 55-71.

Bornmann, L., Marx, W., Gasparyan, A.Y. and Kitas, G.D. (2012), "Diversity, value and limitations of the journal impact factor and alternative metrics", *Rheumatology International*, Vol. 32 No. 7, pp. 1861-1867.

Borys, B. and Jemison, D.B. (1989), "Hybrid arrangements as strategic alliances: theoretical issues in organizational combinations", *Academy of Management Review*, Vol. 14 No. 2, pp. 234-249.

Bose, S. and Bandyopadhyay, A. (2019), "Additive manufacturing: the future of manufacturing in a flat world", *Additive Manufacturing*, CRC press, pp. 451-461.

Boyack, K.W. and Klavans, R. (2010), "Co-Citation analysis, bibliographic coupling, and direct citation: which citation approach represents the research front most accurately?", *Journal of the American Society for Information Science and Technology*, Vol. 61 No. 12, pp. 2389-2404.

Butt, J. (2020), "Exploring the interrelationship between additive manufacturing and industry 4.0", *Designs*, Vol. 4 No. 2, pp. 1-33.

Büyükoçkan, G. and Göçer, F. (2018), "Digital supply chain: literature review and a proposed framework for future research", *Computers in Industry*, Vol. 97, pp. 157-177.

Cahyati, S. and Achdianto, S. (2020), "A prototyping of additive manufacturing cell in cyber physical system for maintenance 4.0 preparation", *International Journal of Advanced Science and Technology*, Vol. 29 No. 05, pp. 575-584.

Cai, Y., Wang, Y. and Burnett, M. (2020), "Using augmented reality to build digital twin for reconfigurable additive manufacturing system", *Journal of Manufacturing Systems*, Vol. 56, pp. 598-604.

Cancino, C.A., Amirbagheri, K., Merigó, J.M. and Dessouky, Y. (2019), "A bibliometric analysis of supply chain analytical techniques published in *Computers & Industrial Engineering*", *Computers & Industrial Engineering*, Vol. 137, (106015), pp. 1-15.

Caschili, S., DE Montis, A., Ganciu, A., Ledda, A. and Barra, M. (2014), "The strategic environment assessment bibliographic network: a quantitative literature review analysis", *Environmental Impact Assessment Review*, Vol. 47, pp. 14-28.

Cawkell, A.E. and Newton, I. (1976), "Understanding science by analysing its literature", *The Information Scientist*, Vol. 2, pp. 543-549.

Chen, D.Q., Preston, D.S. and Swink, M. (2015), "How the use of big data analytics affects value creation in supply chain management", *Journal of Management Information Systems*, Vol. 32 No. 4, pp. 4-39.

Chen, Y., Yang, O., Sampat, C., Bhalode, P., Ramachandran, R. and Ierapetritou, M. (2020), "Digital twins in

- pharmaceutical and biopharmaceutical manufacturing: a literature review”, *Processes*, Vol. 8 No. 1, pp. 1–33.
- Cheng, Y., Zhang, Y., Ji, P., Xu, W., Zhou, Z. and Tao, F. (2018), “Cyber-physical integration for moving digital factories forward towards smart manufacturing: a survey”, *The International Journal of Advanced Manufacturing Technology*, Vol. 97 Nos 1/4, pp. 1209–1221.
- Cherven, K. (2013), *Network Graph Analysis and Visualization with Gephi*, Packt Publishing.
- Christopher, M. (1998), *Logistics and Supply Chain Management: Strategies for Reducing Costs and Improving Service*, 2nd ed., Financial Times Management, London.
- Ciano, M.P., Pozzi, R., Rossi, T. and Strozzi, F. (2020), “Digital twin-enabled smart industrial systems: a bibliometric review”, *International Journal of Computer Integrated Manufacturing*, Vol. 12, pp. 1–19.
- Cimino, C., Negri, E. and Fumagalli, L. (2019), “Review of digital twin applications in manufacturing”, *Computers in Industry*, Vol. 113 No. 103130, pp. 1–15.
- Cimino, C., Negri, E. and Fumagalli, L. (2019), “Review of digital twin applications in manufacturing”, *Computers in Industry*, Vol. 113 No. 103130, pp. 1–51.
- Cousins, P.D., Handfield, R.B., Lawson, B. and Petersen, K.J. (2006), “Creating supply chain relational capital: the impact of formal and informal socialization processes”, *Journal of Operations Management*, Vol. 24 No. 6, pp. 851–863.
- Croxton, K.L., Garcia-Dastugue, S.J., Lambert, D.M. and Rogers, D.S. (2001), “The supply chain management processes”, *The International Journal of Logistics Management*, Vol. 12 No. 2, pp. 13–36.
- DE Paula Ferreira, W., Armellini, F. and DE Santa-Eulalia, L. A. (2020), “Simulation in industry 4.0: a state-of-the-art review”, *Computers & Industrial Engineering*, Vol. 149 No. 106868, pp. 1–17.
- Dietz, M. and Pernul, G. (2020), “Digital twin: empowering enterprises towards a system-of-systems approach”, *Business & Information Systems Engineering*, Vol. 62 No. 2, pp. 179–184.
- Ding, K., Chan, F.T., Zhang, X., Zhou, G. and Zhang, F. (2019), “Defining a digital twin-based cyber-physical production system for autonomous manufacturing in smart shop floors”, *International Journal of Production Research*, Vol. 57 No. 20, pp. 6315–6334.
- Ding, Y. and Cronin, B. (2011), “Popular and/or prestigious? Measures of scholarly esteem”, *Information Processing & Management*, Vol. 47 No. 1, pp. 80–96.
- Ding, Y., Yan, E., Frazho, A. and Caverlee, J. (2009), “PageRank for ranking authors in co-citation networks”, *Journal of the American Society for Information Science and Technology*, Vol. 60 No. 11, pp. 2229–2243.
- Dolgui, A., Ivanov, D. and Sokolov, B. (2020), “Reconfigurable supply chain: the X-network”, *International Journal of Production Research*, Vol. 58 No. 13, pp. 4138–4163.
- Egghe, L. and Rousseau, R. (2002), “Co-citation, bibliographic coupling and a characterization of lattice citation networks”, *Scientometrics*, Vol. 55 No. 3, pp. 349–361.
- Ehrhardt, J.M. and Hoffmann, C.T. (2020), “The Digital Shadow: developing a universal model for the automated optimization of cyber-physical production systems based on real-time data”, *Procedia CIRP*, Vol. 93, pp. 304–310.
- Errandonea, I., Beltrán, S. and Arrizabalaga, S. (2020), “Digital twin for maintenance: a literature review”, *Computers in Industry*, Vol. 123 No. 103316, pp. 1–14.
- Evangelista, P. and Durst, S. (2015), “Knowledge management in environmental sustainability practices of third-party logistics service providers”, *VINE*, Vol. 45 No. 4, pp. 509–529.
- Fahimnia, B., Sarkis, J. and Davarzani, H. (2015a), “Green supply chain management: a review and bibliometric analysis”, *International Journal of Production Economics*, Vol. 162, pp. 101–114.
- Fahimnia, B., Tang, C.S., Davarzani, H. and Sarkis, J. (2015b), “Quantitative models for managing supply chain risks: a review”, *European Journal of Operational Research*, Vol. 247 No. 1, pp. 1–15.
- Fang, Y., Peng, C., Lou, P., Zhou, Z., Hu, J. and Yan, J. (2019), “Digital-twin-based job shop scheduling toward smart manufacturing”, *IEEE Transactions on Industrial Informatics*, Vol. 15 No. 12, pp. 6425–6435.
- Farahani, R.Z., Rezapour, S., Drezner, T. and Fallah, S. (2014), “Competitive supply chain network design: an overview of classifications, models, solution techniques and applications”, *Omega*, Vol. 45, pp. 92–118.
- Fawcett, S.E., Wallin, C., Allred, C., Fawcett, A.M. and Magnan, G.M. (2011), “Information technology as an enabler of supply chain collaboration: a dynamic-capabilities perspective”, *Journal of Supply Chain Management*, Vol. 47 No. 1, pp. 38–59.
- Ferreira, J.J., Fernandes, C., Ratten, V. and Miragaia, D. (2020), “Sports innovation: a bibliometric study”, *Sport Entrepreneurship and Public Policy*, Springer, Cham, pp. 153–170.
- Ford, S.L. (2014), “Additive manufacturing technology: potential implications for U.S. manufacturing competitiveness”, *Journal of International Commerce and Economics*, Vol. 6, pp. 1–35.
- Fu, Y. and Piplani, R. (2004), “Supply-side collaboration and its value in supply chains”, *European Journal of Operational Research*, Vol. 152 No. 1, pp. 281–288.
- Gaikwad, A., Yavari, R., Montazeri, M., Cole, K., Bian, L. and Rao, P. (2020), “Toward the digital twin of additive manufacturing: integrating thermal simulations, sensing, and analytics to detect process faults”, *IIE Transactions*, Vol. 52 No. 11, pp. 1204–1217.
- Gephi (2013), “‘Gephi – makes graphs handy’ – Hacking the humanities”, available at: <http://medhieval.com/hackinghumanities2015/uncategorized/gephi-makes-graphs-handy/> (accessed 10 January 2021).
- Grandjean, M. (2015), “Gephi: introduction to network analysis and visualisation”, pp. 1–12.
- Grieves, M. (2002), “Conceptual ideal for PLM”, *Presentation for the Product Lifecycle Management (PLM) center, University of MI*.
- Grover, V. and Malhotra, M.K. (1999), “A framework for examining the interface between operations and information systems: implications for research in the new millennium”, *Decision Sciences*, Vol. 30 No. 4, pp. 901–920.
- Gutiérrez, C., Garbajosa, J., Diaz, J. and Yagüe, A. (2013), “Providing a consensus definition for the term ‘smart product’”, 2013 *20th IEEE International Conference and Workshops on Engineering of Computer Based Systems (ECBS)*, IEEE, pp. 203–211.

- Hasan, H.R., Salah, K., Jayaraman, R., Omar, M., Yaqoob, I., Pesic, S., Taylor, T. and Boscovic, D. (2020), "A blockchain-based approach for the creation of digital twins", *IEEE Access*, Vol. 8, pp. 34113–34126.
- He, B. and Bai, K.J. (2020), "Digital twin-based sustainable intelligent manufacturing: a review", *Advances in Manufacturing*, Vol. 4, pp. 1–21.
- Hosoya, R., Ding, Z. and Kamioka, T. (2017), "A bibliographic network analysis of big data literature", *PACIS*, p. 38.
- Hu, J. and Zhang, Y. (2015), "Research patterns and trends of recommendation system in China using co-word analysis", *Information Processing & Management*, Vol. 51 No. 4, pp. 329–339.
- Huang, S., Wang, G., Yan, Y. and Fang, X. (2020), "Blockchain-based data management for digital twin of product", *Journal of Manufacturing Systems*, Vol. 54, pp. 361–371.
- Ibekwe-SanJuan, F. (2009), "Information science in the web era: a term-based approach to domain mapping", *Proceedings of the American Society for Information Science and Technology*, Vol. 46 No. 1, pp. 1–23.
- Ijomah, W.L., Bennett, J.P. and Pearce, J. (1999), "Remanufacturing: evidence of environmentally conscious business practice in the UK", *Proceedings first international symposium on environmentally conscious design and inverse manufacturing*, IEEE, pp. 192–196.
- Ivanov, D. (2020), "Predicting the impacts of epidemic outbreaks on global supply chains: a simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 136, (101922), pp. 1–14.
- Ivanov, D. and Das, A. (2020), "Coronavirus (COVID-19/SARS-CoV-2) and supply chain resilience: a research note", *International Journal of Integrated Supply Management*, Vol. 13 No. 1, pp. 90–102.
- Ivanov, D. and Dolgui, A. (2019), "New disruption risk management perspectives in supply chains: digital twins, the ripple effect, and resilience", *IFAC-PapersOnLine*, Vol. 52 No. 13, pp. 337–342.
- Ivanov, D. and Dolgui, A. (2020a), "A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0", *Production Planning & Control*, pp. 1–14.
- Ivanov, D. and Dolgui, A. (2020b), "Researchers' perspectives on Industry 4.0: multi-disciplinary analysis and opportunities for operations management", *International Journal of Production Research*, pp. 1–24.
- Ivanov, D., Dolgui, A., Das, A. and Sokolov, B. (2019), "Digital supply chain twins: Managing the ripple effect, resilience, and disruption risks by data-driven optimization, simulation, and visibility", *In Handbook of Ripple Effects in the Supply Chain*, Springer, Cham, pp. 309–332.
- Jacomy, M. (2009), "Force-atlas graph layout algorithm", available at: <http://gephi.org/2011/forceatlas2-the-new-version-of-our-home-brew-layout>
- Jarneving, B. (2005), "A comparison of two bibliometric methods for mapping of the research front", *Scientometrics*, Vol. 65 No. 2, pp. 245–263.
- Jarneving, B. (2007), "Bibliographic coupling and its application to research-front and other core documents", *Journal of Informetrics*, Vol. 1 No. 4, pp. 287–307.
- Jayaram, J., Tan, K.C. and Nachiappan, S.P. (2010), "Examining the interrelationships between supply chain integration scope and supply chain management efforts", *International Journal of Production Research*, Vol. 48 No. 22, pp. 6837–6857.
- Jones, D., Snider, C., Nassehi, A., Yon, J. and Hicks, B. (2020), "Characterising the Digital Twin: a systematic literature review", *CIRP Journal of Manufacturing Science and Technology*, Vol. 29, pp. 36–52.
- Kähkönen, A.K. and Lintukangas, K. (2018), "Key dimensions of value creation ability of supply management", *International Journal of Operations & Production Management*, Vol. 38 No. 4, pp. 979–996.
- Kavanagh, R., Armstrong, D., Djemame, K., Sommacampagna, D. and Blasi, L. (2015), "Towards an energy-aware cloud architecture for smart grids", *International Conference on the Economics of Grids, Clouds, Systems, and Services*, Springer, Cham, pp. 190–204.
- Kessler, M.M. (1963), "Bibliographic coupling between scientific papers", *American Documentation*, Vol. 14 No. 1, pp. 10–25.
- Knapp, G.L., Mukherjee, T., Zuback, J.S., Wei, H.L., Palmer, T.A., DE, A. and Debroy, T.J.A.M. (2017), "Building blocks for a digital twin of additive manufacturing", *Acta Materialia*, Vol. 135, pp. 390–399.
- Kraus, M.W., Piff, P.K., Mendoza-Denton, R., Rheinschmidt, M.L. and Keltner, D. (2012), "Social class, solipsism, and contextualism: how the rich are different from the poor", *Psychological Review*, Vol. 119 No. 3, pp. 546–572.
- Kritzinger, W., Karner, M., Traar, G., Henjes, J. and Sihm, W. (2018), "Digital twin in manufacturing: a categorical literature review and classification", *IFAC-PapersOnLine*, Vol. 51, pp. 1016–1022.
- Kumar, S., Bongale, A., Patil, S., Bongale, A.M., Kamat, P. and Kotecha, K. (2020), "Demystifying artificial intelligence based digital twins in manufacturing – a bibliometric analysis of trends and techniques", *Library Philosophy and Practice*, Vol. 2020, pp. 1–21.
- Kusiak, A. (2018), "Smart manufacturing", *International Journal of Production Research*, Vol. 56 Nos 1/2, pp. 508–517.
- Leng, J., Yan, D., Liu, Q., Xu, K., Zhao, J.L., Shi, R., Wei, L., Zhang, D. and Chen, X. (2019), "ManuChain: combining permissioned blockchain with a holistic optimization model as bi-level intelligence for smart manufacturing", *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, Vol. 50 No. 1, pp. 182–192.
- Letaifa, S.B. (2014), "The uneasy transition from supply chains to ecosystems", *Management Decision*, Vol. 52 No. 2, pp. 278–295, doi: [10.1108/MD-06-2013-0329](https://doi.org/10.1108/MD-06-2013-0329).
- Li, X., Cao, J., Liu, Z. and Luo, X. (2020), "Sustainable business model based on digital twin platform network: the inspiration from Haier's case study in China", *Sustainability (Switzerland)*, Vol. 12, pp. 1–26.
- Lim, K.Y.H., Zheng, P. and Chen, C.H. (2020), "A state-of-the-art survey of digital twin: techniques, engineering product lifecycle management and business innovation perspectives", *Journal of Intelligent Manufacturing*, Vol. 31 No. 6, pp. 1313–1337.
- Lin, T.Y., Jia, Z., Yang, C., Xiao, Y., Lan, S., Shi, G., Zeng, B. and Li, H. (2021), "Evolutionary digital twin: a new approach

- for intelligent industrial product development”, *Advanced Engineering Informatics*, Vol. 47, p. 101209, pp. 1-16.
- Liu, G.Y., Hu, J.M. and Wang, H.L. (2012), “A co-word analysis of digital library field in China”, *Scientometrics*, Vol. 91 No. 1, pp. 203-217.
- Liu, M., Fang, S., Dong, H. and Xu, C. (2021), “Review of digital twin about concepts, technologies, and industrial applications”, *Journal of Manufacturing Systems*, Vol. 58 No. Part B, pp. 346-361.
- Longo, F., Nicoletti, L. and Padovano, A. (2019), “Ubiquitous knowledge empowers the smart factory: the impacts of a Service-oriented Digital Twin on enterprises' performance”, *Annual Reviews in Control*, Vol. 47, pp. 221-236.
- Lu, Y. and Xu, X. (2018), “Resource virtualization: a core technology for developing cyber-physical production systems”, *Journal of Manufacturing Systems*, Vol. 47, pp. 128-140.
- Lu, Y. and Xu, X. (2019), “Cloud-based manufacturing equipment and big data analytics to enable on-demand manufacturing services”, *Robotics and Computer-Integrated Manufacturing*, Vol. 57, pp. 92-102.
- Lu, Y., Liu, C., Wang, K.I.K., Huang, H. and Xu, X. (2020), “Digital twin-driven smart manufacturing: connotation, reference model, applications and research issues”, *Robotics and Computer-Integrated Manufacturing*, Vol. 61 No. 101837, pp. 1-14.
- Marmolejo-Saucedo, J.A. and Hartmann, S. (2020), “Trends in digitization of the supply chain: a brief literature review”, *EAI Endorsed Transactions on Energy Web*, Vol. 7 No. 29, p. 164113.
- Meriton, R., Bhandal, R., Graham, G. and Brown, A. (2020), “An examination of the generative mechanisms of value in big data-enabled supply chain management research”, *International Journal of Production Research*, Vol. 59 No. 23, pp. 1-28.
- Mishra, D., Gunasekaran, A., Papadopoulos, T. and Hazen, B. (2017), “Green supply chain performance measures: a review and bibliometric analysis”, *Sustainable Production and Consumption*, Vol. 10, pp. 85-99.
- Miskinis, C. (2019), “The history and creation of the digital twin concept”, Challenge Advisory, available at: www.challenge.org/insights/digital-twin-history/ (accessed 27 December 2020).
- Misrudin, F. and Foong, L.C. (2019), “Digitalization in semiconductor manufacturing-simulation forecaster approach in managing manufacturing line performance”, *Procedia Manufacturing*, Vol. 38, pp. 1330-1337.
- Moufaddal, M., Benghabrit, A. and Bouhaddou, I. (2019), “Industry 4.0: a roadmap to digital supply chains”, *2019 1st International Conference on Smart Systems and Data Science (ICSSD)*, IEEE, pp. 1-9.
- Mylrea, M. and Gourisetti, S.N.G. (2017), “Cybersecurity and optimization in smart ‘autonomous’ buildings”, *Autonomy and Artificial Intelligence: A Threat or Savior?*, Springer, Cham, pp. 263-294.
- Nagar, S.V., Chandrashekar, A.C. and Suvarna, M. (2019), “Optimized additive manufacturing technology using digital twins and cyber physical systems”, *International Conference on Remote Engineering and Virtual Instrumentation*, Springer, Cham, pp. 65-73.
- Narula, S., Prakash, S., Dwivedy, M., Talwar, V. and Tiwari, S.P. (2020), “Industry 4.0 adoption key factors: an empirical study on manufacturing industry”, *Journal of Advances in Management Research*.
- Negri, E., Fumagalli, L. and Macchi, M. (2017), “A review of the roles of digital twin in CPS-based production systems”, *Procedia Manufacturing*, Vol. 11, pp. 939-948.
- Newman, M.E. and Girvan, M. (2004), “Finding and evaluating community structure in networks”, *Physical Review E*, Vol. 69 No. 2, p. 026113.
- Nikolakis, N., Alexopoulos, K., Xanthakis, E. and Chrysosolouris, G. (2019), “The digital twin implementation for linking the virtual representation of human-based production tasks to their physical counterpart in the factory-floor”, *International Journal of Computer Integrated Manufacturing*, Vol. 32 No. 1, pp. 1-12.
- Osareh, F. (1996a), “Bibliometrics, citation analysis and co-citation analysis: a review of literature I”, *Libri*, Vol. 46 No. 3, pp. 149-158.
- Osareh, F. (1996b), “Bibliometrics, citation analysis and co-citation analysis: a review of literature I”, *Libri*, Vol. 46 No. 3, pp. 149-158.
- O’Sullivan, J., O’Sullivan, D. and Bruton, K. (2020), “A case-study in the introduction of a digital twin in a large-scale smart manufacturing facility”, *Procedia Manufacturing*, Vol. 51, pp. 1523-1530.
- Pal, R. and Sandberg, E. (2017), “Sustainable value creation through new industrial supply chains in apparel and fashion”, *IOP Conference Series: Materials Science and Engineering*, Vol. 254 No. 20, IOP Publishing, p. 202007.
- Park, Y., Woo, J. and Choi, S. (2020), “A cloud-based digital twin manufacturing system based on an interoperable data Schema for smart manufacturing”, *International Journal of Computer Integrated Manufacturing*, Vol. 33 No. 12, pp. 1259-1276.
- Persson, O. (2010), “Identifying research themes with weighted direct citation links”, *Journal of Informetrics*, Vol. 4 No. 3, pp. 415-422.
- Persson, O., Danell, R. and Schneider, J.W. (2009), “How to use BibExcel for various types of bibliometric analysis”, *Celebrating scholarly communication studies: A Festschrift for Olle Persson at his 60th Birthday*, Vol. 5, pp. 9-24.
- Pournader, M., Shi, Y., Seuring, S. and Koh, S.L. (2020), “Blockchain applications in supply chains, transport and logistics: a systematic review of the literature”, *International Journal of Production Research*, Vol. 58 No. 7, pp. 2063-2081.
- Qi, Q. and Tao, F. (2018), “Digital twin and big data towards smart manufacturing and Industry 4.0: 360 degree comparison”, *IEEE Access*, Vol. 6, pp. 3585-3593.
- Qi, Q. and Tao, F. (2019), “A smart manufacturing service system based on edge computing, fog computing, and cloud computing”, *IEEE Access*, Vol. 7, pp. 86769-86777.
- Radicchi, F., Castellano, C., Cecconi, F., Loreto, V. and Parisi, D. (2004), “Defining and identifying communities in networks”, *Proceedings of the National Academy of Sciences*, Vol. 101 No. 9, pp. 2658-2663.
- Rajagopal, V., Venkatesan, S.P. and Goh, M. (2017), “Decision-making models for supply chain risk mitigation: a review”, *Computers & Industrial Engineering*, Vol. 113, pp. 646-682.
- Ravikumar, S., Agrahari, A. and Singh, S.N. (2015), “Mapping the intellectual structure of scientometrics: a co-word analysis of the journal scientometrics (2005–2010)”, *Scientometrics*, Vol. 102 No. 1, pp. 929-955.
- Rew, L., Mackert, M. and Bonevac, D. (2009), “A systematic review of literature about the genetic testing of adolescents”,

- Journal for Specialists in Pediatric Nursing*, Vol. 14 No. 4, pp. 284-294.
- Rocca, R., Rosa, P., Sassanelli, C., Fumagalli, L. and Terzi, S. (2020), "Integrating virtual reality and digital twin in circular economy practices: a laboratory application case", *Sustainability*, Vol. 12 No. 6, p. 2286.
- Rowley, J. and Slack, F. (2004), "Conducting a literature review", *Management Research News*, Vol. 27 No. 6, pp. 31-39.
- Roy, S., Prasanna Venkatesan, S. and Goh, M. (2020), "Healthcare services: a systematic review of patient-centric logistics issues using simulation", *Journal of the Operational Research Society*, Vol. 72 No. 10, pp. 1-23.
- Roy, R.B., Mishra, D., Pal, S.K., Chakravarty, T., Panda, S., Chandra, M.G., Pal, A., Misra, P., Chakravarty, D. and Misra, S. (2020), "Digital twin: current scenario and a case study on a manufacturing process", *The International Journal of Advanced Manufacturing Technology*, Vol. 107 Nos 9/10, pp. 3691-3714.
- Rymarczyk, J. (2020), "Technologies, opportunities and challenges of the industrial revolution 4.0: theoretical considerations", *Entrepreneurial Business and Economics Review*, Vol. 8 No. 1, pp. 185-198.
- Sanders, N.R. and Swink, M. (2019), "Digital supply chain transformation: visualizing the possibilities", *Supply Chain Management Review*, Vol. 59 No. 3, pp. 42-53.
- Schenkel, M., Caniels, M.C., Krikke, H. and van der Laan, E. (2015), "Understanding value creation in closed loop supply chains—past findings and future directions", *Journal of Manufacturing Systems*, Vol. 37, pp. 729-745.
- Schleich, B., Anwer, N., Mathieu, L. and Wartack, S. (2017), "Shaping the digital twin for design and production engineering", *CIRP Annals*, Vol. 66 No. 1, pp. 141-144.
- Shahidi, A., Hüsing, M. and Corves, B. (2020), "A decentralized structure for the digital shadows of internet of production", *Symposium on Robot Design, Dynamics and Control*, Springer, Cham, pp. 179-186.
- Sierla, S., Kyrki, V., Aarnio, P. and Vyatkin, V. (2018), "Automatic assembly planning based on digital product descriptions", *Computers in Industry*, Vol. 97, pp. 34-46.
- Small, H. (1973), "Co-citation in the scientific literature: a new measure of the relationship between two documents", *Journal of the American Society for Information Science*, Vol. 24 No. 4, pp. 265-269.
- Söderberg, R., Wärnefjord, K., Carlson, J.S. and Lindkvist, L. (2017), "Toward a digital twin for real-time geometry assurance in individualized production", *CIRP Annals*, Vol. 66 No. 1, pp. 137-140.
- Sousa, R., Oliveira, P., Moyano-Fuentes, J., Sacristán-Díaz, M. and Martínez-Jurado, P.J. (2012), "Cooperation in the supply chain and lean production adoption", *International Journal of Operations & Production Management*, Vol. 32 No. 9, pp. 1075-1096.
- Srivastava, S.C., Kubavat, A. and Verma, K. (2018), "Rationale and essentials of systematic reviews for medical and dental literature", *Journal of Orofacial & Health Sciences*, Vol. 9 No. 1, pp. 18-22.
- Stegmann, J. and Grohmann, G. (2003), "Hypothesis generation guided by co-word clustering", *Scientometrics*, Vol. 56 No. 1, pp. 111-135.
- Sun, X., Bao, J.L.I.J., Zhang, Y., Liu, S. and Zhou, B. (2020), "A digital twin-driven approach for the assembly-commissioning of high precision products", *Robotics and Computer-Integrated Manufacturing*, Vol. 61 No. 1018390, pp. 1-14.
- Sundin, E. and Lee, H.M. (2012), "In what way is remanufacturing good for the environment?", *In Design for Innovative Value towards a Sustainable Society*, Springer, Dordrecht, pp. 552-557.
- Surwase, G., Atomic, B., Sagar, A., Atomic, B., Kademani, B. S., Atomic, B. and Bhanumurthy, K. (2011), "Co-citation analysis: an overview ISBN: 935050007-8", *BOSLA National Conference Proceedings CDAC*.
- Tahai, A. and Meyer, M.J. (1999), "A revealed preference study of management journals' direct influences", *Strategic Management Journal*, Vol. 20 No. 3, pp. 279-296.
- Tan, Y., Yang, W., Yoshida, K. and Takakuwa, S. (2019), "Application of IoT-aided simulation to manufacturing systems in cyber-physical system", *Machines*, Vol. 7 No. 1, p. 2.
- Tao, F., Jiangfeng, C., Qinglin, Q., Zhang, M., Zhang, H. and Fangyuan, S. (2018), "Digital twin-driven product design, manufacturing and service with big data", *The International Journal of Advanced Manufacturing Technology*, Vol. 94 Nos 9/12, pp. 3563-3576.
- Tao, F., Qi, Q., Wang, L. and Nee, A.Y.C. (2019a), "Digital twins and cyber-physical systems toward smart manufacturing and Industry 4.0: correlation and comparison", *Engineering*, Vol. 5 No. 4, pp. 653-661.
- Tao, F., Zhang, H., Liu, A. and Nee, A.Y.C. (2019b), "Digital Twin in industry: state-of-the-art", *IEEE Transactions on Industrial Informatics*, Vol. 15 No. 4, pp. 2405-2415.
- Teece, D.J. (2007), "Explicating dynamic capabilities: the nature and microfoundations of (sustainable) enterprise performance", *Strategic Management Journal*, Vol. 28 No. 13, pp. 1319-1350.
- Teece, D.J., Pisano, G. and Shuen, A. (1997), "Dynamic capabilities and strategic management", *Strategic Management Journal*, Vol. 18 No. 7, pp. 509-533.
- Tomiyaama, T., Lutters, E., Stark, R. and Abramovici, M. (2019), "Development capabilities for smart products", *CIRP Annals*, Vol. 68 No. 2, pp. 727-750.
- Tranfield, D., Denyer, D. and Smart, P. (2003), "Towards a methodology for developing evidence-informed management knowledge by means of systematic review", *British Journal of Management*, Vol. 14 No. 3, pp. 207-222.
- Uman, L.S. (2011), "Systematic reviews and meta-analyses", *Journal of the Canadian Academy of Child and Adolescent Psychiatry = Journal de L'academie Canadienne de Psychiatrie de L'enfant et de L'adolescent*, Vol. 20 No. 1, pp. 57-59.
- Van Eck, N.J. and Waltman, L. (2010), "Software survey: VOSviewer, a computer program for bibliometric mapping", *Scientometrics*, Vol. 84 No. 2, pp. 523-538.
- Van Eck, N.J. and Waltman, L. (2013), *VOSviewer Manual*, Vol. 1 No. 1, Universteit Leiden, Leiden, pp. 1-53.
- Van Eck, N. and Waltman, L. (2020), "VOSviewer Manual for VOSviewer Version 1.6.14", Leiden University: Leiden, The Netherlands.
- Verboven, P., Defraeye, T., Datta, A.K. and Nicolai, B. (2020), "Digital twins of food process operations: the next step for food process models?", *Current Opinion in Food Science*, Vol. 35, pp. 79-87.
- Vieira, E. and Gomes, J. (2009), "A comparison of scopus and web of science for a typical university", *Scientometrics*, Vol. 81 No. 2, pp. 587-600.

- Waltman, L., VAN Eck, N.J. and Noyons, E.C. (2010), "A unified approach to mapping and clustering of bibliometric networks", *Journal of Informetrics*, Vol. 4 No. 4, pp. 629–635.
- Wang, C.L. and Ahmed, P.K. (2007), "Dynamic capabilities: a review and research agenda", *International Journal of Management Reviews*, Vol. 9 No. 1, pp. 31–51.
- Wang, P. and Luo, M. (2021), "A digital twin-based big data virtual and real fusion learning reference framework supported by industrial internet towards smart manufacturing", *Journal of Manufacturing Systems*, Vol. 58, pp. 16–32.
- Wang, X.V. and Wang, L. (2019), "Digital twin-based WEEE recycling, recovery and remanufacturing in the background of Industry 4.0", *International Journal of Production Research*, Vol. 57 No. 12, pp. 3892–3902.
- Wang, Y., Wang, S., Yang, B., Zhu, L. and Liu, F. (2020), "Big data driven hierarchical digital twin predictive remanufacturing paradigm: architecture, control mechanism, application scenario and benefits", *Journal of Cleaner Production*, Vol. 248, p. 119299, pp. 1–15.
- Wong, C.Y., McFarlane, D., Zaharudin, A.A. and Agarwal, V. (2002), "The intelligent product driven supply chain", *IEEE international conference on systems, man and cybernetics*, IEEE, Vol. 4, p. 6.
- Wu, F., Yenyurt, S., Kim, D. and Cavusgil, S.T. (2006), "The impact of information technology on supply chain capabilities and firm performance: a resource-based view", *Industrial Marketing Management*, Vol. 35 No. 4, pp. 493–504.
- Yi, Y., Yan, Y., Liu, X., Ni, Z., Feng, J. and Liu, J. (2020), "Digital twin-based smart assembly process design and application framework for complex products and its case study", *Journal of Manufacturing Systems*, Vol. 58 No. 58, pp. 94–107.
- Zhang, C., Zhou, G., Hu, J. and Li, J. (2020), "Deep learning-enabled intelligent process planning for digital twin manufacturing cell", *Knowledge-Based Systems*, Vol. 191, p. 105247.
- Zhang, J., Ding, G., Zou, Y., Qin, S. and Fu, J. (2019), "Review of job shop scheduling research and its new perspectives under industry 4.0", *Journal of Intelligent Manufacturing*, Vol. 30 No. 4, pp. 1809–1830.
- Zhang, Y., Ren, S., Liu, Y., Sakao, T. and Huisingh, D. (2017), "A framework for big data driven product lifecycle management", *Journal of Cleaner Production*, Vol. 159, pp. 229–240.
- Zhang, H., Hou, F., Xie, W., Wang, K., Zhou, X., Zhang, D. and Zhu, X. (2020), "Interaction and assembly processes of abundant and rare microbial communities during a diatom bloom process", *Environmental Microbiology*, Vol. 22 No. 5, pp. 1707–1719.
- Zhang, L., Chen, X., Zhou, W., Cheng, T., Chen, L., Guo, Z., Han, B. and Lu, L. (2020), "Digital twins for additive manufacturing: a state-of-the-art review", *Applied Sciences*, Vol. 10 No. 23, pp. 1–10.
- Zheng, P., Lin, T.J., Chen, C.H. and Xu, X. (2018), "A systematic design approach for service innovation of smart product-service systems", *Journal of Cleaner Production*, Vol. 201, pp. 657–667.
- Zhu, C.Y., Pires, J.N. and Azar, A. (2020), "A novel multi-Brand robotic software interface for industrial additive manufacturing cells", *Industrial Robot: The International Journal of Robotics Research and Application*, Vol. 47 No. 4, pp. 581–592.
- Zhuang, C., Gong, J. and Liu, J. (2020), "Digital twin-based assembly data management and process traceability for complex products", *Journal of Manufacturing Systems*, Vol. 58, pp. 118–131.
- Zina, S., Lombard, M., Lossent, L. and Henriot, C. (2006), "Generic modeling and configuration management in product lifecycle management", *The Proceedings of the Multiconference on 'Computational Engineering in Systems Applications'*, IEEE, Vol. 2, pp. 1252–1258.

Further reading

- Borgatti, S., Everett, M. and Johnson, J. (2013), *Analyzing Social Networks*, SAGE Publications, London.
- Chen, C., Ibekwe-Sanjuan, F. and Hou, J. (2010), "The structure and dynamics of cocitation clusters: a multiple-perspective cocitation analysis", *Journal of the American Society for Information Science and Technology*, Vol. 61 No. 7, pp. 1386–1409.
- Ivanov, D. and Dolgui, A. (2020c), "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*, Vol. 58 No. 10, pp. 2904–2915.
- Kähkönen, A.K. and Lintukangas, K. (2012), "The underlying potential of supply management in value creation", *Journal of Purchasing and Supply Management*, Vol. 18 No. 2, pp. 68–75.
- Tao, F., Zhang, Y., Cheng, Y., Ren, J., Wang, D., Qi, Q. and Li, P. (2020), "Digital twin and blockchain enhanced smart manufacturing service collaboration and management", *Journal of Manufacturing Systems*.
- Yogi, K.S. and Kotzab, H. (2019), "The intellectual foundation of supply chain management performance models: a bibliometric analysis and synthesis", *International Journal of Comparative Management*, Vol. 2 No. 1, pp. 67–91.
- Yu, W., Jacobs, M.A., Chavez, R. and Yang, J. (2019), "Dynamism, disruption orientation, and resilience in the supply chain and the impacts on financial performance: a dynamic capabilities perspective", *International Journal of Production Economics*, Vol. 218, pp. 352–362.

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