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Industry 4.0-driven operations and supply chains for the circular economy: a bibliometric analysis

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Abstract

The Industry 4.0 (I4.0) concept paves the way for the circular economy (CE) as advanced digital technologies enable sustainability initiatives. Hence, I4.0-driven CE-oriented supply chains (SCs) have improved sustainable performance, flexibility and interoperability. In order to smoothly embrace circular practices in digitally enabled SCs, quantitative techniques have been identified as crucial. Therefore, the intersection of I4.0, CE, supply chain management (SCM) and quantitative techniques is an emerging research arena worthy of investigation. This article presents a bibliometric analysis to identify the established and evolving research clusters in the topological analysis by identifying collaboration patterns, interrelations and the studies that significantly dominate the intersection of the analysed fields. Further, this study investigates the current research trends and presents potential directions for future research. The bibliometric analysis highlights that additive manufacturing (AM), big data analytics (BDA) and the Internet of Things (IoT) are the most researched technologies within the intersection of CE and sustainable SCM. Evaluation of intellectual, conceptual and social structures revealed that I4.0-driven sustainable operations and manufacturing are emerging research fields. This study provides research directions to guide scholars in the further investigation of these four identified fields while exploring the potential quantitative methods and techniques that can be applied in I4.0-enabled SCs in the CE context.

Keywords Industry 4.0 · Circular economy · Supply chain management · Quantitative methods

Annex 1. List of Abbreviations

AHP	Analytic hierarchy process
AM	Additive manufacturing
BDA	Big data analytics
BDPA	Big data and predictive analytics
CE	Circular economy
CPS	Cyber-physical systems
CSC	Circular supply chain
DEMATEL	Decision making trial and evaluation laboratory
I4.0	Industry 4.0
IoT	Internet of things
ISO	International Association for Standardization
MCDM	Multi-criteria decision making
SC	Supply chain
SCM	Supply chain management
SD	System dynamics
SEM	Structural equation modelling
SSCM	Sustainable supply chain management
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution

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1 Introduction

Digital technologies play a major role in supporting the transition towards the circular economy (CE) (Nascimento et al. 2019), and it is essential to explore how these enabling technologies support this transition (Bocken et al. 2016). The introduction of the fourth industrial revolution, commonly known as Industry 4.0 (I4.0), and its related technologies facilitate the CE approach by positively influencing the life cycle management of products (Rosa et al. 2019). While such propositions have been suggested multiple times, the scholarly discussion on the association of I4.0 with supply chain management (SCM) and CE is still emerging (Jabbour et al. 2018; Luthra et al. 2020; Okorie et al. 2018). For instance, studies have discussed the integration of I4.0 and CE by focusing on sustainable operations (e.g., Kumar et al. 2021), sustainable manufacturing (e.g., Enyoghasi and Badurdeen 2021) and business processes (e.g., Zheng et al. 2021). Rosa et al. (2019) revealed that several I4.0 technologies, such as additive manufacturing (AM), big data analytics (BDA) and the Internet of Things (IoT), have been identified as digital enablers of CE. Further supporting this argument, Nobre and Tavares (2017) identified BDA and IoT as enablers of CE and discussed the practicality of applying these technologies in the CE context. When adopting CE practices, I4.0-related elements such as simulation play a major role in addressing practical issues related to SCM (Rosa et al. 2019). Nevertheless, Bianchini et al. (2018) emphasised a gap between CE and its practical applications, for which the I4.0 concept coupled with advanced quantitative methods such as BDA can be a solution. Therefore, exploring the scholarly discussion at the intersection of I4.0 technologies, CE, SCM and quantitative methods is a worthwhile investigation.

When discussing the combinations of different fields (e.g., I4.0 and CE, SCM and CE), bibliometric and network analyses can provide additional insights by identifying emerging and established areas of the investigated intersection. Bibliometric analysis can indicate the current and emerging trends and provide an overall structure of the investigated research area (Feng et al. 2017; Muhuri et al. 2019). Moreover, the network analysis can identify the clusters of authors and research topics while highlighting the most influential scholars within the clusters. Network analysis further presents the emerging fields by analysing the recently published scholarly work (Fahimnia et al. 2015). This study presents a comprehensive evaluation of the intersection of I4.0, CE, SCM and quantitative methods by analysing a set of over 400 journal articles and identifying noteworthy studies, researchers and clusters while answering the following research questions (RQs).

- **RQ1:** Which factors are considered when applying quantitative methods for I4.0-enabled operations and SCs in the CE context?
- **RQ2:** Which future research directions and clusters of research streams emerge within the literature on the intersection of I4.0, CE, SCM and quantitative methods?

To answer these questions, we examined the relevant literature via bibliometric and network analyses. The rest of the article is organised as follows. Section 2 discusses the background, and Sect. 3 elaborates on the method applied in the article. Section 4 illustrates the bibliometric and network analyses and relevant findings. Section 5 discusses the overview of the intersection of the four fields (I4.0 and CE, SCM and quantitative methods). Section 6 presents the discussion, and Sect. 7 outlines the conclusion while highlighting key future research directions.

2 Background

Kirchherr et al. (2017) defined CE as the following:

> An economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. (pp. 224–225)

The underlying idea is that CE refers to an economic system that aims to accomplish sustainable development by replacing the end-of-life concept. Scientific research on CE has recently gained considerable attention, and it is still mainly focused on practical levels such as developing models and applying life cycle approaches focusing on closed-loop supply chains, remanufacturing and waste management (Korhonen et al. 2018). However, adopting CE at the operational level, including SCs, is challenging since most organisations still depend on a more linear approach (Husain et al. 2021).

Various barriers hinder the adoption of CE. Kirchherr et al. (2018) discussed four types of barriers related to CE, namely, cultural, markets, regulatory and technological barriers. Cultural barriers predominantly include a lack of public awareness and companies' hesitance to change their culture; market barriers mainly highlight the low cost and pricing of virgin materials, which obstruct the transition towards CE (Kirchherr et al. 2018; Kumar et al. 2019). A lack of supportive policies and obstructive regulations and laws have been identified as the main barriers related to regulatory issues. The main technological barriers studied are a lack of product designs optimised for CE and the quality of remanufactured products (Kirchherr et al. 2018; Ranta et al. 2018). Although the technological barriers do not seem to be a core obstacle for CE (Kirchherr et al. 2018), technologies play a major role in the transition to CE, and it is important to explore those technologies that empower CE (Bocken et al. 2016).

The integration of CE and SC has gained a fresh approach with the introduction of the new circular supply chain (CSC). De Angelis et al. (2018) defined the CSC as 'the embodiment of circular economy principles within supply chain management' (p. 425), while Batista et al. (2018) defined CSC as 'the coordinated forward and reverse supply chains via purposeful business ecosystem integration for value creation from products/services, by-products and useful waste flows through prolonged life cycles that improve the economic, social and environmental sustainability of organisations.' (p. 446). Hence, the CSC approach can comprise closed-loop SC, open-loop SC or both concepts since the waste flows can go through either original equipment manufacturer (in the closed-loop context) or a third party (in the open-loop context) when extending the life cycles of products to improve their sustainability while empowering the CE approach. Further, this highlights that CSC mainly focuses on the resource flow and the environmental aspects, whereas sustainable SC focuses on broader perspectives, including environmental, social and economic sustainability aspects. However, the integration of CSC and technologies is still scant in the scholarly debate (Farooque et al. 2019).

Introduced in 2011, the I4.0 concept exemplifies the automation of processes and procedures in the manufacturing industry (Xu et al. 2018). According to Rüßmann et al. (2015), I4.0 mainly comprises nine pillars:

- AM, mostly known as 3D printing, is a manufacturing technology that uses a computer-aided design file to manufacture 3D products layer by layer using virgin, non-virgin and biobased materials (ASTM International 2013; Colorado et al. 2020; Huang et al. 2015).
- IoT, which can be used to create virtual networks supporting smart factories, is a key aspect in the future of advanced manufacturing (Xu et al. 2018).
- BDA is one of the primary pillars of I4.0, supporting organisations to achieve enhanced operational efficiency and competitive advantage via data-driven analytics (Bag et al. 2020e; Ramadan et al. 2020).
- Cyber-physical systems (CPSs) enable the integration between digital and physical processes, thereby allowing computers to monitor and control physical processes (Rosa et al. 2019; Tjahjono et al. 2017).
- Blockchain is the core technology of the bitcoin and a distributed ledger that enables the transaction of data electronically without depending on trust due to its inherent characteristics of transparency and constancy (Bischoff and Seuring 2021; Kouhizadeh et al. 2020)
- Cloud computing creates a highly distributed digital network via cloud services to intelligently and efficiently connect manufacturing resources (Rajput and Singh 2019; Xu et al. 2018).
- Autonomous robots or smart robots work autonomously by imitating human actions to increase the throughput and quality of the products while decreasing the production cost per unit (Bibby and Dehe 2018).
- Horizontal/vertical integration refers to embedding information and communication systems to integrate production and management levels (vertical integration) and collaboration between organisations (horizontal integration) while sharing real-time information digitally among each other (Dalenogare et al. 2018). Horizontal and vertical integration represent management practices and not technologies. However, since I4.0 enables data integration among companies, departments and functions which enables horizontal and vertical integration, Rüßmann et al. (2015) listed this as one of the nine pillars of I4.0.
- Augmented reality is an innovative technology that projects a digital context on clients' field of view, which has been applied in various activities such as early prototyping, design evaluations and customisations in collaboration with virtual reality (Mourtzis et al. 2018).

Digital transformation technologies can improve the sustainability of the processes by optimising the logistics resources and energy efficiency, thereby paving the path for CE (Junge and Straube 2020). Reike et al. (2018) discussed 10 value-retention options in the CE context, including reduce, refuse, reuse, recycle and remanufacture, to extend the product life cycle and reduce the resource consumption. Many I4.0 technologies have been identified to support these value-retention options (Awan et al. 2021; Jabbour et al. 2018; Rajput and Singh 2019; Rosa et al. 2019). For instance, in supporting sustainable manufacturing processes, AM is the technology most commonly associated with recycling, although BDA and simulation also support recycling (Rosa et al. 2019). Moreover, IoT, CPS and cloud manufacturing have been highlighted as the primary technologies supporting the reuse, refurbish and remanufacturing processes since they enable tracking and tracing the products (Awan et al. 2021; Jabbour et al. 2018; Rosa et al. 2019).

Integration of I4.0 technologies and SC will revolutionise SC operations (Frederico 2021). I4.0 focuses on smart products and processes (Crnjac et al. 2017), presenting extensive possibilities for improving SC operations/processes and sustainability performance (Chauhan and Singh 2019). Although the research on integrating I4.0 and the sustainability of SCs is under-researched (Bag et al. 2018), technologies such as BDA, IoT and CPS support integrating SCs for more flexibility, transparency and connectivity (Fatorachian and Kazemi 2020). Bianchini et al. (2018) further emphasised that BDA and IoT can be platforms to build promising circular models. Therefore, scholarly discussion has evolved regarding the role of big data in facilitating the adoption of the CE concept (Jabbour et al. 2019; Nobre and Tavares 2017; Pagoropoulos et al. 2017; Tseng et al. 2018). Moreover, Mukherjee et al. (2021) identified that blockchain, which is recognised as one of the primary tools of I4.0, has great potential for improving sustainability in SCs. Combined with the CE concept, I4.0-driven SCs would be more interactive, secure and adaptable, with boosted sustainability performance (Rajput and Singh 2019).

3 Research method

Literature reviews identify the potential research gaps via a thorough evaluation of the body of literature while underlining the existing limits (Tranfield et al. 2003). Rowley and Slack (2004) proposed a systematic method to structure a literature review and build the bibliography by scanning the literature and designing mental maps. This study adopted bibliometric and network analyses to easily and more reliably scrutinise large article sets. Moreover, bibliometric analysis can examine the relationships among articles while providing a broader conclusion along with robust visualisations (Feng et al. 2017). The methodology for this study was adopted from the study of Fahimnia et al. (2015) due to the comprehensive approach they followed.

3.1 Defining the appropriate search terms

To retrieve articles focusing on this study area, we used keywords related to I4.0 technologies, CE, SCM and quantitative methods for the data collection. I4.0-related keywords covering nine pillars of technologies and other relevant areas[1] were adopted from Rosa et al. (2019). CE-related keywords, such as ‘closed loop’, ‘open loop’ and ‘circular economy’, and CE implementation strategies listed by Reike et al. (2018) – ‘refuse’, ‘recycle’, ‘refurbish’, ‘reuse’, ‘remanufacture’, ‘reduce’, ‘repurpose’, ‘redesign’, ‘repair’, ‘resell’, ‘rethink’, ‘recover’ or ‘remine’ – were also used in the search strings. To capture the SCM and quantitative methods, we used a broad set of keywords, including ‘simulation’, ‘optimization’, ‘optimisation’, ‘quantitative methods’, and ‘supply chain’. Using specific quantitative methods as keywords would have limited and biased the search and disenabled to capture the broader view on the areas of this study. As shown in Table 1, these keywords were combined to form search strings to retrieve related articles.

[1] E.g., ‘industry 4.0’, ‘additive manufacturing’, ‘big data’, ‘cloud manufacturing’, ‘internet of things’, ‘cyber physical system’, ‘augmented reality’, ‘3D printing’, ‘fourth industrial revolution’, ‘simulation’, ‘smart production’, ‘smart manufacturing’, ‘data mining’, ‘digital’, ‘smart’, ‘intelligent’.

Table 1 Search strings for article retrieval

I4.0 aspect	SCM aspect	Quantitative methods aspect		CE aspect
("industry 4.0" OR "additive manufacturing" OR "cloud manufacturing" OR "internet of things" OR "cyber physical system" OR "augmented reality" OR "3D printing" OR "fourth industrial revolution" OR "simulation" OR "smart production" OR "smart manufacturing" OR "data mining" OR "digital" OR "smart" OR "intelligent")	AND "supply chain*"	AND ("quantitative" OR "model*" OR "method*" OR "optimization" OR "optimisation")	AND ("circular economy" OR "sustainab*")	AND ("refus*" OR "recycl*" OR "refurbish*" OR "reus*" OR "remanufactur*" OR "reduc*" OR "repurpos*" OR "redesign*" OR "repair*" OR "resell*" OR "rethink*" OR "recover*" OR "remin*") AND ("closed loop*" OR "reverse*" OR "open loop*" OR "closed flow*")

3.2 Initial search results and refinements

The literature search was carried out at the title, abstract and keywords levels in the Web of Science database. This database was chosen because of the extensive range of scientific journals (more than 22,000 journals) indexed in this database (Sauer and Seuring 2017). Moreover, we considered only articles published in English in peer-reviewed journals for this study. The initial search showed 526 articles. After removing all the duplicates among the search strings, 433 articles were identified. The results were further refined by considering the articles with a technical and managerial focus and excluding categories such as medical sciences, geography and architecture. This filtering process resulted in 414 articles, which were then used for the bibliometric analysis. The final search result was downloaded as a text file that included all essential information, such as author info, title, abstract, keywords, affiliations and references.

3.3 Data analysis

The data analysis comprised two techniques, namely, bibliometric analysis and network analysis. For this study, we used the Biblioshiny app,[2] which is based on the bibliometrix package version 3.1 of the R programming language. It is a robust tool developed to perform bibliometric and network analyses (Dhiaf et al. 2021). R is an open-source software capable of performing various statistical analyses (Aria and Cuccurullo 2017; Riahi et al. 2021). The workflow of the bibliometrix package comprises three main steps. Firstly, data collection comprises data loading and conversion to the R data frame. Secondly, data analyses consist of three substages: descriptive analysis, network creation (co-citation, co-occurrence and collaboration network analyses) and normalisation. The third and last step is data visualisation, which includes conceptual structure and network mappings (Aria and Cuccurullo, 2017). Excel (Microsoft Corporation, Redmond, USA) was used to prepare several figures and tables included in Sect. 4.

The research process is thereby documented transparently, giving it replicability and reliability. Validity is achieved by having an internally consistent dataset. External validity is addressed by linking the findings from this study to other research in the field, which are presented in the subsequent sections.

4 Bibliometric analysis

The bibliometric analysis presents a quantitative approach for comprehensively analysing large datasets. Sections 4.1, 4.2, and 4.3 predominantly explore the features and current state of the research while discussing the methods and factors that should be considered when applying quantitative methods in I4.0-enabled SC operations in the CE context. Section 4.1 presents the initial data statistics. Section 4.2 discusses the influence of authors and their affiliations on the literature, and Sect. 4.3 introduces keyword statistics. Sections 4.4, 4.5, 4.6, and 4.7 mainly discuss research clusters that have emerged at the intersection of the four fields explored in this study and future directions. The network and citation analysis is presented in Sect. 4.4, co-citation analysis in Sect. 4.5, thematic evolution analysis in Sect. 4.6 and co-authorship analysis in Sect. 4.7.

4.1 Initial data statistics

The timespan of the article set ranged from 2003 to December 2020. Figure 1 shows that publications are emerging at a compound annual growth rate (CAGR) of 35%. The

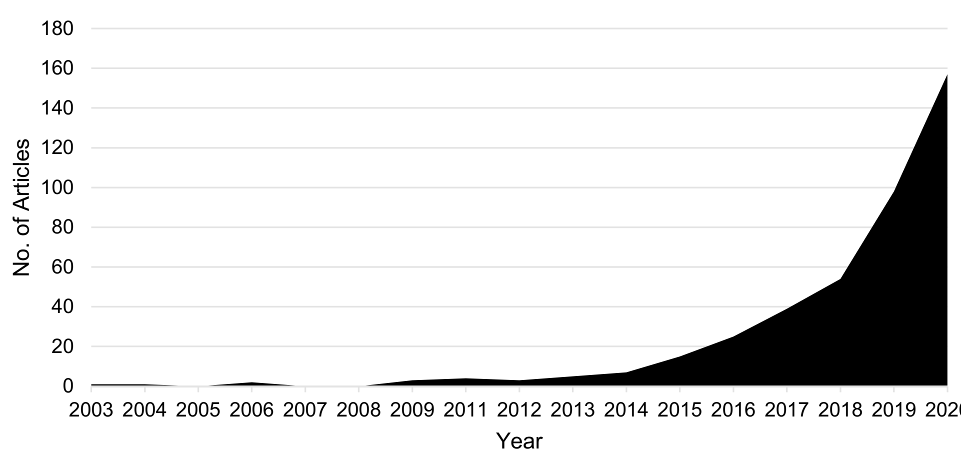

Fig. 1 Trend of publications. Reprinted/adapted by permission from [Springer Nature Customer Service Centre GmbH]: [Springer, Cham] [IFIP Advances in Information and Communication Technology] by [Dolgui A., Bernard A., Lemoine D., von Cieminski G., Romero D.] [COPYRIGHT] (2021)

[2] https://bibliometrix.org/Biblioshiny.html

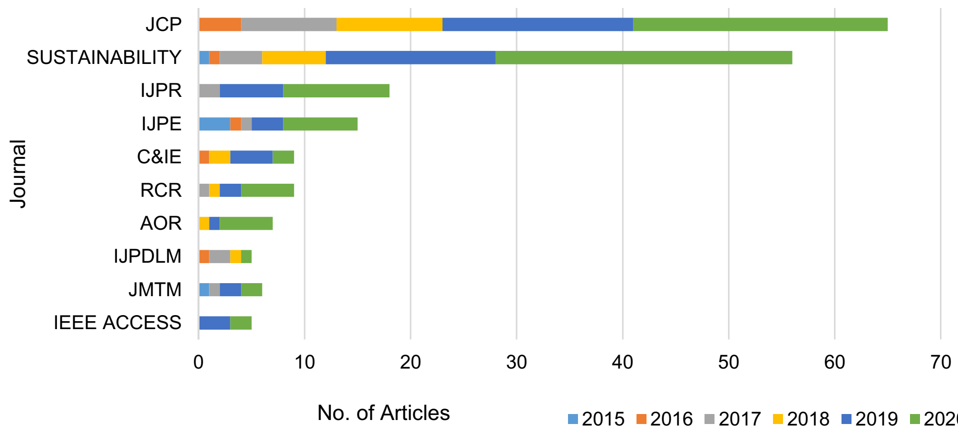

Fig. 2 Top 10 publishing journals. Reprinted/adapted by permission from [Springer Nature Customer Service Centre GmbH]: [Springer, Cham] [IFIP Advances in Information and Communication Technology] by [Dolgui A., Bernard A., Lemoine D., von Cieminski G., Romero D.] [COPYRIGHT] (2021). JCP – Journal of Cleaner Production, IJPR – International Journal of Production Research, IJPE – International Journal of Production Economics, C&IE – Computers and Industrial Engineering, RCR – Resource Conservation and Recycling, AOR – Annals of Operations Research, IJPDLM – International Journal of Physical Distribution and Logistics Management, JMTM – Journal of Manufacturing Technology and Management

growth increased considerably (CAGR of 19% until 2011 and 56% after 2014) after introduction of the I4.0 concept in 2011. The 414 articles were distributed across 157 journals, with 144 articles (35%) published in four journals, namely, *Journal of Cleaner Production* (58), *Sustainability* (53), *International Journal of Production Research* (17) and *International Journal of Production Economics* (16). *Journal of Cleaner Production* and *Sustainability* publish a very high number of articles per year, which explains why they dominate the field. Figure 2 illustrates that the publications of these topics have gained momentum since 2019, and engineering and technology-related journals have also recently received special scholarly attention.

4.2 Author and affiliation influence

The analysis of the authors and their impact revealed that most authors on this intersection are occasional authors. Lotka's (1926) law measures the 'frequency of publications by authors in any given field' (Dhiaf et al. 2021, p239). Several studies has been conducted to investigate the conformity of this measurement (Talukdar 2015). The core idea is that it estimates author productivity, and high frequency percentages indicate the satisfaction of authors to repeat and publish more work in that particular field (Dhiaf et al. 2021). As per Lotka's law, only 3% of the authors published three or more articles on this intersection. This result is further endorsed by the analysis of the top 10 authors (Table 2). Surajit Bag, Shivam Gupta and Yang Liu top the list, with seven publications each, whereas five authors authored five articles each and two authors published four articles each. Hence, the results of Table 2 and Lotka's law exemplify that most of the authors are occasional authors who have yet to collaborate further on the intersection of the four fields. This further reflects that the topic of this study is still emerging. Although the European region is dominant, China and the USA dominate the scientific production output at the country level (Fig. 3). Further, two countries also dominated the two domains considered in this study, CE and I4.0, with China as one of the pioneers of the CE concept and Germany as the forerunner of the I4.0 concept. CE implementation in China is promoted as part of their policy on socio-economic development and transformation. Political involvement in CE development in the European Union has emerged in recent years (Ghisellini et al. 2016). However, a federal policy towards CE has yet to be introduced in the USA (Ghisellini et al. 2016). These political influences on CE implementation may explain the geographical distribution depicted in Fig. 3.

Table 2 Top 10 authors

Author	Country	No of articles
Surajit Bag	South Africa	7
Shivam Gupta	France	7
Yang Liu	Sweden	7
Stephen Childe	UK	5
Rameshwar Dubey	UK	5
Angappa Gunasekaran	USA	5
Sachin Kumar Mangla	UK	5
David Roubaud	France	5
Li Cui	China	4
Jose Arturo Garza-Reyes	UK	4

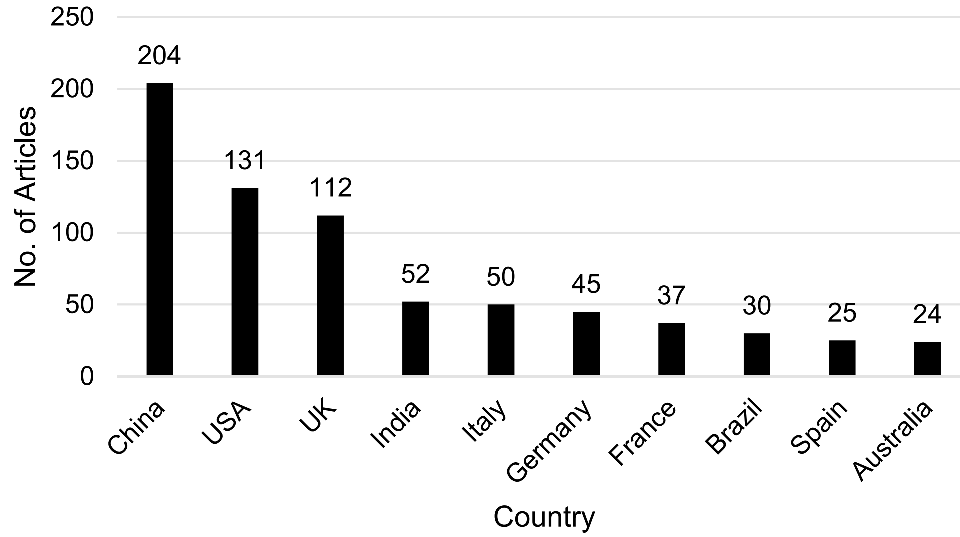

Fig. 3 Country specific scientific contribution

4.3 Keyword statistics

As shown in Table 3, the keywords 'sustainability', 'supply chain/supply chain management' and 'circular economy' were the most frequent, which confirms the keywords used for the literature search. From the I4.0 perspective, it is interesting that AM and BDA were the most prominently used keywords, closely followed by IoT. This result also hints that the current literature focus is on I4.0 technologies. Keywords such as 'optimization', 'simulation' and 'system dynamics' were also among the top 10. This shows that the article set is fairly distributed over all the domains considered in the analysis.

Going beyond the bibliometric analysis, based on the results of Table 3, we further analysed all articles that mentioned 'optimisation/optimization', 'simulation' and 'system dynamics' as keywords to understand the application of quantitative methods. We identified 58 articles, and the top five methods are illustrated in Fig. 4. System dynamics (SD) modelling was the most employed simulation method, while discrete event simulation and agent-based modelling were also commonly operationalised quantitative techniques among the studies.

Table 3 Top 10 author keywords. Reprinted/adapted by permission from [Springer Nature Customer Service Centre GmbH]: [Springer, Cham] [IFIP Advances in Information and Communication Technology] by [Dolgui A., Bernard A., Lemoine D., von Cieminski G., Romero D.] [COPYRIGHT] (2021)

Keyword	Frequency
Sustainability	82
Supply chain/supply chains/supply chain management	68
Circular Economy	33
Additive Manufacturing/3D printing	26
Big data/Big data analytics	26
Industry 4.0	26
Internet of things/IoT/Internet of things (IoT)	22
Optimisation/Optimization	22
Simulation	22
System Dynamics	20

4.4 Network and citation analysis

A citation analysis reveals the degree of connectivity between pairs of articles (Fahimnia et al. 2015) and is primarily based on the number of local or global citations an article has received over time. Global citations represent the number of citations an article has received from all the articles indexed in an entire database, such as Scopus or Web of Science. In comparison, local citations denote the number of citations an article has received from all the articles included in the analysed article set. Therefore, in our study, local citations represent the number of citations a selected article from our 414-article set received from the rest of the articles included in the same article set. Table 4 presents the top 10 articles based on the number of local citations. The gap between local and global citation values (low local citation percentage) shown in Table 4 reflects that the intersection studied in the current article has also received attention from other disciplines. More than 80% of the citations originated from outside of the selected article sample.

Table 4 reveals that the top four documents discuss I4.0 technologies and CE/sustainability. Jabbour et al. (2018) presented a research agenda and a roadmap for sustainable operations integrating CE and I4.0. The studies of Hazen et al. (2016) and Despeisse et al. (2017) outlined research perspectives on BDA and AM associated with sustainable SCs and CE. Dubey et al. (2019), with the highest percentage of local citations, addressed the intersection of big data and predictive analytics (BDPA) and sustainable SCs

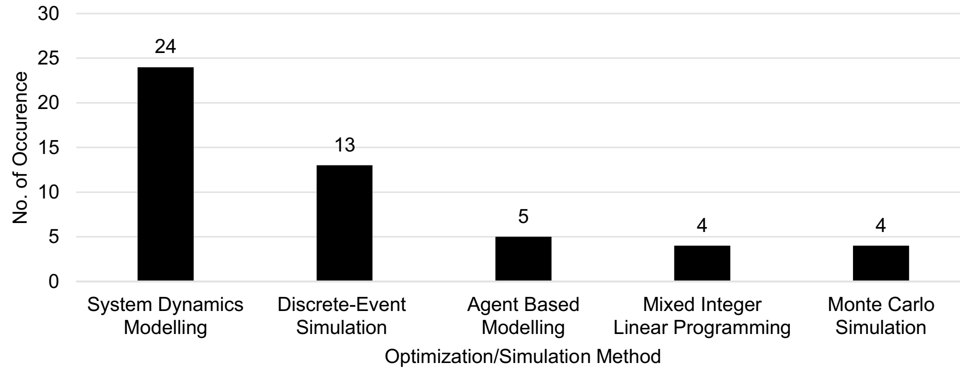

Fig. 4 Top 5 optimisation/simulation methods

focusing on environmental and social sustainability aspects. These studies provide sound reference points for researchers to conduct their future research on I4.0-enabled sustainable SCs/CSCs.

Several studies have highlighted that I4.0 technologies facilitate and enable CE implementation (e.g., Nobre and Tavares 2017; Rosa et al. 2019). To further support this statement, we explored the studies listed in Table 4 in greater detail. Jabbour et al. (2018) highlighted that I4.0 technologies amplify CE efficiency through enhanced productivity. Despeisse et al. (2017) and Nascimento et al. (2019) revealed that 3D printing improves sustainable production and consumption while stimulating CE and its related strategies (e.g., reuse by product lifecycle extension or recycle by optimised consumption of virgin materials). Moreover, blockchain facilitates CE via enhanced data tracking and introduces incentives to promote recycling by issuing cryptographic tokens in exchange for recyclable bottles and cans (Saberi et al. 2019). Hence, I4.0 technologies facilitate and enable CE implementation.

Table 4 Top 10 local cited articles. Reprinted/adapted by permission from [Springer Nature Customer Service Centre GmbH]: [Springer, Cham] [IFIP Advances in Information and Communication Technology] by [Dolgui A., Bernard A., Lemoine D., von Cieminski G., Romero D.] [COPYRIGHT] (2021)

Document	Local citations	Global citations	Local citations (%)
Jabbour et al. (2018)	16	122	13.11
Despeisse et al. (2017)	13	100	13.00
Dubey et al. (2019)	13	75	17.33
Hazen et al. (2016)	12	71	16.90
Dubey et al. (2016)	12	125	9.60
van der Vorst et al. (2009)	11	179	6.15
Gebler et al. (2014)	10	256	3.91
Saberi et al. (2019)	10	179	5.59
Nascimento et al. (2019)	9	59	15.25
Sasson and Johnson (2016)	8	63	12.70

4.5 Intellectual structure and co-citation analysis

The intellectual structure reveals how the scholarly work of an author influences the scientific community, as it shows the relationships between references. Co-citation analysis is the most common analysis conducted under the intellectual structure. It indicates the central, peripheral or bridging researchers while pinpointing the structure of a scientific community in a given field (Zupic and Čater 2015).

When analysing the intellectual structure of a dataset, it is vital to explore the co-citation network. Small (1973) introduced the co-citation analysis concept to measure the correlation degree among two separate articles. This concept is based on the knowledge structure of focused areas/fields and, thus, identifies emerging research directions and points towards existing boundaries in the literature. Since co-citation analysis identifies the associations among the cited references, it also provides insights into author collaborations as well as shifts in paradigms (Feng et al. 2017; Zupic and Čater 2015).

As shown in Fig. 5, the co-citation analysis hinted at three main groups, each of which represents a research area/subject/field. To further explore the relationships between these groups, we examined the PageRank values of the articles, as illustrated in Fig. 5. Both Fig. 5 and the PageRank values were generated and retrieved from the Biblioshiny app, which was the primary software used in this bibliometric study.

Methods such as citation count/rank are used to assess the significance of an article (Ding and Cronin 2011; Fahimnia et al. 2015). Going beyond the conventional citation count approach, PageRank analysis is based on a weighted citation count approach (Ding and Cronin 2011). The number of citations for an article represents its popularity, whereas the number of citations gained by highly cited articles represents the prestige of an article (Fahimnia et al. 2015). The underlying idea is that PageRank measures both the popularity

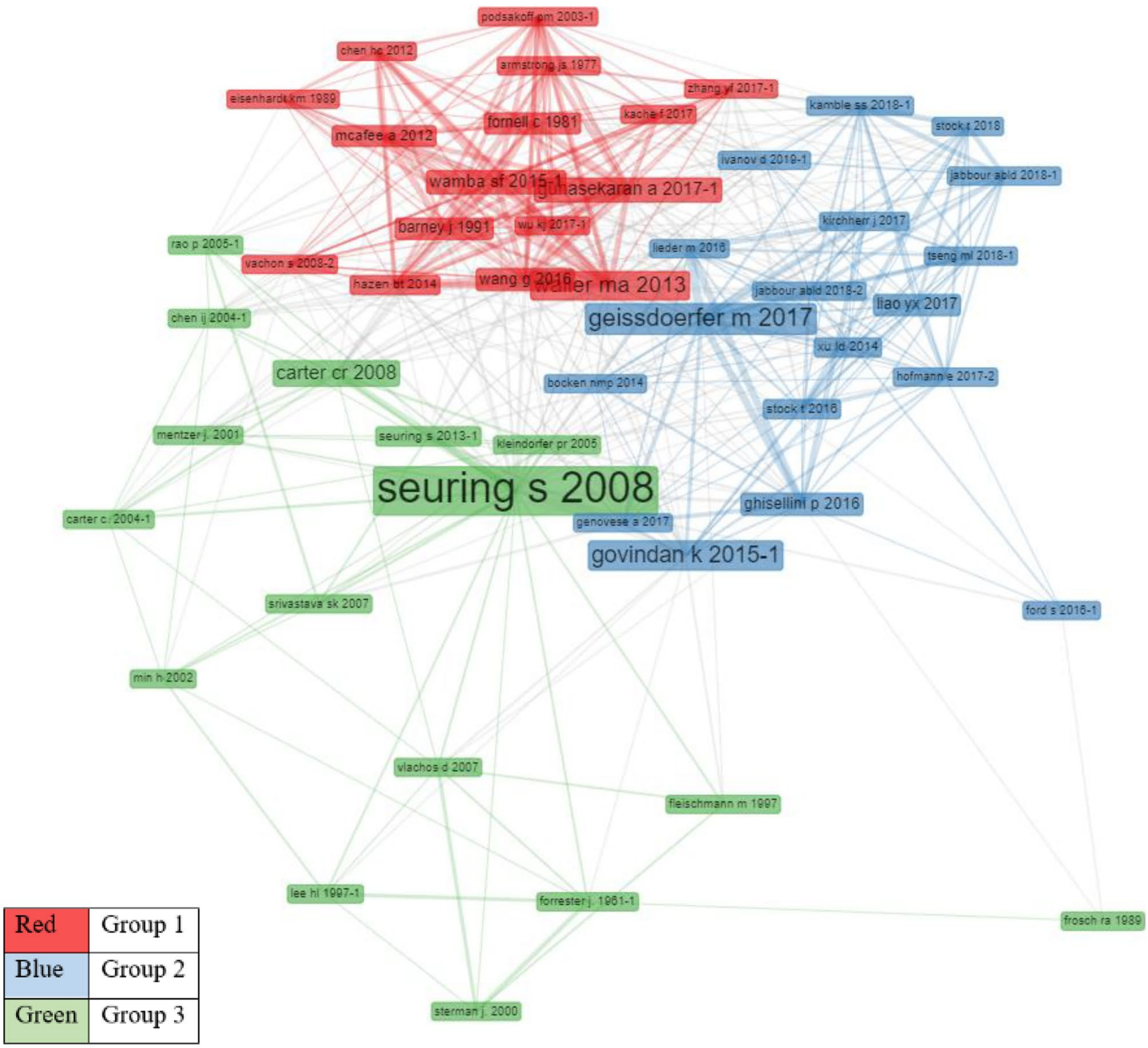

Fig. 5 Co-citation analysis

and prestige of an article while adding more weight to the citations of highly cited articles in a network compared to non-highly cited articles (Ding and Cronin 2011). However, it has been noted that a highly cited article might not necessarily be a prestigious article (Fahimnia et al. 2015). Table 5 shows the top 10 articles identified based on these PageRank values. Further analysis of the top 10 articles selected based on PageRank analysis revealed that Group 1 mainly focuses on BDA and SCM, Group 2 discusses the intersection of I4.0 and CE while Group 3 focuses on quantitative methods and sustainable supply chain management (SSCM).

With a focus on BDA and SCM, Group 1 is comprised of eight main articles with high PageRank scores and a large number of local citations. In this group, Waller

Table 5 Top 10 articles of co-citation network based on PageRank value

Node	Group	PageRank	Local citations
Seuring and Müller (2008)	3	0.04244	41
Waller and Fawcett (2013)	1	0.04031	23
Gunasekaran et al. (2017)	1	0.03583	22
Wang et al. (2016)	1	0.03543	21
Geissdoerfer et al. (2017)	2	0.03541	23
Wamba et al. (2015)	1	0.03482	23
Hazen et al. (2014)	1	0.03076	19
Barney (1991)	1	0.02853	19
Mcafee and Brynjolfsson (2012)	1	0.02744	21
Fornell and Bookstein (1982)	1	0.02631	21

and Fawcett (2013) highlighted future research directions on the intersection of data science, BDPA and SCM. Gunasekaran et al. (2017) studied the impact of BDPA on SC and organisational performance and highlighted several future directions, such as the impact of data analytics on BDPA. Wang et al. (2016) explored the application of BDA in SC strategies and operations while underlining several future research directions. Wamba et al. (2015) presented a framework revealing different perspectives and applications of big data while highlighting the importance of this cutting-edge technology.

Group 2 addresses the integration of I4.0 technologies and CE. For this group, only the work of Geissdoerfer et al. (2017) is listed in Table 5. They discussed the similarities and differences between CE and sustainability and how CE is conceptually related to sustainability. They also emphasised the relevance of exploring SC-wide CE impacts on sustainability.

Group 3 mainly addresses the different aspects of sustainable SCs. Seuring and Müller (2008) outlined the major research areas, limitations and future research directions of the sustainable SC field. Carter and Rogers (2008) discussed the relationships among three main sustainability pillars and their performances within the SCM context via a conceptual lens. Seuring (2013) reviewed quantitative modelling approaches to SSCM and proposed future research directions.

4.6 Conceptual structure

The conceptual structure represents the main themes and trends in a set of publications. Several approaches, such as co-word analysis and factorial analysis, are included in the conceptual structure. We used a mixed approach to develop a thematic network based on a conceptual network.

A co-word network was used to identify clusters of keywords, and these clusters were considered as themes. These themes were detected by applying a clustering algorithm to the co-word network. Each identified theme was characterised by two parameters – centrality and density. Centrality indicates the importance of the given theme to the entire domain, while density measures the development of the theme (Callon et al. 1991; Cobo et al. 2011). Subsequently, we used the Biblioshiny app to operationalise the process created by Cobo et al. (2011) to develop a thematic map. Based on these two measures, the app assigned the identified themes to four quadrants. We divided the total timespan of our study into before and after the introduction of the I4.0 concept using the time slice function in the Biblioshiny app. Figures 6 and 7 illustrate this thematic evolution. Each bubble is named after the keyword with the highest occurrence value (within the cluster), and the bubble size is proportional to the number of keyword occurrences in each cluster.

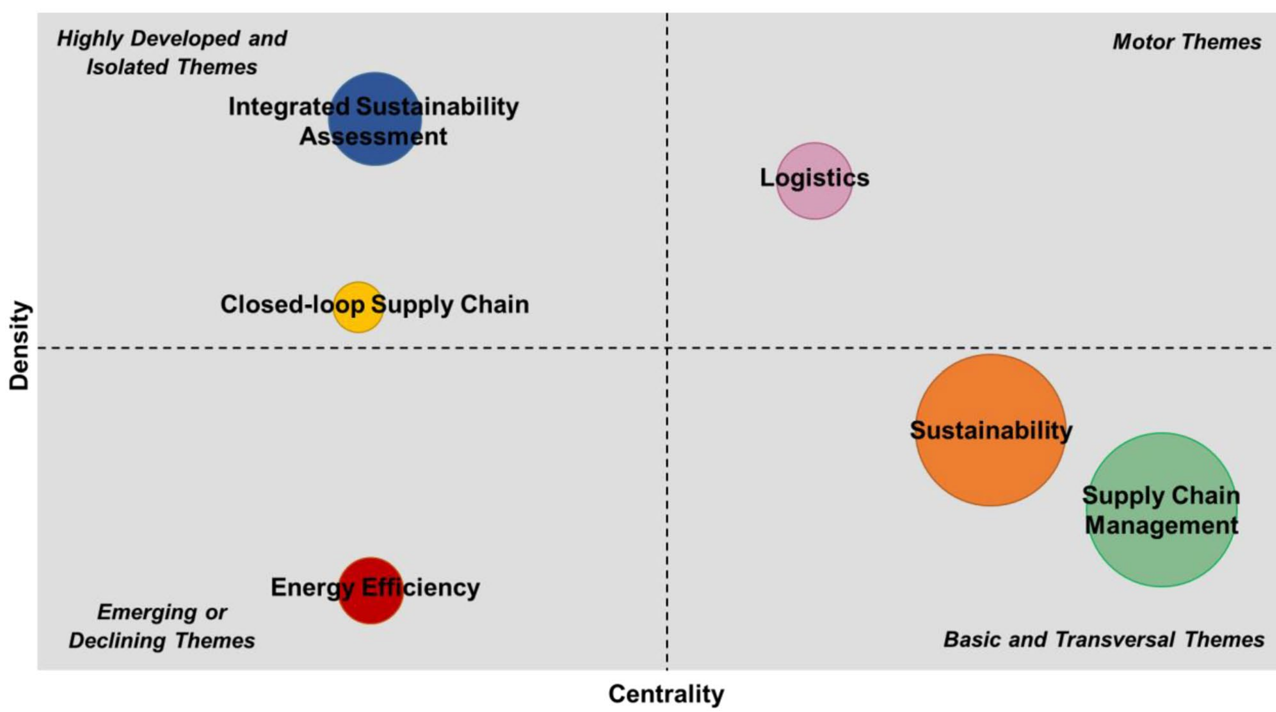

Fig. 6 Thematic map–Before the introduction of I4.0 (2003 – 2012)

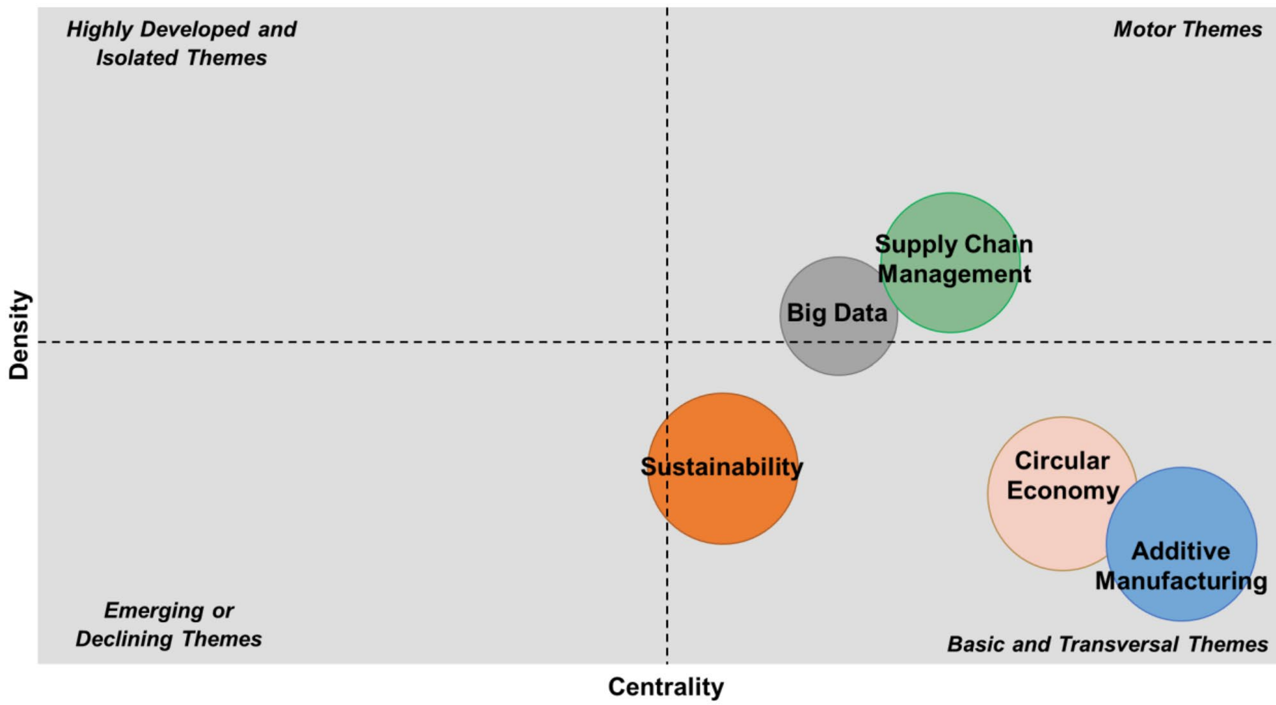

Fig. 7 Thematic map–After the introduction of I4.0 (2013 – 2020)

Cobo et al. (2011) defined the four quadrants in Figs. 6 and 7 as 1) highly developed and isolated themes, 2) emerging or declining themes, 3) motor themes and 4) basic and transversal themes. Specialised and peripheral themes with well-developed internal ties and marginal importance to the field are represented in the highly developed and isolated themes quadrant. Themes that are weakly developed are listed in the emerging or declining themes quadrant. The motor themes quadrant represents the well-developed and important themes for structuring a research area, whereas the basic and transversal themes quadrant clusters the general themes that are important to the research field but have yet to be developed.

Comparing Figs. 6 and 7 by closely examining the themes and their related keywords highlights that with the introduction of the I4.0 concept, AM became a transversal theme together with CE and sustainability, whereas BDA and SCM became motor themes. Moreover, themes such as energy efficiency, logistics, closed-loop supply chains and integrated sustainability assessment disappeared, and new themes emerged. This evolution is further illustrated in Fig. 8. After the launch of the I4.0 concept in 2012, energy efficiency evolved and is now discussed under AM and CE. Similarly, logistics progressed and is now discussed under AM, CE and BDA. Closed-loop supply chain and integrated sustainability assessment are incorporated into SCM and sustainability. This evolution hints at the shift in the research direction with the introduction of the I4.0 concept. Therefore, researchers are encouraged to focus their research on a combination of motor themes and basic and transversal themes. SCM and BDA have been identified as well-developed and established research themes, while sustainability, CE and AM are recognised as basic themes that have yet to be developed.

4.7 Social structure

We analysed the co-authorship network to study the social structure of the article set and to understand how authors or institutions collaborate when conducting scientific research (Peters and Van Raan 1991). This co-authorship network analysis mainly revealed the clusters and hidden communities of authors in a specific research arena. The Biblioshiny app generated a co-authorship network using the cosine formula to compute co-authorship strength (Peters and Van Raan 1991). A close investigation of this network developed for our article set highlighted five clusters with three or more articles, as shown in Table 6. We selected 22 articles related to the clusters and analysed their content to understand the main themes, foci, methods and techniques used in each cluster, as listed in Tables 6 and 7. However, the low number of studies per cluster indicates that the research potential of those themes has yet to be fully investigated and that 97% of the authors published in this intersection are occasional authors (per Lotka's law). The single clusters are briefly explained below.

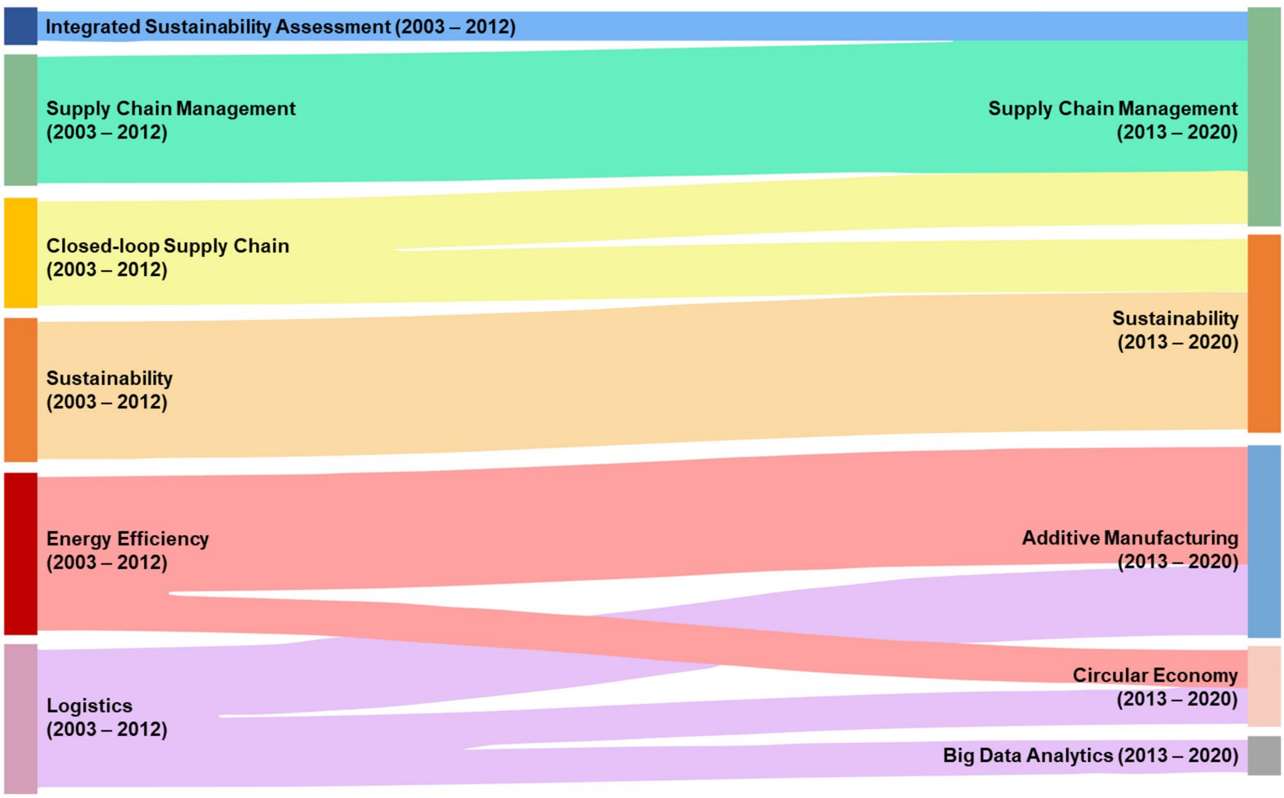

Fig. 8 Thematic evolution (2003 to 2012 and 2013 to 2020)

Cluster 1 studies the impact and effects of BDPA on sustainability performance measures. Authors of this cluster mainly utilise theories such as dynamic capability, institutional theory and resource-based view in their studies. The main method applied in this cluster is BDPA. Several authors have also applied partial least square SEM (Jeble et al. 2018) and confirmatory factor analysis (Dubey et al. 2016).

Cluster 2 explores the role of I4.0 technologies in SSCM and CE performance, mainly regarding remanufacturing (Bag et al. 2020a). The resource-based view (Bag et al. 2020a) and dynamic capabilities (Bag et al. 2020c, f) are the main theories used in this cluster, and SEM is the main method used by the authors.

The studies in Cluster 3 elaborate the barriers, challenges and benefits of I4.0 technologies on sustainability performance and CE implementation strategies such as remanufacturing. The MCDM (Luthra et al. 2020; Ozkan-Ozen et al. 2020), SEM (Bag et al. 2020d) and SD (Kazancoglu et al. 2021) methods are employed to explore these aspects.

Cluster 4 mainly focuses on improving the environmental performance and the performance of real-time logistics services. This cluster comprises articles that use several quantitative methods, such as mixed-integer nonlinear programming (Cao et al. 2018), decision making trial and evaluation laboratory (DEMATEL) (Zhang et al. 2019) and BDPA (Zhang et al. 2017) for I4.0 technologies in the CE and SSCM contexts.

Cluster 5 focuses on assessing the impact of digital technologies on sustainability performance using DEMATEL, exploratory factor analysis and confirmatory factor analysis. With a relatively low number of articles per cluster, Clusters

Table 6 Clustering based on co-authorship network. Reprinted/adapted by permission from [Springer Nature Customer Service Centre GmbH]: [Springer, Cham] [IFIP Advances in Information and Communication Technology] by [Dolgui A., Bernard A., Lemoine D., von Cieminski G., Romero D.] [COPYRIGHT] (2021)

Cluster	Theme of the cluster	No. articles
1	Impact of BDA towards sustainable consumption and operations	5
2	Role of I4.0 technologies in CE and SSCM	5
3	Barriers/challenges for CE implementation in I4.0 environment	5
4	Quantitative methods for I4.0 technologies in CE and SSCM	4
5	Impact of digital technologies on sustainability performance	3

Table 7 Main focus and techniques of the clusters. Reprinted/adapted by permission from [Springer Nature Customer Service Centre GmbH]: [Springer, Cham] [IFIP Advances in Information and Communication Technology] by [Dolgui A., Bernard A., Lemoine D., von Cieminski G., Romero D.] [COPYRIGHT] (2021)

Cluster	Main focus	Main methods and techniques	Key references
1	Impacts of BDPA on sustainability performance measures	BDPA	(Dubey et al. 2019), (Dubey et al. 2018), (Jeble et al. 2018)
2	Effects of I4.0 technologies (BDA) on logistics, SSCM, CE performance and CE imperatives (remanufacture)	Structural Equation Modelling (SEM)	(Bag et al. 2020g), (Bag et al. 2020a), (Bag et al. 2020c)
3	Barriers, challenges and benefits of I4.0 technologies for sustainability performance and CE imperatives (remanufacture)	Multi Criteria Decision Making (MCDM), SEM, SD	(Ozkan-Ozen et al. 2020), (Janssen et al. 2019), (Luthra et al. 2020)
4	Highly efficient real-time logistics services, Environmental performance improvements	Multiple methods (E.g., Mixed integer non-linear programming, BDPA, dynamic optimisation, etc.)	(Liu et al. 2019), (Cao et al. 2018), (Zhang et al. 2017)
5	Sustainability performance and implications of I4.0 technologies	MCDM techniques (E.g., Exploratory factor analysis, Confirmatory factor analysis)	(Li et al. 2020), (Cui et al. 2019)

6–9 investigate the under-explored themes shown in Tables 6 and 7. This indicates future research directions that could be considered at the intersection of I4.0, CE, SCM and quantitative methods. The analysis of methods operationalised in these clusters further indicates that SEM, MCDM techniques, BDPA and SD are the most frequently applied techniques.

5 Overview of the intersection of the four research fields

Apart from the bibliometric analysis, we coded the author keywords of the 414 articles against the four fields we intersected in this study, namely, I4.0, CE, SCM and quantitative methods. We used the keywords we applied in the article retrieval process (in search strings) as a guide when coding the author keywords.

A keyword is 'a word or group of words, possibly in lexicographically standardized form, taken out of a title or of the text of a document characterizing its content and enabling its retrieval' (ISO norm 5963 1985). Author keywords are a valuable information source for the automatic and manual indexing of journal articles (Gil-Leiva and Alonso-Arroyo 2007). Therefore, analysing author keyword patterns reveals important information for future research.

The information on the four fields (I4.0, SCM, CE and quantitative methods) resulted in 15 different keyword sets. Figure 9 shows these intersections and the distribution of the 414 articles across them.

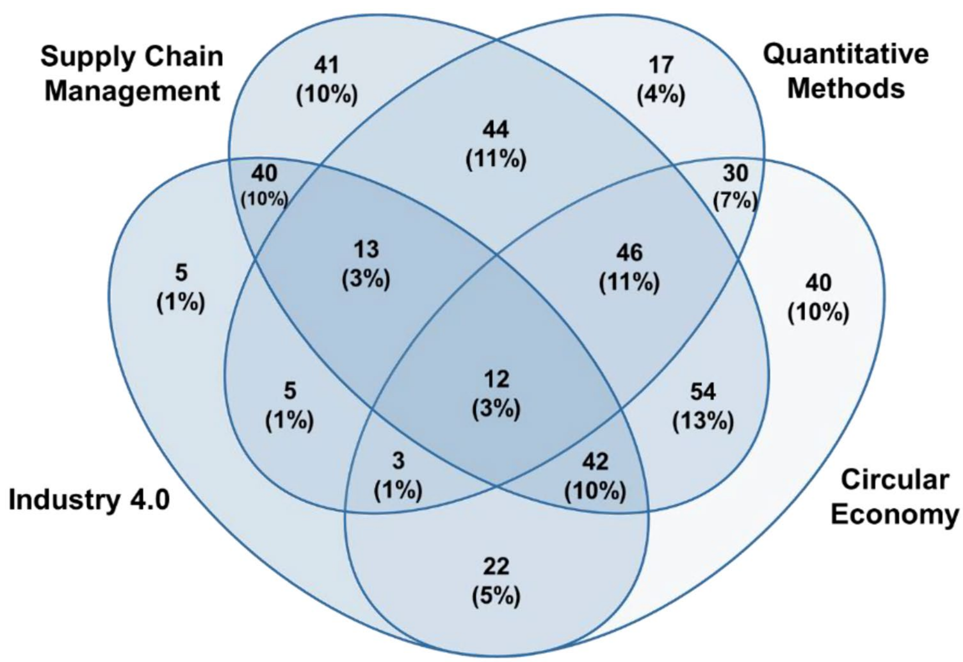

Fig. 9 Venn diagram representing the intersection of four fields

Figure 9 shows that the intersection of SCM and CE is the most studied combination (13%) as per the author keywords coding results. This shows the stable nature of this intersection. However, there are eight sets comprised of less than 10% of the articles, and these combinations mainly intersect with I4.0. This depicts the upcoming research environment surrounding I4.0 and related technologies.

Interestingly, this analysis revealed that certain articles used author keywords related to only one of the specific fields. However, this does not reflect that the article only focused on that specific field. The intersecting other fields could be found either in the title or abstract, as we used the title, abstract and keyword setting in Web of Science to retrieve the 414 articles.

To gain more insights on the keyword sets shown in Fig. 9, we formed word clouds for each set intersecting two or three fields. Word clouds provide information to scholars on the most popular author keywords used in each set. These insights could be useful for researchers who plan to study different combinations of research arenas.

Firstly, we considered the intersections of two fields (Figs. 10, 11, 12, 13, 14, and 15). Related word clouds for the pairwise intersections revealed that whenever CE intersects with the other three fields, 'sustainability' is the major keyword used, which is obvious due to the close relationship between CE and sustainability. Moreover, a close examination of the I4.0-related pairs (see Figs. 10, 14 and 15) showed that AM, BDA and IoT are the most prominent technologies studied, aligned with the results of Sect. 3.3. However, it is noteworthy that the intersection of I4.0 and quantitative methods (see Fig. 15) focuses on the healthcare industry (Visconti 2019).

Fig. 11 CE and quantitative methods, (30 articles)

Fig. 12 SCM and CE (54 articles)

Fig. 10 I4.0 and CE (22 articles)

Fig. 13 SCM and quantitative methods. (44 articles)

Fig. 14 I4.0 and SCM (40 articles)

Fig. 15 I4.0 and quantitative methods (5 articles)

A careful investigation of the SCM and CE intersection, which represents the highest number of articles, emphasised that social sustainability (Klumpp and Zijm 2019; Tirado et al. 2015), digitalisation (Bag et al. 2020b; Junge 2019) and bio/food SCs (Beitzen-heineke et al. 2017; Rijpkema and Rossi 2013) are the popular research areas (see Fig. 13). Further, as illustrated in Fig. 14, the combination of SCM and quantitative methods highlights that game theory (Chen 2017; Gao et al. 2006), genetic algorithm (Cao et al. 2018; Hashim et al. 2017) and SD (Jung 2018; Rebs et al. 2019) are the most employed quantitative techniques. In comparison, agent-based modelling (Albino et al. 2016; Halog and Manik 2011) and Monte Carlo simulation (La et al. 2019; Onat et al. 2014) are the most commonly operationalised quantitative methods at the intersection of CE and quantitative methods.

The intersection of the three fields shown in Figs. 16, 17, 18, and 19 further reveals that research on agricultural themes is evolving and is represented by emerging author keywords such as 'agrochemicals', 'agri-food supply chains', 'short food supply chains' and 'organic products'. Interpretative structural modelling, which can be used to identify the structural relationships among specific items, is the most frequently used quantitative technique at the intersection of I4.0, CE and quantitative methods (Fig. 16). The sets I4.0, SCM and CE as well as I4.0, SCM and quantitative methods are dominated by the keyword 'simulation' followed by 'IoT' (Figs. 17 and 18). Scholars operationalise MCDM techniques, such as the technique for order of preference by similarity to ideal solution (TOPSIS), analytic hierarchy process (AHP), fuzzy DEMATEL and fuzzy MCDM (Figs. 17, 18, and 19). However, the intersection of SCM, CE and quantitative methods mainly focuses on sustainability, with SD as the most used quantitative method at this intersection (Fig. 19).

Fig. 16 I4.0, CE and quantitative methods (3 articles)

Fig. 17 I4.0, SCM and CE (42 articles)

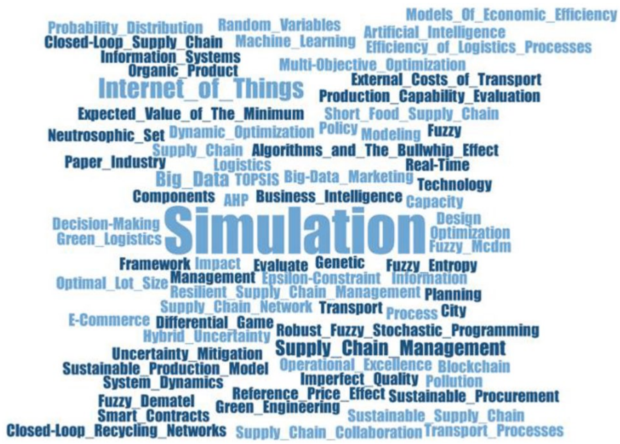

Fig. 18 I4.0, SCM and quantitative methods (13 articles)

Fig. 19 SCM, CE and quantitative methods (46 articles)

6 Discussion

Overall, many scholars have acknowledged the significance of I4.0 technologies for CE, SCM and quantitative methods. This study contributes to the theory and practice while providing a detailed view on the intersection of the four areas explored in this study. Descriptive statistics of the article set illustrated that it is fairly distributed, and authors are still expanding their collaboration network to explore the intersections of the four fields explored in this study. Moreover, the geographical distribution of the articles reflects the policy influence on the implementation of CE and I4.0 technologies.

Initial keyword analysis showed that SD is the most employed quantitative technique in the investigated intersection of this study. However, further in-depth analysis showed that studies exploring the intersection of SCM and CE utilise other quantitative methods besides SD, such as genetic algorithm, game theory and agent-based modelling. In contrast, the majority of the authors employ MCDM techniques such as TOPSIS, AHP and fuzzy DEMATEL in their studies focusing on the intersection of SCM and CE with I4.0. Aligning with this result, the author collaboration network further highlighted that MCDM techniques are popular among the studies exploring the barriers, challenges and role of I4.0 technologies to improve sustainability, supply chain and logistics performance. In comparison, the introduction of BDA has formed a different research direction for analysing big datasets using BDPA compared to the traditional quantitative methods.

Supporting Bocken et al.'s (2016) argument on the importance of exploring technologies facilitating CE, our study revealed that I4.0 technologies facilitate and empower CE implementation. Aligning with the discussions of Awan et al. (2021), Jabbour et al. (2018) and Rosa et al. (2019), the bibliometric and network analyses presented in Sect. 4 and extended author keyword analysis presented in Sect. 5 revealed that the research involving I4.0 primarily focuses on a few technologies, such as AM, BDA and IoT; 85 (21%) out of the 414 articles discussed at least one of these technologies.

BDA is the most discussed I4.0 technology, with scholars discussing its integration with several key topics, such as closed-loop supply chains (Ma and Hu 2020; Xiang and Xu 2020, 2019), agriculture/food supply chains (Jagtap and Duong 2019; Kamble et al. 2020) and dynamic capability view (Akhtar et al. 2018; Bag et al. 2020f; Dubey et al. 2019; Mishra et al. 2020; Ramadan et al. 2020) as a theoretical perspective. Further, the integration of BDA with SCM is extensively discussed, covering important aspects such as the impact of BDPA on SC operations and strategy. This was further validated in the thematic evolution, where BDA was identified as a motor theme along with SCM, indicating formation of a new research avenue. However, the application of BDA with a focus on CSCs and sustainable SCs (Dubey et al. 2019; Hazen et al. 2016) is worth investigation.

AM was identified as another key technology discussed in the literature, with environmental impact (Boon and van Wee 2018; Peng et al. 2018; Tang et al. 2016), life cycle analysis (Cardeal et al. 2020; Cerdas et al. 2017; Tang et al. 2016) and spare parts (den Boer et al. 2020; González-Varona et al. 2020; Isasi-Sanchez et al. 2020) comprising the most discussed topics intersecting AM. Compared to BDA, AM is more associated with CE, supporting sustainable manufacturing processes. AM was identified as a basic theme along with CE, showing the importance of exploring the integration of both areas in future research. Moreover, IoT is the other most discussed I4.0 technology, and it is mostly associated with CE/waste management (Garrido-hidalgo et al. 2020; Zhang et al. 2019), SCM (Haddud et al. 2017; Shokouhyar and Pahlevani 2020) and green logistics (Liu et al. 2019).

However, several other I4.0 technologies, such as CPS, blockchain and cloud computing, are less investigated. For instance, CPS and cloud computing are often discussed alongside other technologies such as IoT (Verdouw et al. 2018) and AM (Elhoone et al. 2020) since it provides a platform to digitally connect supply chain processes and operations. Moreover, investigating the applications of blockchains in CSC is another potential future direction, with authors such as Kouhizadeh et al. (2020) emphasising the need for more research on exploring the potential of blockchain in the CE context. Hence, it is apparent that further research may focus on how I4.0-related technologies such as CPS, cloud computing and blockchain can intersect with the SCM and CE fields.

7 Conclusion

With the evolution of I4.0 and CE concepts, the integration of I4.0 technologies with CE, SCM and quantitative methods is emerging in the scholarly debate. We conducted bibliometric and network analyses to explore what has been studied in these intersecting areas and how these research studies have been conducted. This study assimilated various gaps and facets when applying quantitative methods for I4.0-enabled SCs and operations in the CE context. Hence, it was revealed that the number of publications at this intersection is growing. Moreover, we observed that research noticeably emerged following the introduction of the I4.0 concept in 2011. A thorough analysis identified the most influential authors and articles while pinpointing the emerging research clusters to guide researchers when planning future studies.

Extensive analysis of keyword statistics provided insights into the quantitative methods employed in the literature. Analysis of the intellectual, conceptual and social structures pointed out several groups and clusters, highlighting various future research directions. Analysis of the intellectual structure showcased three groups mainly focusing on SSCM and CE intersecting with I4.0 and quantitative methods. Interestingly, BDA was a dominant I4.0 technology in one of these clusters. This finding was further supported by the results of the conceptual structure, which revealed that BDA is a well-developed and important theme that emerged after the introduction of the I4.0 concept.

The analysis revealed several future directions for scholars:

1. The conceptual structure analysis identified that AM and CE are important and evolving research fields that need to be further explored.
2. Investigation of the five clusters for the social structure identified I4.0-driven sustainable business models, operations, manufacturing and performance in the CE context as emerging topics that merit further investigation.
3. Healthcare and agricultural industries aiming to integrate I4.0, sustainability concepts and CE in their SCs is another future direction.
4. The application of quantitative methods in the I4.0 context has become the state of the art with the emergence of BDA and BDPA. This opens new research avenues for scholars to explore large datasets effectively and efficiently.
5. Only a limited number of I4.0 technologies (e.g., AM, IoT and BDA) have been studied with a focus on CE and SSCM. This highlights the importance of further research integrating other I4.0-related technologies, such as CPS, cloud computing and blockchain.

This study has several limitations. Firstly, the interpretation of the analysis was dependent on the author perceptions and classifications of the collected article set. Secondly, the bibliometric analysis was conducted based on the dataset retrieved from the Web of Science database. Therefore, some articles that may only be indexed in Scopus or other databases may have been missed during the selection process.

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Declarations

Competing of interest The authors have no competing interests to declare that are relevant to the content of this article.

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