Industry 4.0 Driven Quantitative Methods for Circular Supply Chains: A Bibliometric Analysis

Biman Darshana Hettiarachchi[1(✉)], Stefan Seuring[1], and Marcus Brandenburg[1,2]

[1] Chair of Supply Chain Management, University of Kassel, Kleine Rosenstraße 1–3, 34109 Kassel, Germany
{Biman.Hettiarachchi,seuring}@uni-kassel.de

[2] School of Business, Flensburg University of Applied Sciences, Kanzleistr. 91-93, 24943 Flensburg, Germany
marcus.brandenburg@hs-flensburg.de

Abstract. The Industry 4.0 (I4.0) concept comprises advanced digital technologies that facilitate the digitally enabled sustainability approach leading to a Circular Economy (CE). I4.0 driven CE initiative leads to a paradigm shift in supply chain management (SCM), where quantitative methods provide practical solutions to issues that arise when adopting circular practices. Therefore, the intersection of I4.0, CE, SCM and quantitative methods has been identified as an upcoming area worthwhile investigation. Hence, we conduct a bibliometric analysis on extant literature to visualise and unravel the current scholarly discussion while providing insights to the scholars and practitioners who pursue the current dynamics, trends, prospects pertaining to the intersection mentioned above.

Keywords: Industry 4.0 · Circular economy · Supply chain management

1 Introduction

The role of digital technologies has been identified as crucial in the transition towards the Circular Economy (CE) [1]. This digitally enabled CE approach is facilitated by the Industry 4.0 (I4.0) technologies influencing its performance with a positive impact on the life cycle management of products. Hence, several elements of I4.0 were identified as digital enablers for CE [2]. Especially, I4.0 elements such as simulation along with quantitative methods have been recognised as practical techniques to address issues related to supply chain management (SCM) when adopting circular practices [2]. However, studies disseminating such methods are dispersed in the SCM discourse, focusing on the reverse and closed-loop supply chains in the CE context. Hence, this study accumulates such scholarly work and answers which facets, factors, and limitations are to be considered when applying quantitative methods and techniques for I4.0 enabled operations and supply chains in the CE context. Moreover, this review aims to pinpoint possible research directions while highlighting the boundaries of knowledge.

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2 Background

CE aims to achieve sustainable development along with improved social equity and environmental and economic prosperity [3]. Integrated with I4.0, a technology-driven CE centric supply chain would be more sustainable, adaptable, secured, and interactive [4], ultimately paving the path to achieve the aims of CE.

Introduced in 2011, I4.0 exemplifies a set of automation technologies such as the Internet of Things (IoT), Cyber-Physical Systems (CPS), and cloud computing in the manufacturing industry [5]. It comprises nine pillars, namely, additive manufacturing (AM), simulation, augmented and virtual reality, big data and analytics (BDA), the Internet of Things (IoT), autonomous robots and vehicles, horizontal/vertical system integration, cloud, fog, and edge technologies, and blockchain and cyber-security [6, 7]. I4.0 represents a fundamental paradigm shift in SCM [8] which presents an immense possibilities to improve the SCM processes in areas such as responsiveness, efficiency, and sustainable performance [9]. Moreover, I4.0 technologies positively influence the lifecycle management of a product where technologies such as AM, BDA and IoT were identified as digital enablers of CE [2].

3 Methodology

Bibliometric analysis is adopted to analyse the relationships among articles efficiently and reliably and visualise the results to identify future research directions while providing comprehensive insights on the analysed research field [10]. Rowley and Slack [11] proposed a systematic methodology to scan resources, design the mind map to build the bibliography and structure a literature review. Literature review underlines the boundaries of the existing literature while identifying potential research gaps through a comprehensive evaluation of the body of literature [12]. In this study, we adopted the methodology followed by Fahimnia et al. [13] to conduct the bibliometric analysis.

To identify the relevant papers related to the focus of this study, keywords related to four areas, namely, I4.0, CE, SCM and quantitative methods, were selected. I4.0 related keywords covered all nine technological pillars and related areas proposed by Rosa et al. [2]. CE related keywords captured the different approaches for CE such as "circular economy", "closed loop*", "open loop*", and 10 CE implementation strategies identified by Reike et al. [14]. SCM and quantitative method aspects were comprehended by including keywords such as "supply chain*", "simulation", "optimisation" and "quantitative methods". The literature search only focused on papers published in English in peer-reviewed scientific journals, where the search was carried on title, abstracts and keywords in the Web of Science database. The initial search resulted in 526 papers. After removing duplicate papers among the search strings, the final dataset included 414 papers with a focus on technical and management perspectives. They were published from 2003 to December 2020.

The distribution of papers over the considered time horizon, as depicted in Fig. 1, shows a compound annual growth rate (CAGR) of 35%. Within the last five years, the CAGR accounted for 58%. This highlights the interest of scholars and practitioners in the intersection of I4.0, CE, SCM and quantitative methods.

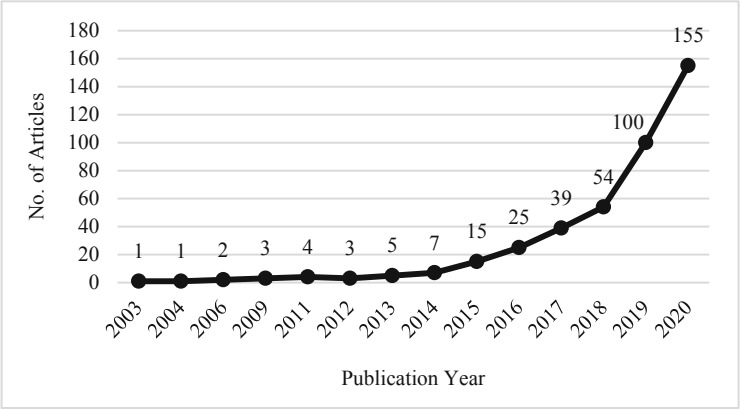

Fig. 1. Publishing trend

4 Bibliometric Analysis

We performed the bibliometric analysis using Biblioshiny software, which uses bibliometrix package of R to generate results. Moreover, data cleaning and data visualisation were completed using MS Excel. The key findings of the bibliometric analysis are discussed in this section.

Figure 2 presents the top 10 journals. These journals accounted for approximately 45% of the total number of articles selected for the study. Journal of Cleaner Production tops the list with 58 articles, closely followed by Sustainability with 53 papers. International Journal of Production Research and International Journal of Production Economics published 17 and 16 studies, respectively. This journal distribution depicts that journals from operations management and sustainability dominate the investigated research domain while journals representing the technology domain are emerging.

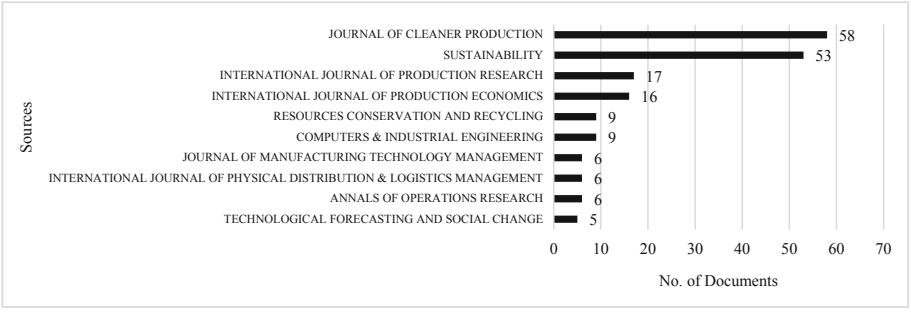

Fig. 2. Most relevant sources

Figure 3 depicts the most local cited documents, which illustrates the number of citations an article received from the articles included in the analysed collection (414 papers). The top four local cited documents are research agendas and road maps discussing the

intersection of I4.0 technologies and CE/sustainability. This shows the sources where the literature has started evolving in our analysed collection, and these articles provide insights on future research directions.

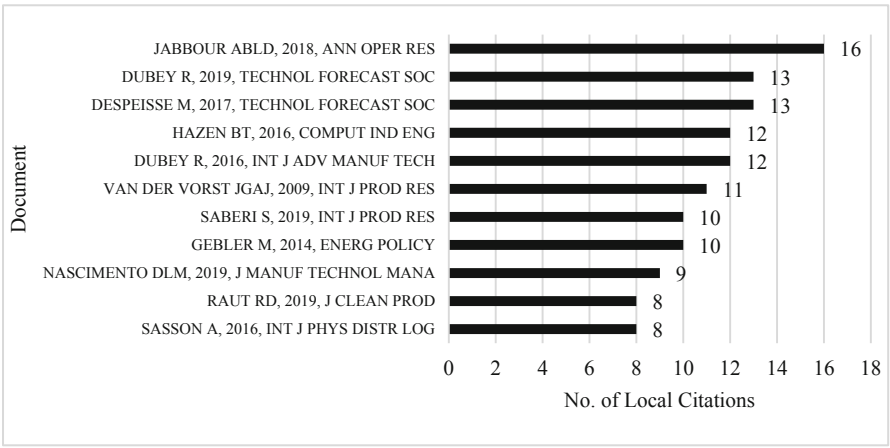

Fig. 3. Most local cited documents

A thorough scan of the content of these articles listed in Fig. 3 revealed that I4.0 technologies facilitate and enable CE implementation. For instance, Jabbour et al. [15] highlighted that I4.0 technologies may amplify the profit and efficiency by improved productivity whilst facilitating the CE. Despeisse et al. [16] also underlined that 3D printing stimulates more improved sustainable production and consumption while paving the path to enable CE. Moreover, Nascimento et al. [1] emphasised that 3D printing and I4.0 promote the CE and its related practices such as reuse, which extend the lifecycle of a product and recycle, which optimises the consumption of natural resources. It is interesting to see that blockchain also facilitates CE by improving the recycling process through enhanced data tracking and introducing various incentives such as cryptographic tokens in exchange for recyclable bottles and cans [17].

Analysis of the top 10 keywords shown in Fig. 4 reveals that sustainability and supply chains top the table, followed by the CE. AM and BDA were the most frequently discussed I4.0 related technologies. This finding is further aligned with the results of Fig. 3 where articles published by Despeisse et al. [16] and Hazen et al. [18] discuss research agendas related to AM and BDA intersecting CE and sustainable supply chains. I4.0 becoming the fourth in the most used keyword list along with AM and BDA also supports the findings depicted in Fig. 3 as the most local cited article by Jabbour et al. [15] provides a roadmap and research agenda for sustainable operations incorporating I4.0 and CE. Further, after a close investigation of all keywords listed in 414 papers, it is noteworthy that I4.0 technologies such as CPS, cloud computing, autonomous robots, augmented reality, and horizontal and vertical integration are the least explored areas intersecting CE, SCM and quantitative methods related research fields.

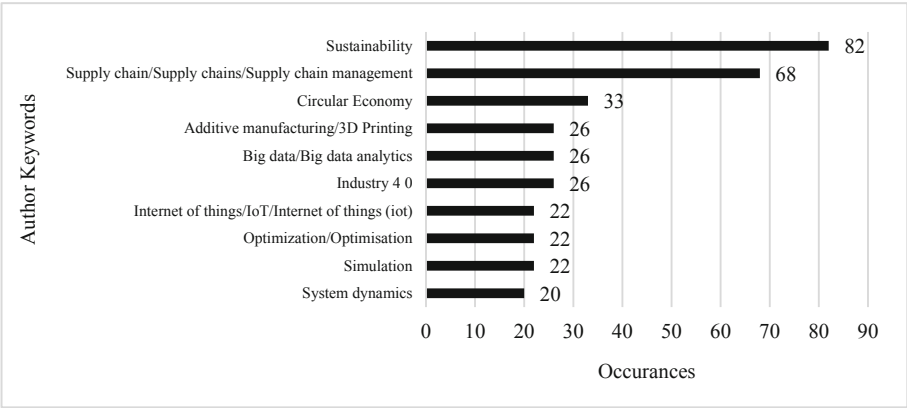

Fig. 4. Most frequent keywords

Examining the author collaboration network highlighted five main thematic clusters. These clusters include three or more papers per cluster, as shown in Table 1.

Table 1. Thematic clusters

Cluster no.	Theme of the cluster	Main methods and techniques	No. papers	Key references
1	Impact of BDA towards sustainable consumption and operation	Big data and predictive analytics (BDPA)	5	[19–21]
2	Role of I4.0 technologies in CE and sustainable SCM (SSCM)	Structural equation modelling (SEM)	5	[22–24]
3	Barriers/challenges for CE implementation in I4.0 environment	Multiple methods	5	[25–27]
4	Quantitative methods for I4.0 technologies in CE and SSCM	Multiple methods	4	[28–30]
5	Impact of digital technologies on sustainability performance	Multi-criteria decision making (MCDM) techniques	3	[31, 32]

Cluster 1 investigates the impacts of BDPA on sustainability performance measures. The effects of I4.0 technologies (specially BDA) on logistics, SSCM, CE performance and CE implementation strategies such as remanufacturing has been studied using SEM in cluster 2. Articles in cluster 3 and 4 employ multiple quantitative methods/techniques

such as system dynamics, MCDM methods (e.g., DEMATEL) and mixed integer non-linear programming. Cluster 3 investigates the barriers, challenges and benefits of I4.0 technologies on sustainability performance, where cluster 4 explores how different quantitative methods can be operationalised to achieve highly efficient logistics services under the I4.0 enabled CE and SSCM environment. Cluster 5 underlines the impacts of digital technologies on sustainability performance while understanding the implications of I4.0 technologies. The comparably low number of studies per cluster suggests that the research potential of these topics is not yet fully exploited.

5 Conclusion and Future Directions

This paper presented a structured review on the intersection of I4.0, CE, SCM and quantitative methods. A comprehensive bibliometric analysis was conducted on this upcoming research arena that paves the path for new research avenues. The results identified the most influential authors, articles and pointed out the evolving research clusters in this intersection of four research fields. The study also identified research agendas and road maps discussing the juncture of I4.0 and CE/SSCM, which were identified as the most cited articles of the investigated scope of our study. Further investigation of these studies highlighted that I4.0 is becoming a digital enabler of CE. I4.0 driven sustainable supply chains and manufacturing supply chains are emerging for future research directions where AM, IoT and BDA are the most prominent technologies discussed in those research fields. Careful investigation of the author collaboration network provided several suggestions for future research opportunities connecting I4.0 with sustainable business models, sustainable operations and sustainability performance focusing CE. Moreover, it is noteworthy to mention that quantitative methods gained a new approach with the introduction of BDA.

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